Collision avoidance of autonomous ships in inland waterways – A survey and open research problems

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Abstract. Promoting autonomous surface ships in inland waterways traffic (IWT) is a potential solution towards reducing road traffic and transport emission footprints. Over the last decade, there has been a growing research on autonomous ships for open waters. However, applying this research to the IWT domain is not straightforward. The IWT, due to its confined waterways, poses a different challenge than the open sea case. Due to the confined waterways, inland ships face several hydrodynamic phenomena that they rarely encountered in the open sea, such as shallow water, banks, or ship-to-ship effects. Furthermore, the higher traffic density in inland waterways also requires a different solution for sensing and control systems.

This paper offers an overview of the current developments on autonomous collision avoidance for inland waterway ships that covering different problems of safety navigation for ship in IWT. A short analysis is presented to highlight the strengths and weaknesses of each approach. We also discuss the current research gaps and what could be improved to enable the operation of inland autonomous ships.

1. Introduction

Waterways transport is often seen as a green solution toward decreasing road congestion. The emission footprint of waterways transport is significantly lower than that of road traffic [1]. However, while maritime transport took a compelling market share of freight transport at the intra-EU level in 2020 (29%), the Inland Waterway Transports (IWTs) only has 5.8% of the market share for inland freight transport in the EU [2]. Promoting IWTs could enhance sustainable mobility and alleviate heavily congested transportation routes. One of the main reasons that hamper the widespread use of inland waterways transport is the operating cost, especially crew wages. At this point, autonomous ships become a potential solution for enabling the wide use of IWT. The use of autonomous ships could reduce the crew cost and fuel cost [3] and increase the cargo capacity [4]. Arguably, the main obstacle in introducing autonomous ships into use is the guarantee of safety for both autonomous ships themselves and other unmanned ships.

The recent decade has witnessed the rapid development of autonomous ships [5]. The navigation of ships moves from relying on a minimal crews onboard to partial support by the autonomous control and fully operated by the autonomous control in the future. However, to achieve fully autonomous ships, one critical condition is the safety of navigation that must be assured. Safe navigation should guarantee the collision-free sailing of a ship from the start point to the endpoint. The advancements towards safety navigation includes: the improvement of maneuvering system [6]; sensors system [7]; and collision avoidance (COLAV) system [8]. The development of the maneuvering system helps the ship better track the planned route in different situations. The sensor system improves the situation awareness and the COLAV system helps ships avoid collision with static and dynamic obstacles.

IWT holds some distinct characteristics that it does not share with maritime traffic. Inland waterways are bodies of water, e.g., rivers, and canals, located within a country's borders and used for transportation. Inland waterways are normally referred to as confined waterways in which a waterway is limited in depth and width. The confined environment reduces the sailing space and changes the hydrodynamic properties of ships. While the shallow water change the longitudinal movement of ships, the interaction with water banks and other ship also affect the lateral movement of ships [6]. Moreover, due to the confined environment, ships sailing in inland waterways experience ship-to-ship hydrodynamic interaction more often than in open water. It leads to maneuvering control systems needing to adapt to the changes [9].

In IWTs, ships encounter obstacles (both dynamic and static) at a close distance more often than in the open sea. Thus, an inland autonomous ship requires a different sensor suite than a seagoing ship [7]. Furthermore, ships must also follow inland traffic rules, which differ from those applied at sea, i.e., the Convention on the International Regulations for Preventing Collision at Sea (COLREGs). Therefore the sensor and COLAV system must satisfy specific requirements to guarantee safe navigation.

1.1. Related works

Several attempts have been made to give an overview of the state-of-art development of collision avoidance systems for autonomous ships. A survey on state-of-art algorithms on motion control of maritime autonomous surface ships is introduced in [9]. The research in [8] discussed the approaches to control algorithms for the COLAV problem and the link between manned and unmanned ships. Comprehensive reviews of collaboration between ships are presented in [10, 11]. Furthermore, a survey of the ship-to-ship hydrodynamic can be found in [6]. However, those literature reviews mainly focus on the open water domain.

Besides, there are notable review papers within the inland waterways domain. In [12], the knowledge gap in maneuverability prediction for inland waterways and the difference between inland ships and seagoing ships is discussed. The logistic aspects of IWT are described in [13]. It is worth mentioning the sensors evaluation for inland autonomous ships that presented in [7]. That being said, to the best of our knowledge, there is no survey that concentrates on collision avoidance and the related problem of inland waterways ships specifically.

1.2. Contributions

This paper aims to synthesize the current developments in collision avoidance for autonomous ships operating in inland waterways. Several approaches are reviewed and analyzed to emphasize the strengths and weaknesses. In comparison with the existing studies, the main contribution of our paper are:

- An overview covering different aspects of the developments of the COLAV system for inland autonomous ships.
- Identifying the knowledge gap and the open problems in COLAV for autonomous inland ships.

1.3. Outlines

The rest of this paper is organized as follows. The methodology and scope of this research are described in Section 2. The state-of-art studies on COLAV for inland waterways ships are introduced in Section 3. Then in Section 4, we discuss the open research questions for COLAV for autonomous inland ships. Finally the conclusion is given in Section 5

2. Research framework

2.1. Research scope

The research scope of this paper focuses on the COLAV problems of autonomous ships in inland waterways. We attempt to synthesize the difference between the seagoing and inland autonomous ships. Furthermore, the review is not limited to the domain of inland waterways but also covers other confined waterways, e.g., harbor and fjord, since they share similar characteristics.

2.2. Methodology

A systematic review is conducted based on the criteria in Table 1. We search the keywords in the Web of Science database within the field of title, abstract, and author keywords. We exclude papers that are not in English or published before 2000 and papers in the field of air, ground, underwater, space, biology, or medicine. Besides, additional papers are not included in the search but are found in the reference lists of the selected papers are included. The review process is recorded using the PRISMA method, [14], and presented in Fig. 1.

3. COLAV for inland autonomous ship

Generally speaking, the problem of COLAV can be viewed as an optimal control problem (OCP). The OCP is described as follows: Given a starting waypoint and an end waypoint, the algorithm needs to find a collision-free path in the working space to connect two waypoints with minimum effort in terms of energy or time to arrive at the end waypoint. The solution must

Table 1: Systematic review's search criteria

Subject	Description
Database	Web of Science
Search keyword	(“collision avoidance” OR “path planning” OR “navigation”) AND (ship OR vessel OR barge OR ASV)AND(“confined water” OR “narrow water” OR “shallow water” OR “inland water” OR harbour OR “urban waterway”)
Exclusion field	Air, ground, underwater, space, biology, medicine
Language	English
Time interval	2000 - January 2023

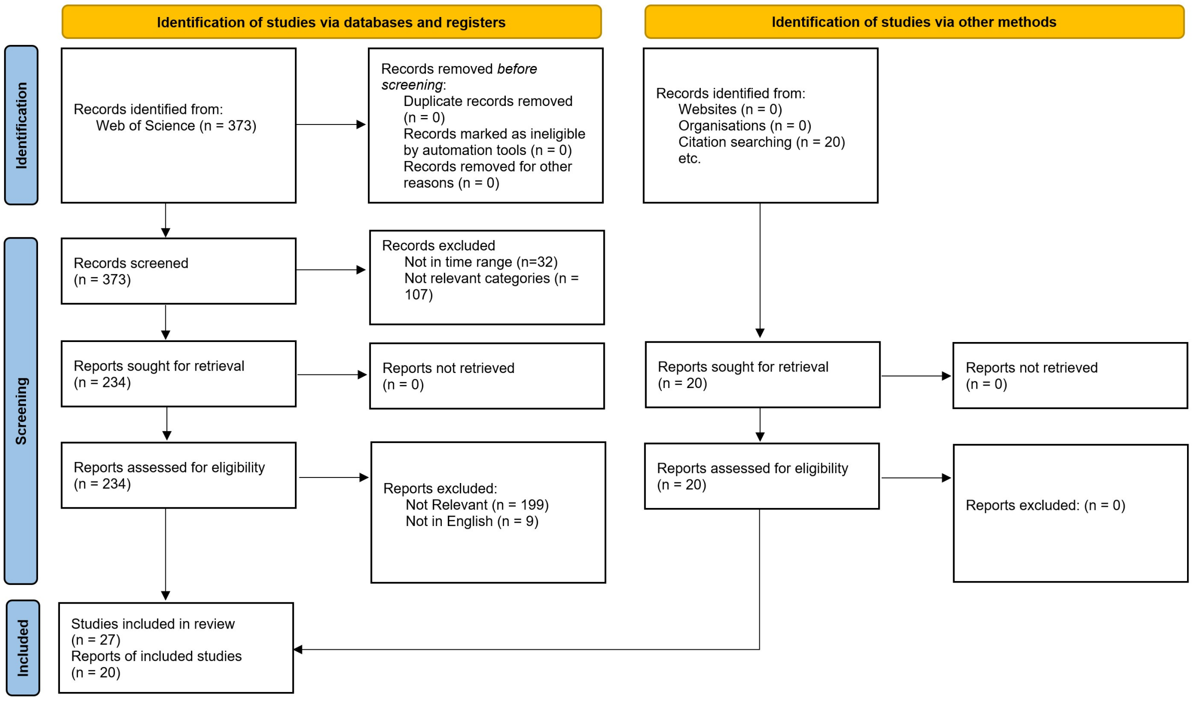


Figure 1: Systematic review of collision avoidance of autonomous ship in inland waterways presented with PRISMA 2020 flow diagram [14]

satisfy additional constraints such as traffic rules compliance, output constraints, or cooperation, depending on the situation. Based on the number of participating ships, one can divide the COLAV problem into single-agent COLAV or collaborative COLAV problem.

In the single-agent COLAV problem, the own ship (OS), i.e., the ship that one owns, acts as an isolated agent making decisions based on its perception of the surrounding environment without exchanging her intention with nearby ships. The target ship (TS), i.e., the ship that sails in the proximal area of the OS, is considered a dynamic obstacle whose intention is predicted by the OS based on its knowledge. The single-agent COLAV (Sa-COLAV) problem has received more attention in the literature. The challenge here is how to predict the future position of TS. The most convenient way is assuming that the speed and course of TS are constant and the future position is estimated following the physical laws [15]. However, this assumption is unrealistic since the TS might also be aware of collision and may change their course during the OS encounter [16]. It is more crucial in confined waterways since a small error in estimating the TS trajectory could result in a collision [8].

On the other hand, the collaboration COLAV (C-COLAV) problem considers the benefit of the OS and the benefits of the target ships (TS). Accordingly, the ship in an area of interest will exchange information and make a consent solution through negotiation. By exchanging intentions, the OS can increase its perception and efficiently avoid collisions in congested waterway traffic. However, sharing information and collaboration between ships are not a simple tasks. Firstly we must decide what information needs to transfer to optimize the COLAV algorithm and, simultaneously, not burden the communication network. Secondly, a method for negotiation for ships is also vital to make a consensus solution between ships. An optimized protocol for communicating and sharing information between ships is still an open problem [10].

3.1. *Single-agent COLAV for inland waterways ship*

The Sa-COLAV control algorithms mainly focuses on seagoing ships [8], which are the most dominant cases globally. However, with the increasing need for inland freight transport, IWTs have received attention recently. Due to the confined waterways and distinct traffic scenarios, the conventional COLAV algorithms designed for the open sea are unsuitable. The COLAV algorithms for open water mainly focus on the scenario of two ship encounters, while an inland ship typically faces more than one TS at a time [17]. Unlike seagoing ships, an inland ship encounters dynamic obstacles more often, with smaller margin and at a closer range. Therefore, the inland ship requires a more precise COLAV algorithm to deal with various encounter scenarios and smaller distances and margins. There are two main problems in Sa-COLAV for inland waterways ship: path planning and following in confined area, avoid collision with dynamic obstacles.

3.1.1. Path planning in confined area Path planning aims to find the best path that connects the start and endpoint with a given map with known static obstacles. The inland waterways, due to their small in depth and width, poses challenges to the safety of ship navigation. The slow dynamics of ships are another factors that makes finding a feasible solution difficult.

Lachmeyer *et al.* [18] applied nonlinear programming (NLP) for path planning for ships in confined waterways. Unlike other methods that only consider the center of gravity (CoG) in the planning problem, this research concerns the position of the ship's CoG, bow, and stern. The polygon-based and constructive solid geometry constraints are used to formulate the channel constraints. A simulation study showed the algorithm's capability to guide the ship in confined areas, such as entering a lock.

An autonomous docking algorithm that use OCP-based trajectory planning combined with the dynamic positioning (DP) controller is presented in [19]. This research separates the docking control system into two subsystems: trajectory planner and trajectory-tracking system. The NLP solver is used to find the feasible trajectory, and then the DP controller guarantees the ship to track the planned trajectory. The DP controller helps the ship handle external disturbance and model mismatching better. The experimental test in confined waters in Trondheim confirmed the safety and performance of this proposal.

A path planning method based on the Voronoi diagram (VD) is presented by [20]. The planning algorithm includes two steps. In the first step, a set of feasible waypoints was created using VD to guide the ship on a collision-free path. Then, Fermat's spiral method generates a smooth way of connecting these waypoints. The advantage of this method is taking into account the depth constraint and current information, which are very useful when a ship is sailing in a complex environment. An illustrative example of path planning using real map data from the region of Sør Trondelag is shown to confirm the performance of the approach.

Bergman *et al.* [21] introduced a motion planner approach for ships in confined waterways using an optimization-based method. The proposed solution accounts for the complex hydrodynamic of the ship in the cluttered environment in OCP and solves it in two steps. Firstly, a feasible but suboptimal solution is calculated using the lattice-based motion planner. Then this suboptimal solution is improved in the second step using receding-horizon optimization. Navigation safety is ensured by keeping the ship in a local spatial constraint, that is a convex polytope buffer with edges parallel to the ship's edges. The simulation study case of autonomous docking in Cape Town harbor is used to verify the performance of the proposed work. In this simulation, the ship can energy-efficiency entering docking positions in the port through narrow waterways.

3.1.2. Path following and collision avoidance with dynamic obstacles The IWT scenario poses particular COLAV problems for autonomous vessels. Due to the limitation set by the banks, the

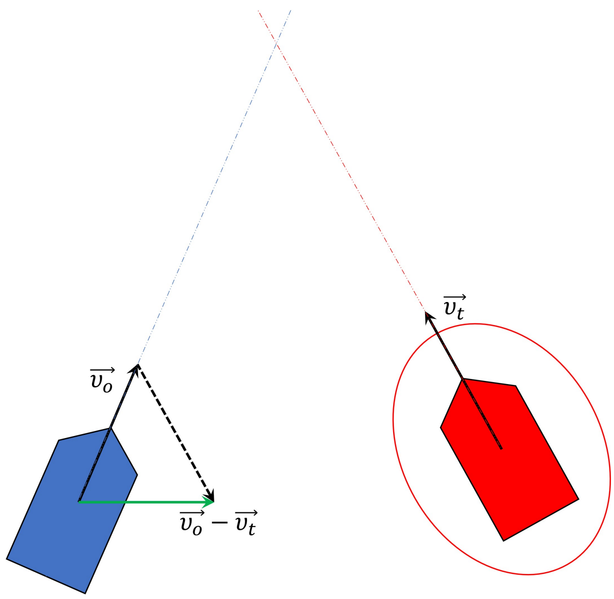


Figure 2: Velocity Obstacle method: The TS (red) has a risk of collision with the OS because the vector $\vec{v}_o - \vec{v}_t$ (green vector) points toward the TS.

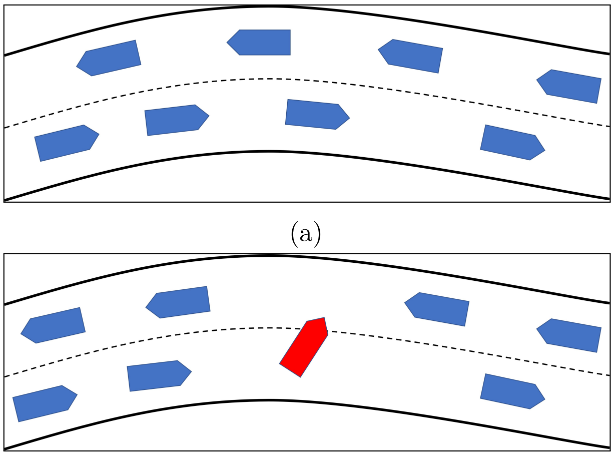
IWT usually move following virtual lanes in a road-like formation (see Fig. 3a). Consequently, the most encountered cases between the two ships are head-on and overtaking, while the crossing situation is lesser seen. At the same time, the OS has to watch more target ships and give faster collision resolution due to the smaller ship-to-ship distance.

One of the most popular methods to deal with dynamic obstacles is the Velocity Obstacle (VO) method [17, 22, 23]. The VO method uses the estimated velocity vector of both OS and TS to determine whether or not the risk of collision is in the future. Accordingly, a dynamic obstacle is considered a potential risk if the vector $\vec{v}_o - \vec{v}_t$ points toward the TS (see Fig. 2), where $\vec{v}_o$ and $\vec{v}_t$ are the estimated velocity vector of OS and TS respectively. Zhang *et al.* [24] applied this method for multiple dynamic obstacle avoidance in close quarters cases. Specifically, a buffer zone is added outside of the collision ring. Then if a TS move fast into the buffer zone, the OS will enter the close-quarter plan which abandon all COLAV regulations and sail away from the current area. From the simulation verification, the algorithm can guarantee the ship's safe navigation in case four ships encounter.

Lutz & Gilles [25] proposed a COLAV algorithm for ships in inland waterways traffic separation scheme (TSS). Because ships in TSS have to sail in a certain lane, the authors have proposed a setpoint filter model for the COLAV problem, which uses the offset distance from the bank as the only input. Then by solving the COLAV optimization problem, an appropriate lane changing plan is computed that satisfies two criteria: guide the ship to avoid obstacles and keep it in a specific traffic line at a time.

Another approach to deal with the dynamic obstacles in inland waterways is the potential field method [26, 27]. The basic concept of the potential field method is based on the physical phenomenon that describes the energy field interaction between particles. Following this, obstacle (including static and dynamic) and waterway banks in the ship's working environment can be considered an energy/risk source with its energy distribution field—the closer the boat to the risk source, the higher chance of collision. Therefore, the ship can avoid collision by sailing toward the minimum energy/risk area.

One of the situations that potentially cause accidents in inland waterways is the ship-crossing case. The risk of accident arises when a ship wants to cross the lane, e.g., join or leave a lane for



(a)

(b)

Figure 3: Ship sail in inland waterways traffic: a) Ship sail follow lane; b) A ship (red) want to cross lane

berthing, change direction of sailing (see Fig. 3b). Cheng *et al.* [28] proposed a decision-making method based on Bayesian Network (BN) for the OS crossing lane. A BN is a graphical model that describes probabilistic relationships between variables (or nodes) in a predefined set [29], in which each node is an event that has a probability for events that lead to another event/decision (child node). In this research, the BN considers the influence factors, e.g., traffic density in the lane, the distance between the OS to near TS, speed of the OS, and planning time of deviation of CS, to give an appropriate crossing strategy. The probability relationships between influence factors and the decision are defined based on expert experience. Zhang *et al.* [30] enhanced the result by considering the influence factors from traffic regulation and predicting the TS intention. The authors divide the case of crossing lanes into two scenarios: joining the near lane (same moving direction with the OS) and joining the opposite lane (opposite moving direction with the OS). Furthermore, a systematic method is presented to quantify the probabilistic relationship between nodes.

3.2. Collaboration COLAV for inland waterway ship

The C-COLAV problem has recently received significant attention in the research community. The collaboration between ships helps overcome one of the most challenging problems in Sa-COLAV: the target ship motion prediction. Navigation safety, in this case, is achieved through negotiation to result in a final collision avoidance solution. The C-COLAV problem is often formulated as a multi-agent OCP. The OCP is solved in a centralized approach [31, 32] or distributed approach [33, 34].

The centralized approach uses one central/master processing unit, which can be assigned to a particular ship or the traffic coordination center (TCC), to seek the global optimum solution. The centralized process guarantees the global optimum since it simultaneously solves the OCP for all agents. However, in practical cases, the communication between ships to TCC may be unreliable, and harm the robustness of the ships network. On the other hand, in the distributed approach, ships solve the OCP individually based on the broadcasted information of other ships. Based on the chosen framework, the OCP can be solved sequentially by each ship (non-iterative framework) or in parallel by agreement through iterations (iterative framework). It is a fact that the distributed approach cannot always guarantee the global optimum solution. However, this approach ensures the robustness of the whole system; even in the case of a lost

Table 2: Overview of inland Sa-COLAV

Paper	Control task	COLAV method	Type of obstacles	Verification method	Verification environments (or tasks)
[18]	Path planning	Polygon-based optimization	Static	Simulation	Entering lock
[19]	Path planning	OCP-based combine w/ DP	Static	Field experiment	Docking
[20]	Path planning	VD-based	Static & dynamic	Simulation	Confined water in Norway
[21]	Path planning	OCP based motion planner	Static	Simulation	Docking
[24]	COLAV w/ dynamic obstacles	Velocity obstacle	Static & dynamic	Simulation	Inland waterway
[25]	path following	OCP based setpoint filter model	Static & dynamic	Simulation	Inland waterway
[26, 27]	path following	Potential field	Static & dynamic	Simulation	Inland waterway
[28, 30]	COLAV w/ dynamic obstacles	Decision making based BN	Dynamic	Simulation	TSS

connection between ship-to-ship, each ship can still keep seeking a solution as a Sa-COLAV. A comprehensive review of communication framework for collaboration between ships can be found in [10].

When it comes to inland waterways traffic, there are two main scenarios of C-COLAV: the bi-direction waterway and intersection crossing (see Table 3).

3.2.1. Bi-direction waterways collaborative COLAV The bi-direction waterway (BDW) refers to ships sailing along a confined waterway with only two directions: upstream or downstream. In this scenario, the most common encounter situation is head-on and overtaking due to the limited sailing direction.

The research that is presented in [35, 33] formulated the C-COLAV in bi-direction waterways as a train-like formation control problem. The problem is solved by a distributed MPC (DMPC) based on Alternating Direction of Multipliers Method (ADMM) in a serial manner. Besides, using the single-layer distributed framework allows ships to negotiate directly with other ships in the network without needing a coordinator. Following the serial iterative scheme, only one ship solves the COLAV problem, i.e., one ship performs an action at a time while all other ships wait for the decision from the active one. This scheme allows each agent ship to receive the most up-to-date from the neighboring ship, avoiding potential conflict between agents. The scalability and performance of the algorithm are verified in simulation with scenarios of up to 30 ships.

Tang *et al.* [36] proposed a distributed control algorithm for navigating ship formation through narrow channels with unknown curvatures. A curvature observer is used to guarantee smooth sailing in narrow channels. Each ship will follow the next preceding ship in the ship-train and estimates the channel's curvature from the trajectory of the preceding ship. A cascade two-level controller is proposed. On which the lower-level controller guarantees the trajectory tracking. The higher-level control takes responsibility for the formation-keeping of ships. Further more, the higher-level control also guarantees for collision-free navigation between ships and ship to bank. The numerical simulations and basin experiments are deployed to verify the algorithm's performance.

A distributed MPC control for COLAV with COLREGS compliance for physically-connected multi-vessel system is proposed in [37]. This system includes two tug boats cooperating to tow a bigger ship, e.g., a container ship. Due to the physical constraints between vessels, the maneuverability of the system is limited. Therefore it puts more challenge in the COLAV task, especially in confined waterways. The COLAV problem is solved in two steps: the first step is finding a collision-free path, and the second step is the cooperative control of multiple vessels.

3.2.2. Intersection crossing collaborative COLAV The intersection crossing (IC) situation happens when ships sail across an intersection or a lock. The situation may involve multiple vessels arriving from different directions.

Ferranti *et al.* [34] proposed a cooperative COLAV using the ADMM framework. Following the proposed method in this research, the problem of COLAV for multiple ships is first formulated in a centralized manner. Then this centralized problem is reformulated into a distributed COLAV problem, where the local problems are solved parallel in each ship. Besides parallel solving of the COLAV problem, each ship will continuously exchange the solution, i.e., the planned trajectory, with other ships through the ADMM framework. A simulation study is performed to demonstrate the algorithm's performance.

Another Distributed MPC (DMPC) based on ADMM is introduced in [38]. Unlike the method in [34], this proposed DMPC is not fully distributed since it requires a coordinator to compute the share variable, i.e., a variable that is shared between agents. However, due to the presence of a coordinator, the amount of information exchange between ships is reduced. Moreover, by applying the successive linearization technique to the collision avoidance constraints, the convergence speed of the proposed algorithm is significantly improved. This method is further extended in [39], with the tube-based MPC to increase the system's robustness with respect to the environmental disturbance.

A different approach for the intersection crossing problem can be found in [40], where the problem is modeled as a job shop scheduling problem and is solved by a intersection controller (IC). By using the assumption that each waterway has two separate lanes (as the typical land road), the intersection area can be represented as four blocks (see Fig. 4). Following that, each ship that crosses the intersection has to sail through the blocks in a predetermined sequence. The goal is to find an appropriate crossing time for every ship that satisfies that there is no more than one ship in each block at a time. This method is further improved in [33] with the removal of the two lanes assumption. Besides, the number and position of the crossing block are not pre-determined. Instead, it is dynamically assigned based on the situation, i.e., the crossing block is where the ship's paths cross each other. This paper also extends the scale of system and considers the collaboration of multiple ICs using the ADMM framework. Accordingly, ICs in a connected waterway network can exchange information to reduce conflict and congestion at intersections.

4. Open problem in COLAV for autonomous inland ships

4.1. Traffic rules compliance

As with many other types of vehicles, ships' operation in waterway traffic must comply with specific traffic rules. For instance, a ship sailing in open water must comply with COLREGS rules provided by International Maritime Organization (IMO). Compliance with the traffic rules is necessary since the behavior of autonomous ships have to be readily observable and predictable for not only other autonomous but also non-autonomous ships.

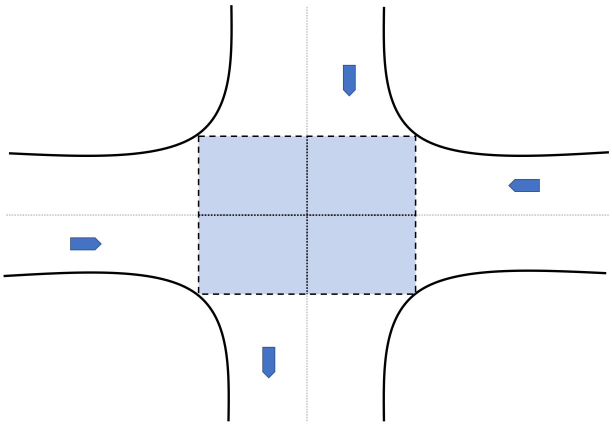


Figure 4: Intersection crossing scenario with block separate regions.

Table 3: Overview of inland C-COLAV

Paper	Traffic scenario		Communication scheme	COLAV method	Rules compliance	Verification method
	BDW	IC				
[38]	-	✓	Distributed w/ coordinator	DMPC w/ Fast-ADMM	-	Simulation w/ 5 vessels
[39]	-	✓	Distributed w/ coordinator	Tube-based DMPC w/ ADMM	-	Simulation w/ 3 vessels
[35]	✓	-	Fully distributed	DMPC w/ serial iterative ADMM	-	Simulation w/ up to 30 vessels
[40]	-	✓	Centralized	MIP$^{(1)}$	-	Simulation w/ 9 vessels
[34]	-	✓	Fully distributed	DMPC w/ parallel iterative ADMM	-	Simulation w/ 3 vessels
[33]	✓	✓	Decentralized	MIP w/ ADMM	-	Simulation w/ 30 vessels
[36]	✓	-	Distributed w/ coordinator	FFTC$^{(2)}$	-	Indoor experiment w/ 3 vessels
[37]	✓	-	Distributed w/ coordinator	DMPC w/ ADMM	COLREGS compliance	Simulation experiment w/ 3 vessels*

$^{(1)}$: Mixed Integer Programming.
$^{(2)}$: Flexible Formation Control Protocol.
* : The simulation setup including 1 container ship with 2 tug boats.

Depending on the local region, the inland waterways are governed by different rules, e.g., the *Police regulations for the navigation of the Rhine* is applied for Rhine river, the *Binnenvaartpolitiereglement* is applied for Netherlands inland waterways. The main difference between the inland waterways rules in comparison with COLREGS is that the priority of a ship (stand-on or give-way) when encountering another ship is determined by the ship's position in the waterways and does not depend on the target ships (as the COLREGS). For example, according to *Binnenvaartpolitiereglement*, when it comes to head-on situations, the OS will have stand-on responsibility if she sails on the starboard side of the waterways.

The struggle to apply the traffic rules to the COLAV algorithms is that the rules are often described as binary situations. One solution for this is introducing binary variables to indicate the status of rules violation as in [41]. However, the binary variables may become a computation burden when applied to a continuous solution-space algorithm such as MPC. Another approach is predetermining the traffic situation and introducing it to the MPC as an environment constraint ([42]). That being said, when it comes to C-COLAV, the situation change after an agent update its decision, so the traffic situation must be re-evaluated. As a result, most of the research in the field of C-COLAV for inland waterways ships either does not consider traffic rules or only COLREGS rules.

4.2. Negotiation framework

The communication framework is how agents in a network exchange information to solve the C-COLAV problem collaboratively. The framework can be developed as a centralized‘ ([40]), decentralized ([33]), or fully distributed network ([34, 35]). On the one hand, the centralized and decentralized methods are preferably used to solve the problem of IC C-COLAV since it allows the traffic control center to take control of the autonomous ship in the traffic node. On the other hand, the distributed scheme is used more often in the BDW C-COLAV, where the traffic control center is absent.

In C-COLAV, the order in which each agent makes the decision is also important. Depending on the framework, agents can compute their solution simultaneously with others (parallel) or freeze and wait for their turn (serial). The parallel framework can reduce the computation time since it allows parallel computing. However, due to agents' simultaneous decision-making, the agents' solutions may conflict with others. Therefore, an efficient consensus algorithm is needed when applying a parallel scheme. The serial scheme, on the the other hand, requires time for negotiation because of the waiting time between agents. However, the conflict is avoided since all agents have up-to-date information about the decision of others.

When developing the communication framework, the authors often assume that the connection between agents is perfect, i.e., no packet loss or delay, and agents have the same computation speed. In another way, the network is assumed to be synchronous, when all the agents receive/send data at the same time. However, the connection between ship to ship, in general, is not perfect. While the packet loss and delay cause the loss of information exchanged between ships, the different computation speed of ships leads to the asynchronous communication network. If the assumption of perfect connection does not hold, it could harm the overall stability of the network and, can lead to a collision.

4.3. Cyber-security

The cyber-security threats pose a challenge to the communication framework. The increment of the level of autonomy and the intensive communication between ships make ships more vulnerable to cyber-attacks, [43]. For instance, a sensor system being spoofed or jammed can lead to misinformation in navigation, and a communication protocol with no encryption can be altered or jammed, [44]. Moreover, an artificial agent can be created within the network if the communication protocol is not secured. These cyber-attack attempts could lead to horrific accidents. Therefore, securing the system against cyber-attack and protecting the integrity of the information is one major criterion when developing an autonomous ships and their operating concent, and communication framework.

4.4. Collaboration between different types of ships

Since the typical IWT will include both manned and unmanned ships, it is evident that only some can perform cooperative actions during collision avoidance situations. The AIS, the current standard for information exchange between ship-to-ship and ship-to-shore, only provides very limited navigation information, which is the course and speed of the ship. The use of advanced route exchange protocols, such as STM [45], MONALISA 2.0 [46], and VDES/AIS 2.0 [47], can provide detailed information on planned routes. However, these protocols are only an informed communication method and do not include negotiation protocol. Therefore, an autonomous ship could not expect the neighboring ship, which aided with the protocols as mentioned earlier, to participate in the C-COLAV situation consistently.

Based on the level of participation in the C-COLAV situation, we can divide ships into three classes as follows:

1) **Class 1 - Non-cooperative:** The ship that shares no navigation information, or only basic navigation information, and does not participate in C-COLAV, e.g., a manned ship with aided AIS.
2) **Class 2 - Partial cooperative:** The ship that shares detailed navigation information and plans but does not participate in C-COLAV, e.g., a manned or unmanned ship with an aided route exchange system.
3) **Class 3 - Cooperative:** The ship that shares detailed navigation information and participates in C-COLAV, i.e., modifies her course according to the information received from others.

Depending on the level of cooperation, a TS may be treated differently. For example, a non-cooperative TS can be seen as a dynamic obstacle, and its motion is predicted using intention prediction methods such as [48]. In comparison, a partial or full cooperative TS can be taken into account as an agent in a collaboration framework since their intention is shared.

5. Conclusion

In this paper, we presented a systematic literature review of the current development of collision avoidance for autonomous ships in IWT. Differences between seagoing and inland waterway ships have been identified, including hydrodynamic effects, sensor characteristics, and traffic scenarios. Due to these differences, the guidance & COLAV system of inland waterway require distinct solutions.

We categorized the research in the field of COLAV for inland ships based on the number of participant agents, which are Sa-COLAV and C-COLAV. In each category, we reviewed each research's theory approach, strengths, and limitations. In general, the research in the category of Sa-COLAV mainly focuses on dealing with constrained environments. The goal of Sa-COLAV algorithms is to guarantee safety guidance for the ships through waterways with limited width and depth and the dynamic obstacles coming in close quarters. On the other hand, the C-COLAV research addresses the traffic problems that arise between ships when they are cooperating sailing in IWT. Because of the distinct traffic scenarios of IWT compared to open water, the C-COLAV problem for inland ships is more crucial and receives more attention from the research community. Despite the great effort devoted to improving the autonomous COLAV system, some problems still need to be solved. We observed that none of the existing COLAV algorithms were designed to comply with IWT rules. Besides, strong assumptions used when developing the algorithms, as discussed in Section 4, could cause struggles when deploying the system in a real-world environment.

In the future, our research will focus on addressing the abovementioned limitations and improving the autonomous COLAV system. Our goal is to develop a C-COLAV that complies with inland traffic rules and allows ships with different autonomy levels to collaborate working.

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