Research on ontology-based situation understanding and decision-making approach for MASS

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Abstract. Aiming at the problems of miscellaneous navigation safety information and the difficulty of multi-source heterogeneous information fusion, a novel ontology-based collision avoidance decision making method is proposed in this paper. first of all, the structured ontology model of navigation situation is built on the basis of analysing the hierarchy and interactivity of various scene elements in driving scene and constructing the semantic model of entity class and binary attribute of scene elements, implement effective modelling of navigation scenarios. Secondly, the knowledge base of collision avoidance decision and online reasoning system are constructed based on the semantic expression of typical scene elements to realize the efficient utilization of navigation prior knowledge. Finally, the simulation experiment is carried out for the typical ship encounter scenarios in open water. The results show that the ontology method can effectively improve the cognition ability of Maritime Autonomous Surface Ships (MASS), and meet the requirements for real-time, safety and rationality of collision avoidance decision.

1. Introduction
The concept of scene understanding was first proposed by Endsley, and was used to describe the process of pilots’ perception, interpretation, and prediction of aircraft operations [1]. The perception and understanding of the ship's driving scene are the primary prerequisite for the safe navigation of an autonomous ship. A true autonomous ship should be able to understand the semantic meaning of sensor data, so as to make safe driving decisions such as steady course, steering, and emergency stop. Most of the existing driving scene analysis and applications are mainly focused on the perception of the scene. The driving scene data is obtained through various sensors such as AIS, radar, electronic charts, etc. Amit Sharma determined the specific information needs at three different levels of perception, comprehension, and projection by analyzing the factors that affect the understanding of the scene in the actual goal directed task [2], Mogens Blanke discretized the elements of the navigation scene and proposed an autonomous situation awareness framework based on the DES theory, which realized the demonstration of the collision risk of three ships [3], X.Y. Zhou used probability theory to quantify the scene perception process to achieve the goal of guiding the navigational safety of autonomous ships [4], O.V. Smirnova analyzed the current existing situational awareness model, neither used the ontology-based method to perceive...
the navigational situation nor gave out of the implementation method [5], Wanqi Wei et al. constructed a multi-entity Bayesian network for the uncertainty of navigation information and expressed the fuzzy navigation information in a probabilistic form[6]. These methods focus on the process of environment perception, and process the acquired data information to realize the scene understanding based on rules and driving environment. However, they are not capable of combining the scene understanding and collision avoidance decision, and this makes it difficult for these methods to cope with the navigation needs of ships in different sailing areas and different encounter scenarios. Therefore, it is necessary to construct a knowledge representation method capable of handling the fusion of complex and multi-source safety information, and able to imitate the process of experienced ship pilots cognizing the current ship's navigation environment through lookout, so as to assist autonomous ships generate reasonable driving decisions.

The ultimate goal of perception and understanding of navigation scenarios is to support the decision-making of autonomous ships’ driving behavior. The autonomous decision-making of ships is an important manifestation of the highly intelligent ship's autonomous navigation. There are many methods of research on autonomous ship collision avoidance decision-making, which are mainly divided into the following four categories: The first is to build a collision avoidance expert system based on driving knowledge and collision avoidance rules, and to realize anthropomorphic collision avoidance decisions by matching the ship's encounter eigenvalues [7-9], the second is the artificial intelligence algorithm, which uses reinforcement learning, deep learning and other methods to set rules as reward functions to train agents to achieve the goal of safe navigation of ships [10-12]. The third is a deterministic algorithm, typically there are artificial potential field [13], velocity obstacle algorithm [14], graph search algorithm [15], etc. In order to plan the navigable area of the ship to achieve the goal of collision avoidance decision, these methods handle obstacles reasonably, such as constructing a repulsion field, calculating the speed obstacle interval and soon. The fourth is intelligent optimization algorithms, such as A* algorithm [16-17], evolutionary algorithm [18], ant colony algorithm [19], etc. using search strategies, information exchange between groups to find an approximate optimal path, and calculate collision avoidance decision information. In summary, most collision avoidance algorithms convert collision avoidance rules into navigational constraints and give rule-based collision avoidance decisions. However, this process failed to truly combine the ship’s navigation safety information with collision avoidance decisions, also lacked a comprehensive understanding of the driving environment.

This paper proposes an ontology model containing navigation scenes based on ontology methods and a reasoning rule library based on driving experience. Compared with the previous algorithm the model based on ontology for scene understanding and decision-making has two advantages: At the algorithm level, the scene understanding and collision avoidance methods based on the ontology model have good interpretability. The reason is that the existing algorithms lack the support of the driving experience, the method proposed in this paper is based on the COLREGS and good seamanship. In the rule base, the steering action is based on the rules of the decision-making, which are in line with actual maneuvering requirements. In terms of environment modelling, compared with the widely used grid map method obtained entity attributes and relationships by searching row by row, the environment representation method based on ontology model can directly restore the attributes and relationships of scene elements from the acquired information, and semantic-based navigation scenarios can improve the reasoning ability of rules and provide decision support for safe navigation of ships.

In this study, it is assumed that the navigation area is open water, and that radar data and decoded AIS data are known. Using AIS data containing rich ship information to construct the ship navigation environment information, including wind, wave and flow properties. In addition, the use of onboard radar information to construct the properties of the target ship, including the target ship's course, velocity, the range between target ship and own ship as well as TCPA and DCPA. When building the rule base, the main consideration is the COLREGS (include R13, R14, R15, R16) of the two ships encounter situations, and the good seamanship of the ship's decision-making behavior.
This paper mainly considers the restrictions of rules and maneuvering experience on the decision-making behavior of ships under the situation of two ships’ encounter. Furthermore, this work has not dealt with the problem of multi-ship collision avoidance, the multi-ship scene understanding and collision avoidance issues will be further discussed in the future work.

2. Navigation scene ontology model

In order to express the relationship between the autonomous ship and the navigation environment more clearly and accurately, the entity and corresponding entity attributes are constructed by analysing the composition of the entity model and the scene elements of the real navigation environment. An instantiated scene expression is based on the two ships’ encounter situation in the open water is shown.

2.1. Ontology

Ontology first originated in the field of philosophy, and recently developed into fields such as computational science and information science. It has been widely used in the semantic web, biomedicine and other fields. Ontology contains different types of knowledge such as facts, rules, definitions, etc. It has no inference function itself, and needs to be combined with an inference engine to form a knowledge system to solve the problem of artificial intelligence. The composition of the ontology model is as Figure 1.

![Figure 1. Composition of ontology model](image)

A complete ontology knowledge model consists of Terminological Box (TBox) and Assertional Box (ABox), where TBox is used to construct a conceptual model of objectively existing objects, which consists of classes, attributes, and relationships, and is stored in the knowledge base in the form of prior knowledge. ABox is a materialized representation of the concepts in TBox, which instantiates the individuals actually observed in the scene and stores it in the knowledge base as the scene knowledge in the scene. For example, in the actual navigation scenario, the class "obstacle" is defined in the TBox. When there is a target ship in front of the own ship, MMSI= 412701000, it is instantiated as a specific "obstacle" instance and stored in the ABox.

2.2. Elements of a navigation scene

Determining the scene elements is the first step in constructing the ontology model. By combining the rules and the constraints of ship navigation restrictions, the ship’s navigation scene elements are divided into autonomous ships (own ship), environmental elements, obstacle elements, and chart elements (navigation area elements). The composition of scene elements is shown in Figure 2.
From the perspective of autonomous ship collision avoidance decision, this figure divides the navigation scene elements into two parts. One part is the information related to the autonomous ship itself, including position and collision avoidance decision information. The decision information includes lateral steering decision and longitudinal speed change decision. The other part is related information of traffic environment, mainly including weather conditions, obstacle conditions and navigation area. The specific composition and interpretation of the entities of various elements are elaborated in Section 2.3.

### 2.3. Navigation scene ontology model

After the hierarchical division of the scene elements, these elements need to be conceptualized to construct the TBox to complete the construction of the navigation scene in ontology model. The autonomous ship (own ship), environmental elements, obstacle elements and chart elements are transformed into entities, and the attributes of the entities are constructed to describe the relationship between the autonomous ship and the navigation environment. The conceptual model of the navigation scene ontology based on figure 2 is organized by 4 parts:

- **Chart entity**: Chart is an important source of knowledge of ship's navigation scene, The ship's navigation scene is constrained by constructing the type pairs of different navigation areas to facilitate the construction of navigation rules for different navigation areas.
- **Environmental entity**: Environmental entities are used to describe current weather conditions and sea conditions, mainly including wind, waves, currents and visibility, wind, waves, currents, water depth, etc.
- **Autonomous ship entity**: this entity is used to describe autonomous ship's navigation state, which include position, velocity, course, possible driving decision include the change of velocity and course.
- **Obstacle entity**: Obstacle entities are divided into two categories, one is dynamic obstacles including various types of ships and marine animal, and the other is static obstacles including various types of navigation aids and marine structures;

After the construction of the entity class is completed, the interactivity and characteristics of the scene elements need to be converted into properties of related entities. The properties mainly have three parts including position attributes, relationship attributes and data attributes. The properties listed in the relevant part of this article are shown in Table 1.
### Table 1. Navigation ontology model property

| Name               | Property          | Domain               | Range               |
|--------------------|-------------------|----------------------|---------------------|
| Position property  |                   |                      |                     |
| hasLongitude       | autonomous ship   | double               |                     |
| hasLatitude        | autonomous ship   | double               |                     |
| hasForntObstancle  | autonomous ship   |                     | obstacle(dynamic/static) |
| hasLeftObstancle   | autonomous ship   |                     | obstacle(dynamic/static) |
| hasRightObstancle  | autonomous ship   |                     | obstacle(dynamic/static) |
| hasBehindObstancle | autonomous ship   |                     | obstacle(dynamic/static) |
| hasTCPA            | target ship       | double               |                     |
| hasDCPA            | autonomous ship   | double               |                     |
| hasVelocity        | autonomous ship   | double               |                     |
| hasRange           | autonomous ship   | double               |                     |
| hasCourse          | autonomous ship   | double               |                     |
| Data property      |                   |                      |                     |
| hasWind            | Navigation Area   | int                  |                     |
| hasCurrent         | Navigation Area   | double               |                     |
| hasVisibility      | Navigation Area   | int                  |                     |

By constructing the entity and the properties of the entity, the dynamic and static characteristics of the autonomous ship and the navigation environment in the actual navigation scene can be clearly expressed. The reconstructed navigation safety information scene is realized in the "brain" of own autonomous ship's driving system, this process can be regarded as the polit's cognitive process of looking at the surrounding environment in the brain.

```
navigationarea(opensea),haswind(opensea,2)
hascurrent(opensea,1.7),hasvisibility(opensea,8)
```

**Figure 3.** Instantiation of collision avoidance scenarios in open sea

Figure 3 shows the instantiation of ABox in an open sea navigation scenario.

Assuming that the autonomous ship's navigation area is open sea, there are no obstacles other than a target ship, the current navigation environment is instantiated as `navigationarea(opensea)`, the wind level is instantiated as `haswind(opensea,2)`, and the current rate is instantiated as `hascurrent(opensea,1.7)`, the visibility level is instantiated as `hasvisibility(opensea,8)`, the obstacle information is instantiated as `obstacle(targetship)`, the course and velocity of the target ship can be instantiated as `hasCourse(targetship,180)`, `hasVelocity(targetship,7.5)`, Instantiate the calculated distance of the target ship, TCPA, DCPA into `hasRange(targetship,2.1)`, `hasTCPA(targetship,20)`, `hasDCPA(targetship,0.5)`, the course and speed related to the autonomous ship (ownship) can be turned into `hasCourse(ownship,0.00)`, `hasVelocity(ownship,8.6)`. At this point, the instantiation process of the entire navigation element is completed, and that can be regard as the process of ABox.
3. Navigation Decision Rule Base

The construction of the navigation scene ontology model is equivalent to the pilot’s prior knowledge of the environment, and the navigation decision rule base is equivalent to the acquired and accumulated driving experience of the ship’s pilot, including seamanship and navigation rules. By combining the ontology model and the rule base, the process of simulating experienced pilots to make collision avoidance decisions can be realized.

Considering the huge workload of building a complete rule base for the entire navigation area, this paper uses SWI-Prolog software to build a navigation rule base for open sea to store and query rules.

The rule base lays the foundation for building a comprehensive rule base and solves the problem of collision avoidance decision based on scene understanding. The rule base is mainly composed of two parts. The first part uses the results of the instantiation of the ontology model to reason about the encounter situation to come up with the specific encounter situation, the second part further refines the constraints under the current situation and matches matching collision avoidance decision information with driving experience. The following explains the two parts of the rules.

3.1. Rules for situation classification

On the basis of following the spirit of COLREGS, the encounter situation between the two ships is divided into five situations: heading-on, overtaking, overtaken, left crossing situation, right crossing situation. Consider specifying in the provisions of the collision avoidance rules 'When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly' And may involve a situation where uncoordinated collision avoidance exists, this paper sets the angle of overtaking as 107.5°, and 351° as the boundary between the heading-on and crossing encounter situation. Examples and explanations of some prolog rules in the prolog rule base are shown in Table 2.

| Encounter Situation | Instantiation information | Reasoning condition |
|---------------------|---------------------------|---------------------|
| Overtaking          | ts_hasBT(ts,BT), ts_hasTCPA(ts,TCPA), ts_hasRange(ts,R), ts_hasVelocity(ts,VT), os_hasVelocity(os,VO), ts_hasCT(ts,CT), os_hasCO(os,CO). | 107.5+CT≤CO+BT+180≤CT+252.5, VO>VT, R≤3, TCPA>0. |
| Heading-on          | ts_hasBT(ts,BT), ts_hasCT(ts,CT), ts_hasCR(ts,CR), os_hasCO(os,CO). | BT=351(OR BT≤5), 174≤|CT-CO|≤186, CR>0. |
| Right crossing      | ts_hasBT(ts,BT), ts_hasCT(ts,CT), ts_hasCR(ts,CR), os_hasCO(os,CO). | 0≤BT≤117.5, 0≤|CT-CO|≤180, CR>0. |

In Table 2, the velocity and course attributes of the target ship will be dynamically loaded according to the system settings. It should be noted that the variables in the rule base are expressed in capital letters (the same settings are used in Table 3), such as ts_hasTCPA(ts,TCPA), it indicates that the target ship (ts) has the attribute value TCPA at the current moment. After the decision is made, the data will be automatically deleted, a new round of data will be instantiated to express navigation information about own ship and target ship.

3.2. Rules for avoidance decision

In nautical practice, an experienced ship pilot does not give a specific steering angle, but instead steers the ship by order such as ‘port pass astern’ or ‘starboard pass ahead’. Therefore, on the basis of meeting the rules for encounter situation, the rule base combines the common practices of seafarers and the influence of seamanship on the steering collision avoidance method, and
simplifies the ship collision avoidance actions into 16 action rules. The base includes encounter situation (ES), decision condition (DC) and execution action (EA). Some rules are shown in Table 3.

| Encounter situation | Prolog rules          | Decision conditions          | Action rules |
|---------------------|-----------------------|------------------------------|--------------|
| heading on          | encounter_situation_TS(ts,heading_on) | 180≤CT-CO≤270, CT>=BT+180   | starboard    |
| right cross         |                       | 180≤CT-CO≤270, CT<BT+180    | port         |
| (small angle)       |                       | 270≤CT-CO≤360, CT>=BT+180   | port         |
| right cross         |                       | 270≤CT-CO≤360, CT<BT+180    | starboard    |
| (large angle)       |                       |                              |              |

4. Experiment

4.1. Simulation environment
In order to verify the usability and effectiveness of the proposed model, a two-dimensional simulation environment based on python was built, and the connection between prolog and python was realized through the plug-in pyswip. By converting various types of navigation data in python into facts in prolog to implement rule-based query, python implements collision avoidance decision by turning decisions returned by the rule base. In order to realize collision avoidance decision based on prior knowledge simulation experiments are carried out on the encounter situations that may be occurred in navigation practice such as heading on, overtaking, and right crossing in simulation environment. In open sea, the initial navigation states information of own ship and target ship is shown in Table 4.

| Encounter type | Ship in situation | Initial position of the ship | Direction of approach of the obstacle | Velocity of the ship (nm) |
|----------------|-------------------|------------------------------|--------------------------------------|--------------------------|
| Heading on     | own ship          | (118.30°,38.82°)            | —                                    | (+6.8, -4.2)             |
| Overtaking     | own ship          | (118.26°,38.87°)            | Bow                                  | (-6.5, +3.8)             |
| Crossing1      | own ship          | (118.30°,38.82°)            | —                                    | (+6.8, -4.1)             |
| (small angle)  | targetship2       | (118.29°,38.84°)            | Bow                                  | (+6.3, -4.0)             |
| Crossing2      | own ship          | (118.25°,38.82°)            | —                                    | (+5.3, +6.2)             |
| (large angle)  | targetship3       | (118.32°,38.84°)            | Starboard                            | (-2.1, -11.8)            |
| Crossing2      | own ship          | (118.25°,38.83°)            | —                                    | (+4.6, +5.9)             |
| (large angle)  | targetship4       | (118.27°,38.82°)            | Starboard                            | (+10.5, -0.9)            |
4.2. Heading-on

In Figure 4(a), own ship takes 520s from the initial position to the current position. At this time, the relative bearing and distance of the target ship are instantiated as $ts\_hasBT(ts, 353)$ and $ts\_hasRange(ts, 0.65)$ in the prolog rule base, which satisfies the reasoning system’s conditions. The system output the situation is heading-on, and the total collision risk reaches 0.5, which meets the collision avoidance decision requirements for starboard under the encounter situation, and feeds the decision back to own ship to perform the right turn avoidance action as shown in Figure 4(b).

At $t = 650s$, own ship and target ship have not formed encounter situation, the reasoning system output meeting situation is None, and own ship arrived at CPA (closest point of approach), it is confine with navigation practice ‘when the other ship passed through own ship’s abeam, own ship start restore course.’ The condition of starting restore course is satisfied, the reasoning system outputs the decision of restore course of flight as shown in Figure 4(c), after the restore course is executed, own ship has returned to the original course, as shown in Figure 4(d).
4.3. Overtaking

In this scene, when own ship sails to the position shown in Figure 5(a), the relative bearing and distance of the target ship are instantiated as $ts\_hasBT(ts,357)$ and $ts\_hasRange(ts,0.39)$ in the prolog rule base. The condition of overtaking from the right behind of the target ship is satisfied in the reasoning system, and the reasoning result will be executed. The effect after turning is as shown in Figure 5(b). When own ship and target ship reach the position in Figure 5(c), own ship and target ship no longer constitute an encounter situation, so the output of the reasoning system is None, and own ship will pass the CPA, the reasoning system output the restore course decision. Figure 5(d) shows the effect after the decision is completed.

4.4. Crossing 1

Figure 6 shows the execution process of the reasoning system when small angle crossing occurs. When own ship navigates to the position shown in Figure 6(a), the relative bearing and distance of the target ship are instantiated as $ts\_hasBT(ts,353)$ and $ts\_hasRange(ts,0.85)$ in the
prolog rule base. At this time, the judgment condition of small angle crossing is activated, and the system deduced that the encounter situation is small angle crossing. At the same time, according to the judgment basis of risk degree proposed in Section 3.2, the reasoning system give the decision of starboard stern pass, which conforms to the nautical practice experience. Figure 6(b) shows the results of the collision avoidance decision. When own ship sails to the CPA in Figure 6(c), own ship starts to make the decision to restore course. After the decision to restore course is made, own ship has returned to the original course, as shown in Figure 6(d).

4.5. Crossing 2

Figure 7 shows a complete right large angle crossing situation and the reasoning process of own ship. Figure 7 (a) shows that the target ship will pass by starboard of own ship in the direction of own ship’s beam, and own ship’s responsibility is give-way. The relative bearing and distance of the target ship are instantiated as ts_hasBT(ts,19) and ts_hasRange(ts,0.6) in the prolog rule base, these information together with own ship’s course and speed is transmitted to the reasoning system, and it can be concluded that the situation is right large angle crossing. Meantime, the conclusion the avoidance action deduced is starboard astern pass, Figure 7(b) shows the results of the collision avoidance decision. When own ship sails to the CPA in Figure 7(c), own ship starts to make the decision to restore course. own ship has returned to the original course, as shown in Figure 4(d).

4.6. Result analysis

The results of simulation experiments show that the method based on ontology model proposed in this paper can deduce the steering and collision avoidance action conforming to the actual pilot experience, which provides support for the safe navigation of ships. However, there are still a few problems in the experiment, such as crossing situation, restore course given by reasoning system may contradict with collision risk degree, this phenomenon may be caused by the collision of time or space collision risk accidentally become bigger when own ship is steering, nevertheless, collision risk degree start to decrease sharply after this moment, so this method still guarantees the safety of navigation of ship, and this measure is allowed in the navigation practice.
5. Conclusion
Aiming at the problems of complex navigation safety information and difficulties in the fusion of multi-source heterogeneous information in the process of collision avoidance, an entity and entity attributes are constructed to semantically express the elements of the navigation scene, moreover, a completed ontology model of the conceptual navigation scene is constructed for the entire navigation area. At the same time, the navigation rule base based on a priori knowledge are designed at open sea for realizing the reasoning and query of the ship's encounter situation and collision avoidance actions. Furthermore, a simulation experiment is designed based on the velocity obstacle method to verify the proposed model. However, the rule base designed in this paper does not contain the rules for collision avoidance in restricted waters. It is necessary to further increase the completeness of the rule base in accordance with the detailed provisions of the collision avoidance rules for the sake of realizing the anthropomorphic driving decision of ships in different navigation areas.

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References
[1] Endsley, M. R. 1995. Toward a theory of situation awareness in dynamic systems. Human factors. 37 32-64
[2] Sharma, A., Nazir, S., Ernstsen, J. 2019. Situation awareness information requirements for maritime navigation: A goal directed task analysis. Safety Science. 120 745-752
[3] Hansen, Peter, Papageorgiou, Dimitrios, Blanke, Mogens, Galeazzi, Roberto, Lützen, Marie, Mogensen, John, Bennedsen, Mette, Hansen, Dort. 2020. COLREGs-based Situation Awareness for Marine Vessels - a Discrete Event Systems Approach
[4] Zhou, X. Y., Liu, Z. J., Wu, Z. L., Wang, F. W. 2019. Quantitative processing of situation awareness for autonomous ships navigation. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation. 13 25-31
[5] Smirnova, O. V. 2018. Situation Awareness for Navigation Safety Control. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation 12 383-388
[6] Wei, W., Gao, S., Chu, X., Sidibâ©, A. 2018, May. SNS-MEBN Based Method for Situational Awareness of Ship Navigation. In 2018 3rd International Conference on Information Systems Engineering (China: Shanghai) pp 73-77
[7] Li, L., Chen, G., Li, G. 2015. Study on Auto Decision-Making and Its Simulation Control for Vessel Collision Avoidance. In Proceedings of the 2015 Chinese Intelligent Automation Conference (Berlin: Heidelberg) pp 265-275
[8] Chen, G., Yin, Y., Li, L. 2010, October. Mechanism and simulation of personifying intelligent decision-making for vessel collision avoidance. In 2010 International Conference on Computer Application and System Modeling (China: Taiyuan) chapter 4 pp V4-681
[9] Li, L., Yang, S., Suo, Y., Chen, G., Wang, J. 2008, Automation method for personifying intelligent decision-making for vessel collision avoidance. In 2008 IEEE International Conference on Automation and Logistics (China: Qingdao) pp 1876-1881
[10] Zhao, L., Roh, M. I. 2019. COLREGs-compliant multiship collision avoidance based on deep reinforcement learning. Ocean Engineering. 191 106436
[11] Ma, Y., Zhao, Y., Wang, Y., Gan, L., Zheng, Y. 2020. Collision-avoidance under COLREGS
for unmanned surface vehicles via deep reinforcement learning. *Maritime Policy Management* **47** 665-686

[12] Guo, S., Zhang, X., Zheng, Y., Du, Y. 2020. An Autonomous Path Planning Model for Unmanned Ships Based on Deep Reinforcement Learning. *Sensors* **20** 426

[13] Lyu, H., Yin, Y. 2019. COLREGS-constrained real-time path planning for autonomous ships using modified artificial potential fields. *The Journal of Navigation* **72** 588-608

[14] Huang, Y., Chen, L., van Gelder, P. H. A. J. M. 2019. Generalized velocity obstacle algorithm for preventing ship collisions at sea. *Ocean Engineering* **173** 142-156.

[15] Niu, H., Savvaris, A., Tsourdos, A., Ji, Z. 2019. Voronoi-visibility roadmap-based path planning algorithm for unmanned surface vehicles. *Journal of Navigation* **72** 850-874.

[16] Singh, Y., Sharma, S., Sutton, R., Hatton, D., Khan, A. 2018. A constrained A* approach towards optimal path planning for an unmanned surface vehicle in a maritime environment containing dynamic obstacles and ocean currents. *Ocean Engineering* **169** 187-201.

[17] Gu, S., Zhou, C., Wen, Y., Zhong, X., Zhu, M., Xiao, C., Du, Z. 2020. A motion planning method for unmanned surface vehicle in restricted waters. *Proceedings of the Institution of Mechanical Engineer. M* **234** 332-345.

[18] Zhang, W., Xu, Y., Xie, J. 2019, April. Path Planning of USV Based on Improved Hybrid Genetic Algorithm. In *2019 European Navigation Conference ENC* (Poland:Warsaw) pp 1-7.

[19] Wang, H., Guo, F., Yao, H., He, S., Xu, X. 2019. Collision avoidance planning method of USV based on improved ant colony optimization algorithm. *IEEE Access* **7** 52964-75.