Simulation Study on Automatic Piloting of Ships in Typical Inland Waterways

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Abstract: This article is based on typical inland waterway channels in China and conducts autonomous navigation simulation experiments of the vessel in four types of ship encounter situations—overtaking, head-on meeting, crossing, and intersecting—on the OpenCPN software platform. The experiments have reached the following conclusions: Firstly, during the course-keeping phase, the course control method can make the vessel travel along the planned route normally and keep the ship's position within a small range near the planned route, which is in line with the practice of inland waterway vessel navigation; Secondly, during the collision avoidance phase, the collision avoidance decision method can provide reasonable and effective avoidance action plans for the vessel according to different situations and the "Inland Navigation Collision Regulations", ensuring that the target vessel passes outside the vessel's domain of the vessel, while also ensuring that the vessel's domain does not exceed the channel boundaries; Thirdly, in the resumption of navigation phase, the course control method can make the vessel return to the planned route to continue navigation after the collision avoidance task is completed, maintaining the vessel's adherence to the planned route.

Keywords: Autopilot; Pursuit Crossing; Head-on Encounters; Crossing Encounters; Cross-country Encounters

1. Introduction

The inland waterway shipping industry is an integral part of global waterway transport and is important for promoting regional economic development and optimizing logistics structures. With the expansion of global trade, inland waterway transport is experiencing a steady increase in demand due to its cost-effectiveness and environmental friendliness. Against this backdrop, the strengthening of environmental regulations, especially the International Maritime Organization's enhancement of ship emission standards, has accelerated the industry's pursuit of green ship technology [1]. At the same time, breakthroughs in intelligent and automated technologies have brought new growth opportunities for the shipping industry, improving the safety of navigation and the efficiency of management.

2. Characteristics of Typical Inland Waterway Environment

China is rich in inland navigation resources, with a developed waterway network, and the waterways with better navigation conditions are mainly concentrated in the "Three Rivers and Two Rivers" waterway system [2]. The Yangtze River, as the most important waterway for inland navigation, has many tributaries, and the navigability of the upper and lower reaches varies greatly. The upstream Jinsha River has a small tonnage of navigable ships, and part of the navigation section can only be navigated seasonally, while with the opening of the entire 12.5-metre-deep water channel between Nanjing and the mouth of the Yangtze River in the lower reaches of the Yangtze River, the width of the channel in this section is relatively large, and it can be used by 50,000-tonne ocean liners throughout the year. The navigational environments of different sections of the inland waterway are very different, and it is difficult to realize autonomous navigation of ships in the whole inland waterway environment at this stage. Therefore, the research scope of this paper is limited to the typical waterways of inland waterways.

2.1 Limited Channel Width

The limited width of the waterway restricts the maneuvering of ships. Taking the Wuqiao waterway in the lower reaches of the Yangtze River as an example, the waterway is a narrow straight channel, with a channel width of less than 100 meters during the dry season. Due to the width of the channel and the influence of the surrounding beaches and submerged continents, it is difficult for ships to man oeuvre in this waterway.

2.2 High Navigational Density

The density of navigation is large, the distance between ships is relatively close, the ships meet frequently, and the meeting situation is mostly a pair of sailing encounters and catching up with each other, which is prone to collision hazards. For example, there are hundreds of ships in the navigable waters with a total length of about 7 nautical miles in the Wuhu section of the Yangtze River. Ship pilots should always keep an uninterrupted lookout when navigating in this water area, and should ensure that the ship's main engine is in a state of readiness.

2.3 Large Changes in Navigation Channels

The water depth of the waterway rises and falls with the seasons and varies greatly. During periods of abundant water, the water level of the channel rises and the water depth is rich; during periods of dry water, the water level of the channel falls back rapidly and the water depth is shallow. Some tide-sensitive waterways are subject to the synergistic effect of runoff from upstream of the river as well as downstream tidal currents off the mouth of the river, and the water level also shows significant temporal variations. In waters with insufficient water depth, vessels are prone to grounding and reefing accidents. The water depth in the inland waterway can meet the draft requirements of the representative ship type, but the water depth outside the channel varies greatly, making it difficult to ensure the safe navigation of ships [3]. Therefore, under normal circumstances, autonomous vessels should travel within the fairway and cannot sail out of the fairway, and avoidance actions are restricted by the fairway boundary.

2.4 Waterways without Confluence of Main and Tributary Streams and Forked River Mouths

According to the Inland Waterways Collision Avoidance Rules on "Confluence of Main and Tributary Waters" and "Forked River Estuary", no confluence of main and tributary waters means that there is no confluence of waters in the channel waters that are not of the same origin as that of the main and tributary waters; and no forked river estuary means that there is no diversion in the channel in the navigation section. The term "no fork" means that there is no diversion of the river channel in the navigation section [4-6]. As there are many types and numbers of vessels in the confluence of main streams and tributaries and in the mouths of forks, and the traffic flow is complicated, these waters are not considered in the study at this stage for the time being.

3. Autonomous Navigation Decision Making for Ships in Typical Inland Waterways

3.1 The Basic Process of Autonomous Navigational Decision-making for Ships in Typical Inland Waterways

The decision-making process of autonomous navigation for ships on typical inland waterways is a process of using machines to replace ship drivers in decision-making on the basis of summarising the Inland Waterways Collision Avoidance Rules and good shipcraft. Specifically, the basic process of autonomous navigation decision-making can be summarised into three stages: track keeping stage, collision avoidance stage and resumption stage. Among them, the tasks of track keeping stage and resumption stage are mainly to make the ship travelling according to the planned route. In the collision avoidance stage, when a ship takes avoidance action in accordance with the rules and effectively to avoid a collision, it usually causes the ship to deviate from the planned route.

The decision-making process for autonomous ship navigation is shown:

First, in the track-keeping phase, it is necessary to judge in real time whether there is a danger of collision between the ship and other ships. If it exists, it enters the collision avoidance phase; if it does not exist, the ship continues to sail in accordance with the planned route.

Secondly, after the ship has taken effective avoidance action, judge whether the ship and the other ship have sailed through the clearance. If so, the collision avoidance is over and the ship enters the resumption phase; if not, the ship is required to continue the collision avoidance.

Thirdly. During the resumption of the voyage, it is still necessary to judge whether there is a danger of collision between the ship and other ships. If there is, the resumption of the voyage will be interrupted and the ship will return to the collision avoidance stage immediately; if not, the ship will continue to resume the voyage until it resumes its planned route.

3.2 Overall Framework Design for Autonomous Navigation Decision-making for Ships in Typical Inland Waterways

In the real inland river environment, the target vessel may take uncoordinated avoidance actions and the trajectory is difficult to predict. In order to reduce or avoid the possible uncoordinated avoidance actions of the two vessels, the vessel needs to monitor the dynamics of all the other vessels in real time during the whole process of autonomous navigation decision-making, obtain the movement information of the other vessels without interruption, and calculate the possible passing distance of the two vessels. If the other ship's action is effective, the ship maintains the current speed and heading. If his ship's action cannot guarantee the safe passage of the two ships, the ship will use the acquired new dynamic data as the basis to decide the avoidance action that the ship should take [7]. Based on the method of real-time monitoring the dynamics of other ships, the overall framework for designing autonomous navigation decision-making for ships in typical waterways of inland waterways.

The details of the block diagram regarding the autonomous navigation decision-making module are as follows:

Firstly, using the reliable information obtained by the ship's navigation and navigational aids, including position, heading, speed and steering rate, etc., to analyse the encounter situation between the two ships and determine whether there is a risk of collision between the two ships.

Secondly, according to the result of analysing the encounter situation between the ship and the other ship, the decision-making stage of the ship is divided. If the ship is divided into the decision-making stage of collision avoidance, the other ship with the risk of collision will be marked as the target ship, the encounter situation between the two ships will be identified, and the ship will be determined as a straight ship or a give way ship.

Thirdly, according to the results of the stage division, the ship's action plan is obtained. If the ship is in the track keeping stage, the ship's action programme should be obtained according to the track control method; if the ship is in the collision avoidance decision-making stage, the ship's effective avoidance action programme should be obtained according to the collision avoidance decision-making method; if the ship sails past the target vessel after taking avoidance action, the ship's action programme should be obtained according to the resumption of navigation method and the corresponding action programme should be implemented. All phases of the ship's course of action can be accomplished by controlling the main engine and rudder and adjusting the speed and heading.

4. Simulation Experiment

4.1 Simulation Experiment Environment

In this experiment, the Wuhan section of the lower reaches of the Yangtze River is selected to simulate the real traffic environment of ships. The electronic channel charts of this section are installed in OpenCPN software, with the corresponding numbers: CN5W00WQ.000, CN5W0QSJ.000, CN5ZWHAK.000, and the constructed digital model of typical inland waterways is marked on the electronic channel charts.

The simulation section is in a non-tidal river section, and the simulation experiment simulates a ship travelling upstream from Qingshan Clip Waterway to Hankou Waterway. According to the provisions of Article 8 of the Rules for Collision Avoidance on Inland Rivers, the upstream motor vessel should travel along the slow current or one side of the channel, while the downstream vessel can travel along the main stream or the middle of the channel, and at the same time, combined with the relevant provisions of the lower Yangtze River alignment system, the ship's planned route is set.

4.2 Meeting of the Two Ships

In this paper, we set up four kinds of two-vessel encounter situations: pursuit, opposite encounter, transverse encounter and cross encounter, and carry out autonomous navigation simulation experiments in OpenCPN software platform, so as to test whether the autonomous navigation decision-making method proposed in this paper can guide the ship to complete the established navigation goals autonomously.

4.2.1 Crossing

Experiment 1 designed a scenario in which the Own Ship (OS) chased over the Target Ship (TS). The results obtained by combining the parameters of the initial states of the two ships and using the inland waterway DCPA/TCPA model are shown in Table 1.

Table 1. Initial State Parameters of the Vessel in the Aftermath Situation

shipbuilding	OS	TS
MMSI	412001000	412002000
initial position	30°40.376'n,114°26.428'e	30°39.399'n,114°23.749'e
Heading (°)	246	240
Speed (kn)	13.6	3.89
DCPA (m)	50	50
TCPA(s)	941	941

The data in Table 1 indicate that there will be a collision danger between the two vessels, according to Article 11 of the Inland Waterway Collision Avoidance Rules, OS, as an overrunning vessel, should assume the responsibility of a give way vessel to take avoidance action on its own initiative.OS takes a diversionary avoidance action while overrunning the TS and completes the resumption of the voyage after sailing past the give way clear of the TS.OS travels along the planned course for a certain period of time (41 seconds), and then, in order to overrun the TS, it takes a leftward turning During the steering process, the crossing distance between OS and TS gradually became larger. When the OS's heading changed from 246° to 243°, it then adjusted its heading so that the OS continued to travel in the direction of the fairway. After the OS passes the clearing TS, the next turning point (No. 06) is the target point to perform the re-routing procedure, and finally the OS returns to the planned route to continue travelling. The distance between the two vessels at the time of the closest encounter was about 75.4 m. The OS was located at the port side of the TS and the TS was outside of the OS's ship's domain, and the OS's speed was reduced from 13.6 knots to 12.4 knots at the present time, which was due to the increase in the ship's resistance caused by the OS's constant change of direction in the curved channel, and therefore the speed reduction process was realistic. The above experiment shows that the avoidance action taken by the OS in the pursuit situation is effective.

4.2.2 Docking encounters

Experiment 2 designed a scenario in which OS and TS meet in pairs sailing, combining the parameters of the initial states of the two vessels and using the inland waterway DCPA/TCPA model to obtain the results as shown in Table 2.

Table 2. Initial State Parameters of the Ship in the Pairwise Encounter Situation

shipbuilding	OS	TS
MMSI	412001000	412002000
initial position	30°40.376'n,114°26.428'e	30°37.078'n,114°19.986'e
Heading (°)	246	050
Speed (kn)	13.6	9.72
DCPA (m)	53	53
TCPA(s)	1000	1000

The data in Table 2 indicate that there will be a collision risk between the two vessels, and the OS, as a non-tidal upstream vessel, should assume the responsibility of the yielding vessel in accordance with the corresponding provisions of the Inland Waterways Collision Avoidance Rules and take the initiative to take yielding action.The OS, as the yielding vessel, takes the action of diverting to avoid the collision in the onward encounter situation and completes the resumption of the voyage after sailing past the yielding TS.The OS, after travelling along the planned course for a certain period of time (100 seconds), takes the After travelling along the planned course for a certain period of time (100 seconds), the OS takes a turning action to the right in order to increase the closest encounter distance between her and the TS. When the OS's heading is adjusted to 249°, it then adjusts its heading to the left to ensure that the OS continues to follow the course. Once the OS had passed the clearing TS, the next turning point (No. 06) was used as the target point to carry out the re-routing procedure, which eventually allowed the OS to return to the planned course.

The distance between the two ships at the closest point of encounter was about 72 m. The OS was on the port side of the TS and the TS was outside of the OS's ship's domain at that point of time [8]. The above experiments show that the avoidance action taken by the OS in a head-to-head encounter situation is effective.

4.2.3 Crossing

Experiment 3 designed a scenario in which the TS is a construction vessel underway, travelling slowly and laterally through the channel and meeting with an OS travelling down the channel. The results obtained by combining the parameters of the initial states of the two vessels and using the inland waterway DCPA/TCPA model are shown in Table 3.

Table 3. Initial State Parameters of the Vessel for Crossing Situations

shipbuilding	OS	TS
MMSI	412001000	412005000
initial position	30°40.291'n,114°26.199'e	30°38.867'n,114°22.209'e
Heading (°)	246	145
Speed (kn)	13.6	0.97
DCPA (m)	26	26
TCPA(s)	972	972

Table 3 shows that there will be a danger of collision between the two vessels, although TS crosses the channel, OS should assume the responsibility of the giving way vessel according to the Inland Waterways Collision Avoidance Rules and take the initiative to take avoidance action because the construction vessel underway enjoys the right to sail straight during the encounter.OS takes the action of changing direction to avoid the TS as the giving way vessel throughout the encounter and completes the resumption of the voyage after sailing past the giving way to clear the TS.OS follows the planned course for a period of time (72 seconds) and then takes action of turning right in order to avoid the TS. After a period of time (72 seconds), it took action to turn to the right to avoid the TS. When the OS's heading changed from 246° to 249°, the course was then adjusted to ensure that the OS continued in the direction of the course [9]. Once the OS had cleared the TS, the re-routing procedure was carried out, which eventually allowed the OS to return to the planned course.

The distance between the two vessels at the closest point of encounter during the entire crossing encounter was about 79.2 m. OS was at the stern of TS at that point and TS was outside OS's vessel field. The experiment showed that the avoidance action taken by the OS in the cross-over encounter situation was effective.

4.2.4 Cross-encounters

Experiment 4 designed a scenario in which OS and TS constitute a cross-encounter. The results obtained by combining the parameters of the initial states of the two vessels and using the inland waterway DCPA/TCPA model are shown in Table 4.

Table 4. Initial State Parameters of Ships in Cross Encounter Situation

shipbuilding	OS	TS
MMSI	412001000	412002000
initial position	30°39.063'n,114°23.135'e	30°36.6'n,114°19'e
Heading (°)	240	58
Speed (kn)	13.6	3.89
DCPA (m)	18	18
TCPA(s)	890	890

The data in Table 4 indicates that the risk of collision between the two vessels has been constituted, and in accordance with Article 12.5 of the Rules for Collision Avoidance on Inland Rivers on the division of responsibility for vessels in a cross-meeting situation, this vessel should actively and positively assume the responsibility of giving way to the passing vessel and take the initiative to take evasive action.

OS, as the giving way vessel, took evasive action to change direction in the cross-encounter situation and resumed the voyage after passing the giving way TS. As the remaining time for the encounter was only 890 seconds and the speed of the TS was relatively slow, the OS took the avoidance action of turning left to avoid the TS at the beginning of the encounter. Upon reaching the target heading of 235°, the course was then adjusted to ensure that the OS continued in the direction of the fairway. When the OS passed the clearing TS, the next turning point (No. 09) was the target point to perform the re-routing procedure, which finally enabled the OS to return to the planned course and continue travelling.

During the entire cross-encounter, the distance between the two vessels at the closest moment of encounter was about 79.8 m. OS was located right directly across from TS and TS was outside OS's ship's domain at that moment [10]. The above experiment shows that the avoidance action taken by the OS in the cross-meeting situation is effective.

5. Conclusion

The two main functions of an autonomous navigation decision-making system for ships in typical inland waterways are track control and collision avoidance decision-making. The above experiments lead to the following conclusions:

Firstly, in the track keeping phase, the track control method enables the vessel to follow the planned route during normal navigation and keep the vessel position in a smaller range near the planned route, which is in line with the navigation practice of inland waterway vessels;

Secondly, in the collision avoidance stage, the collision avoidance decision-making method can provide the vessel with reasonable and effective avoidance action plans according to different encounter situations and in conjunction with the Inland Waterway Collision Avoidance Rules, to enable the target vessel to pass outside the vessel's ship area and at the same time to ensure that the vessel's ship area does not go beyond the fairway boundary;

Thirdly, during the resumption phase, the trajectory control method can enable the ship to resume to the planned route to continue sailing after the completion of the collision avoidance task, and maintain the ship's following of the planned route.

The experimental results show that the autonomous navigation decision-making method for ships in typical inland waterways proposed in this paper is effective, which not only has the ability of trajectory control, but also is able to guide ships to navigate safely under the constraints of the ship's motion control, Inland Waterways Collision Avoidance Rules and the boundaries of inland waterways.

Acknowledgments

This work was supported by "Research on Digital and Intelligent Safety of Typical Inland Waterway Navigation" (Project No. 2024CSLKT3-622).

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