USV Geometric Collision Avoidance Algorithm for Multiple Marine Vehicles

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***Abstract*—In recent years, Unmanned Surface Vehicles (USVs) have grown in popularity, with an increasing number of applications in the civil, military and research domains. When the USVs are operating in the same area with other marine vessels, the collision avoidance algorithm is the key to keep the safety of both the ownship vehicle and the encountered vessels. This paper presents the development and validation of the geometric collision avoidance algorithm based on the International Regulations for Preventing Collisions at Sea (Colregs). The proposed algorithm allows the USV to avoid multiple dynamic and static vessels simultaneously while obeying the Colregs and keeping the USV a constant clearance from the collision risk. The proposed algorithm includes collision detection algorithm, decision making, collision resolution algorithm and resolution guidance algorithm. The collision detection algorithm describes the process of identifying the intruders as a collision. The decision making algorithm will take into account of Colregs and the traffic information to make the decision between keep-way and give-way. If there is a collision risk and the USV should give-way, the collision resolution waypoint will be generated by the collision resolution algorithm. Then the resolution guidance algorithm will be implemented to ensure the safety of the USV while the USV is avoiding the intruders. Finally, the proposed algorithm was validated in both multiple dynamic intruders scenario and the multiple static-dynamic mixed intruders scenario.**

***Keywords*—USV; Geometric Collision Avoidance Algorithm; Colregs; Multiple Collision Risks; Decision Making.**

I. Introduction

Unmanned Surface Vehicles (USVs) have attracted a huge amount of interest in recent years because of their ease of use and low operation costs. USVs are ideal for deployment in missions that are tedious or dangerous for humans. USVs have been implemented in both the civil markets and the military. Examples of those developed platforms include Singapore-based Zycraft Independent Unmanned Surface Vehicle (IUSV), Protector USV, Israeli project SeaStar, Swedish Piraya USV, British Thales Halcycon USV and British C-Cat. The IUSV, according to [1], is designed to support naval forces or provide merchant ships escort through pirate-prone waters. The Protector USV produced by Rafael Advanced Defence Systems Ltd [2], is capable of performing intelligence, surveillance and reconnaissance missions, naval warfare and force protection. The C-Cat USV, developed by ASV Ltd [3], is designed for water quality sampling, environmental assessments and hydrography.

Developing a high-level autonomous system, which can operate in unpredictable or unstructured environment is still a challenging task, since it requires robust guidance and control strategies to ensure the safety of the ownship and also any encountered vessel. When the USVs are operating in the same area with manned vessels, the collision avoidance algorithms are key in maintaining the safety of both the ownship vehicles and any encountered vehicles. Instead of developing new traffic rules for the unmanned systems, USVs are expected to obey the existing rules of the sea [4].

In recent years, different approaches have been proposed for solving the collision avoidance problem. Collision avoidance using a potential field method has been investigated by [5]. In essence this method uses an artificial potential field which governs vehicle kinematics, but cannot always guarantee that the relative distance is greater than a minimum safe separation distance due to the difficulty of predicting the minimum relative distance. Larson et al. [6] developed a two-tiered approach consisting a deliberative or far-field model and a reactive or near-field model. The USV was equipped with monocular vision, stereo vision, radar and AIS. The proposed algorithm was validated during the sea trial and the USV demonstrated to avoid the dynamic and static obstacles. However, this work mainly focuses on avoiding a single dynamic obstacle and single static obstacle and not the avoidance of multiple dynamic obstacles. Almeida et al. [7] employed radar sensor to detect collisions. The proposed algorithm was integrated into an USV and tested in different weather conditions to investigate the impact on radar performance. The tests were performed under different weather conditions ranging from heavy rain to clear sky to assess the impact on radar performance. The collision avoidance strategy developed by [8] integrated Line of Sight with the manual biasing scheme, but the only single dynamic collision was simulated in this study. Marco et al. [9] proposed a collision avoidance algorithm based on virtual target path following guidance algorithm and this algorithm was developed for USV multi-agent frameworks. In the investigation, Marco et al. focused on the cooperative guidance algorithm of multiple USVs. Zhuang et al. [10] proposed an

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autonomous motion planning method based on the Colregs. Lu et al. [11] verified collision avoidance behaviours for USVs using probabilistic model checking. Loe [12] reviewed several collision avoidance approaches including both local methods and global methods. Local methods include Potential Field (PF), Vector Field (VF) and Dynamic Window approach (DW). The global methods include Rapidly-Exploring Random Tree (RRT), A* and Constrained Nonlinear Optimization.

In this paper, geometric collision avoidance algorithm based on Colregs is proposed and the demonstration of avoiding single collision and multiple collisions is made under the assumption that:

- Vehicle dynamics are represented by point mass in Cartesian coordinates.
- Intruders are non-manoeuvring during the collision avoidance manoeuvre.
- The USV ownship can obtain the deterministic position and velocity vectors of other intruders using the onboard sensors, communication data link or estimator.

This implies that ownship USV can predict the trajectories and future state information using the current position and velocity vector and their linear projections. Note that these assumptions are for ease of analysis and are not a restriction of the approach.

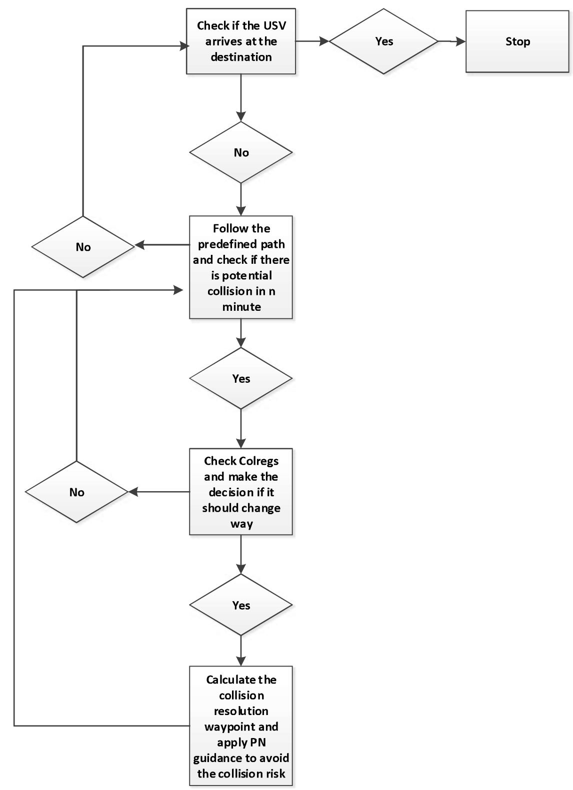

Fig. 1: The Architecture of the Collision Avoidance Algorithm

II. ARCHITECTURE OF THE ALGORITHM

The architecture of the collision avoidance algorithm is shown in Fig. 1. The proposed algorithm includes four parts: collision detection, decision making, collision resolution and resolution guidance.

When the USV is following the predefined path, it keeps detecting and tracking the nearby traffic information. Each intruder is assumed to have a safety radius d_m. In any case, if the Closest Approach Distance d_r between the USV and the intruders is smaller than d_m, it is considered to be a collision. The USV is required to avoid the collision in time n, which is a configurable value defined by the users. Time to Closest Point of Approach (TCPA) is denoted by t_{tcpa}. The relations between n and t_{tcpa} are defined by the status flags, which defines the emergent level of the traffic. The decision making system is defined according to the status flags and Colregs. It is used for deciding whether to keep on current heading or give way if there is a collision risk.

If the USV makes the decision to alter the course angle, the collision resolution waypoint will be calculated and the Proportional Navigation (PN) guidance algorithm will guide the USV to the collision resolution waypoint. Once the collision is avoided, the USV will continue to follow the predefined path and check if there is any other potential collision.

III. COLLISION DETECTION

The collision detection algorithm is based on the concept of collision geometry. If the distance between the USV with other vessels is smaller than the minimum separation distance d_m within a specific time, it is defined as a collision risk. The definition of collision detection is introduced by using the same concepts presented in [13] [14] [15], such as the Closest Approach Distance (CAD), Closest Point Approach (CPA) and Time to Closest Point of Approach (TCPA).

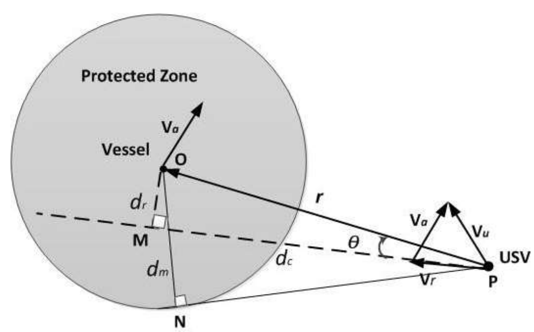

Fig. 2: Collision Detection Algorithm

The USV speed $\overrightarrow{V_u}$, the vessel speed $\overrightarrow{V_a}$ and the relative speed $\overrightarrow{V_r}$ form the velocity triangle as illustrated in Fig. 2. The relative speed can be calculated using (1).

$$\overrightarrow{V_r} = \overrightarrow{V_u} - \overrightarrow{V_a} \quad (1)$$

The angle between $\overrightarrow{V_r}$ and the line-of-sight from the USV to vessel is denoted by θ. The closest approach distance d_r and the distance r between the vessel and the USV satisfies (2).

$$d_r = r sin(\theta) \quad (2)$$

When $d_r \leq d_m$, a potential conflict is assumed to exist. The distance between USV and the Closest Point of Approach M is denoted by d_c, the Time to Closest Point of Approach is denoted by t_{tcpa}. t_{tcpa} can be calculated using (3).

$$t_{tcpa} = \frac{d_c}{V_r} \quad (3)$$

IV. Decision making

Status flags are defined to describe the emergent level of the detected intruders based on t_{tcpa}. The status flags and the Colregs are both taken into account to make the decision about whether the USV should give way or stay on course (keep way). The descriptions of status flags and the Colregs are given as follows.

A. Status Flag

To describe the USV status in different traffic situations, four collision status flags are defined:

- Status flag 0: $t_{tcpa} > 2n$, means there is no potential collision. Note that n is a time constraint defined by the user.
- Status flag 1: $n < t_{tcpa} \leq 2n$, means caution.
- Status flag 2: $t_{tcpa} \leq n$, means danger. The USV requires to analyse the Colregs and make a decision whether alter course (give-way) or stay on course (keep way).
- Status flag 3: $t_{tcpa} \leq n$, the USV decision is to alter course based on Colregs; The collision resolution and resolution guidance algorithm will be triggered to navigate the USV to avoid the collision.

B. Colregs

The Colregs is the abbreviation of International Regulations for Preventing Collisions at Sea. According to the Colregs [4], Head-on situation, Crossing situation, and Overtaking situation are defined to describe the situation of the traffic.

1) Head-On Situation: When two power-driven vessels are meeting head-on, both must change course to starboard so that they pass on the port side of the other. In Fig. 3, both vessel A and vessel B should turn to starboard to give way to each other.

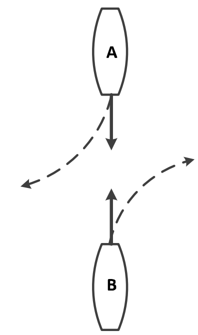

Fig. 3: Head-on Situation

2) Crossing Situation: When two power-driven vessels are crossing, the vessel which has the other on the starboard side must give way and avoid crossing ahead of her. In Fig. 4, the vessel A should give way to vessel B and vessel B should keep its way.

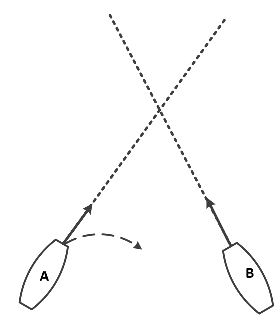

Fig. 4: Crossing Situation

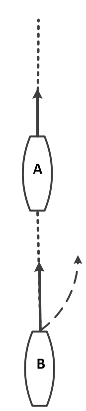

Fig. 5: Overtaking Situation

3) Overtaking Situation: An overtaking vessel must keep out of the way of the vessel being overtaken. Overtaking means approaching another vessel at more than 22.5 degrees abaft her beam. In Fig. 5, vessel B is overtaking the way of vessel A and vessel B should give way to vessel A. Although the Colregs does not specify which side of the boat it must overtake, common practice on the water dictates that the overtaking boat should pass on the starboard side of the traffic boat [16] [17].

C. Collision Avoidance Metrics

According to the Colregs, when the USV and the intruder have a potential collision, the USV will either give way to the intruder or keep way to wait for the intruder to alter course.

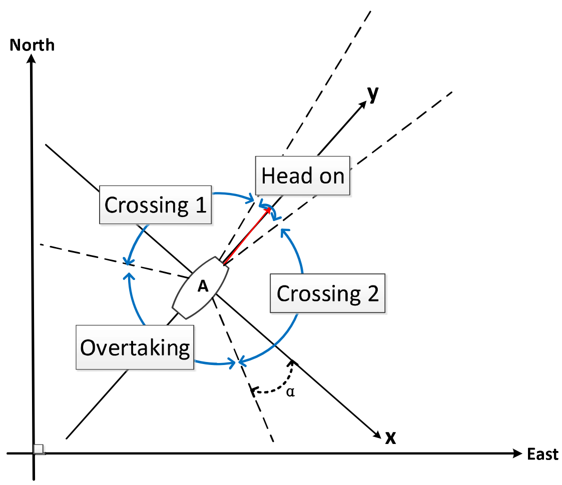

Fig. 6: Collision avoidance metrics

In Fig. 6, assume the USV is denoted by the vessel A and the vessel A is heading to the y direction. The relative position of the intruder with respect to vessel A can be divided into the head-on area, crossing 1 area, crossing 2 area and overtaking area. According to the Colregs, $\alpha = 22.5^0$. The head-on angle range is assumed to be 20^0. When the vessel A is on a potential collision with the intruder, only when the intruder is in the head-on area and the crossing 2 area, the vessel A should alter course. Otherwise, vessel A should keep way. The altering course is realized by applying the collision resolution algorithm and the resolution guidance algorithm.

V. COLLISION RESOLUTION

The proposed collision resolution algorithm can generate the collision resolution waypoint for one collision situation or multiple collisions risks.

A. Single Collision Scenario

When the USV detects that a potential collision will occur in n minutes and the USV is required to turn to starboard side to avoid the potential collision in accordance with Colregs, the port side tangent point of the safety circle of the intruder vessel will be chosen as the collision resolution point. As shown in Fig. 7, the USV is denoted by the vessel A and the intruder is represented by the vessel B, from A to the safety zone of vessel B there are two tangent points M and N, because N is on the port side of B, tangent point N will be chosen as the collision resolution waypoint.

The algorithm for calculating the position of the tangent point is given as follows. The positions of A and B are denoted by (x_A, y_A) and (x_B, y_B). The safety radius is represented by d_m. The positions of two tangent points are denoted by (x_M, y_M) and (x_N, y_N), respectively.

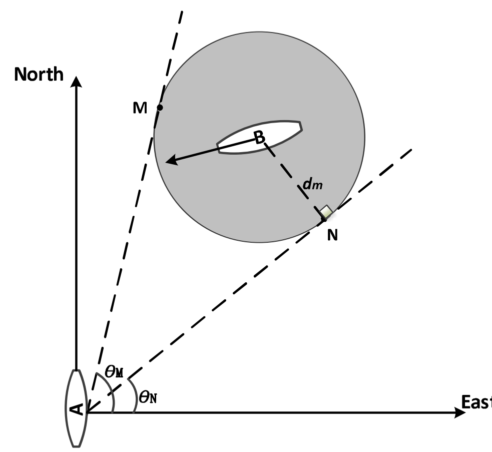

Fig. 7: Collision Resolution (Single Collision Scenario)

The tangent point position (x, y) can be derived from (4) and (5).

$$(x - x_B)^2 + (y - y_B)^2 = d_m^2 \tag{4}$$

$$(y - y_B)(y - y_A) = -(x - x_B)(x - x_A) \tag{5}$$

Since these two equations will give us two solutions (x_M, y_M) and (x_N, y_N). Hence an approach for calculating the starboard side waypoint is needed. The approach is given in (6) and (7).

$$\Delta\theta = \theta_M - \theta_N \tag{6}$$

$$0 < \Delta\theta < \pi \quad or \quad \Delta\theta < -\pi \tag{7}$$

If $\Delta\theta$ satisfies the condition in (7), (x_N, y_N) is the starboard side tangent point, otherwise, (x_M, y_M) is the starboard side tangent point.

B. Multiple Collisions Scenario

In Fig. 8, assume vessel A is the USV and vessel B, vessel C and vessel D are the intruders. Only when the intruders are in the head-on area or the starboard side crossing area, the ownship USV should turn to the starboard side. The boundary of the head-on area is denoted by AP and the boundary of the crossing area is denoted by AR.

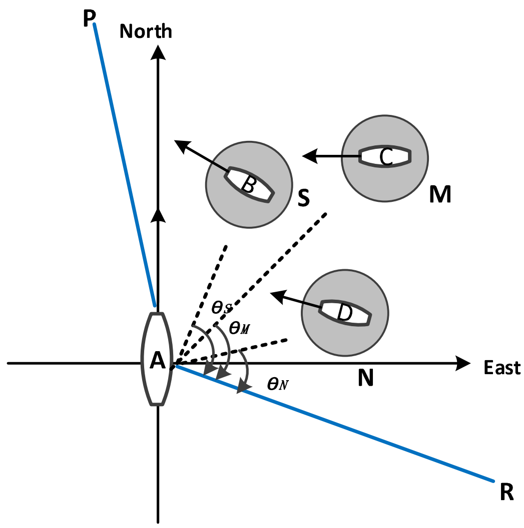

Fig. 8: Collision Resolution (Multiple Collision Scenario)

According to the previous analysis, only the tangent point that is on the port side of the intruder safety circle will be selected as the collision resolution waypoint. The port side tangent points of the safety circles of the vessel B, vessel C, and vessel D are denoted by S, M and N, respectively. Taking into consideration the relative speed between the USV and the tangent point, we can use the method presented in [15] to calculate the required heading angles of the USV to head to the point S, M and N, which are denoted by θ_S, θ_M and θ_N.

When USV encounters multiple potential collisions, multiple collision resolution waypoints will be generated. Thus, the approach of selecting one collision resolution waypoint to avoid all the intruders is needed. The approach is given in (8).

$$\theta_X = \min\{\theta_S, \theta_M, \theta_N\} \tag{8}$$

In this case, $\theta_X = \theta_N$. The corresponding tangent point of safety circle D, which is N, is chosen as the collision resolution waypoint.

VI. RESOLUTION GUIDANCE

Once the collision resolution waypoint is calculated, the proportional navigation (PN) waypoint guidance algorithm will be implemented to navigate the USV to travel to the collision resolution waypoint.

In Fig. 9, assuming vessel A is the ownship USV and vessel B is the intruder, the collision resolution waypoint is the tangent point S. Point S is traveling at the same speed as vessel B, which is $\overrightarrow{V_B}$, while vessel A is travelling at $\overrightarrow{V_A}$ and the lateral acceleration is $\overrightarrow{a}$. The line-of-sight angle between A and tangent point S is denoted by θ_r and the changing rate is denoted by $\dot{\theta}_r$.

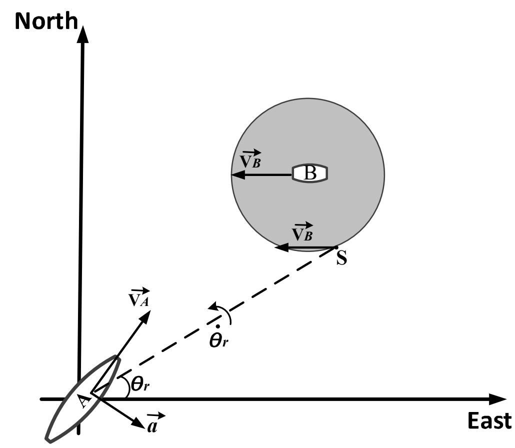

Fig. 9: Proportional Navigation

By changing the lateral acceleration of the ownship USV, we can change the speed direction of USV and navigate it to arrive at the resolution waypoint S. The lateral acceleration can be calculated by (9).

$$\alpha = N \times \dot{\theta_r} \times V_r \tag{9}$$

In the equation (9), N is a proportional constant that requires to be regulated in the implementation. V_r is the relative speed between USV and vessel B. The angular velocity of USV $\dot{\theta_A}$ can be derived by (10).

$$\dot{\theta_A} = \frac{\alpha}{V_A} \tag{10}$$

VII. NUMERICAL SIMULATION

Two scenarios were simulated, namely the multiple dynamic intruders scenario and the multiple static-dynamic intruders scenario.

A. Multiple Dynamic Intruders Scenario

In this scenario, six dynamic intruders were set up. The USV started from $(0, -500)$ with the aim to travel to destination $(0, 1000)$. The USV initial heading and speed is given below:

$$\begin{cases} USV_\psi = 0 \\ USV_v = 4 \end{cases}$$

The heading unit is radians, and the speed unit is meters per second. The six intruders were assumed to keep a constant speed and heading. The intruders' start point, heading, and speed are given:

$$\begin{cases} intruder(1)_x = 1000 \\ intruder(1)_y = 300 \\ intruder(1)_v = 4 \\ intruder(1)_\psi = \pi \end{cases} \quad \begin{cases} intruder(2)_x = -20 \\ intruder(2)_y = 450 \\ intruder(2)_v = 2 \\ intruder(2)_\psi = 1.5\pi \end{cases}$$

$$\begin{cases} intruder(3)_x = 1600 \\ intruder(3)_y = 700 \\ intruder(3)_v = 4 \\ intruder(3)_\psi = \pi \end{cases} \quad \begin{cases} intruder(4)_x = 1200 \\ intruder(4)_y = 300 \\ intruder(4)_v = 4 \\ intruder(4)_\psi = \pi \end{cases}$$

$$\begin{cases} intruder(5)_x = 1000 \\ intruder(5)_y = 0 \\ intruder(5)_v = 2 \\ intruder(5)_\psi = \pi \end{cases} \quad \begin{cases} intruder(6)_x = -800 \\ intruder(6)_y = -200 \\ intruder(6)_v = 2 \\ intruder(6)_\psi = 0 \end{cases}$$

Each intruder safety radius was assumed to be 100 meters and in any case, the USV should not enter into the safety circle. It is assumed that if there is a potential collision in 1 minute time frame, the USV should take action to avoid the collision according to the Colregs. The proportional constant N of PN guidance law was set to be 10.

The ownship USV and the intruders started their missions as shown in Fig. 10. The USV was marked as large yellow triangle and the intruders are marked as small blue triangle. The USV start point and final destination were marked as green dots. For clarity, the intruder numbers are also shown.

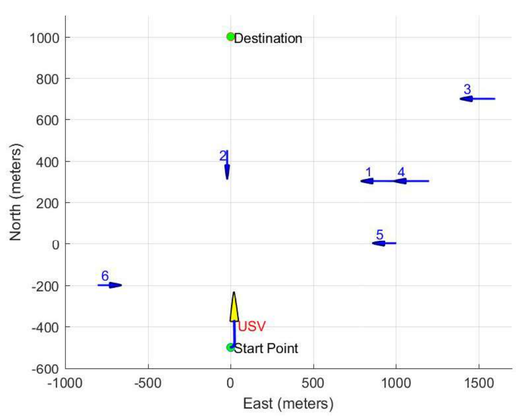

Fig. 10: Multiple dynamic intruders scenario (t = 35s, the USV is represented by the large yellow triangle and the other vessels are represented by the small blue triangles)

At 127 seconds, the USV encountered the No.2 intruder and calculated there existed a potential collision and according to the Colregs, it is a head-on situation. Therefore, the USV altered course to the starboard side to avoid the collision, as shown in Fig. 11. For clarity, the intruder that is being avoided, will be marked as red square.

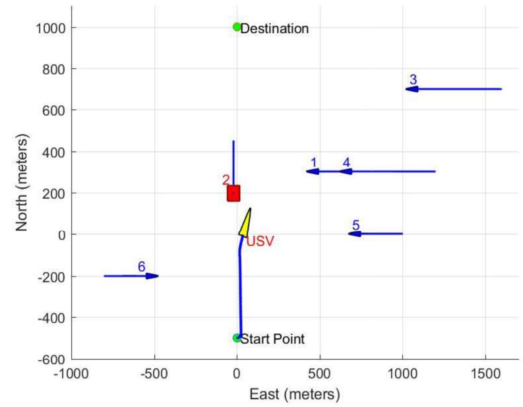

Fig. 11: Multiple dynamic intruders scenario (t = 127s, the collision risk being avoided is represented by the red square)

When the USV was avoiding the No.2 intruder, it detected it also had potential collision with the No.1 intruder. In this case, the multiple collision resolution algorithm will be triggered, and then the port side tangent point of the safety circle of No.1 intruder was chosen as the collision resolution waypoint, because when the No.1 intruder was avoided, the No.2 intruder will also be avoided. As shown in Fig. 12, the No.1 intruder was marked as red square.

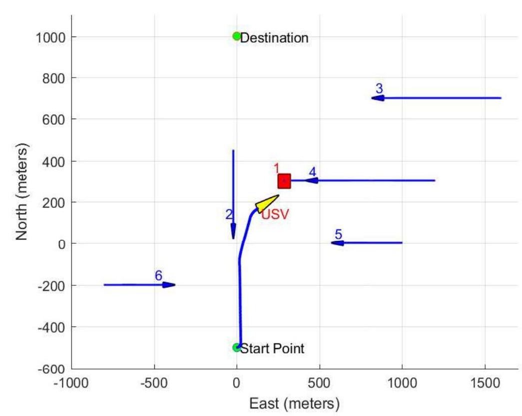

Fig. 12: Multiple dynamic intruders scenario (t = 178s)

However, due to the crowded situation, when the USV is avoiding the No.1 intruder, it detected it will also have a collision risk with No.4 intruder at the same time and it altered the course again as shown in Fig. 13.

After No.4 intruder was avoided, the USV computed there was no collision in the next 1 minute time frame if it changes course to travel directly to the final destination waypoint. Therefore, it altered course to travel back to the final waypoint

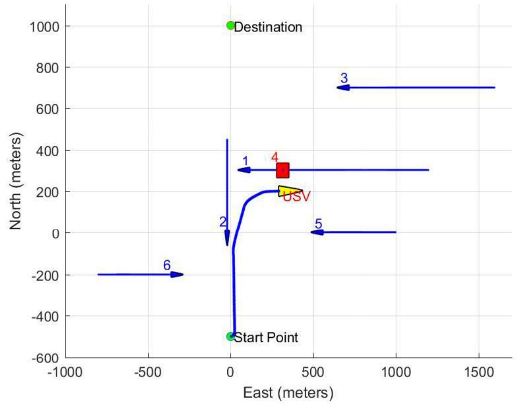

Fig. 13: Multiple dynamic intruders scenario (t = 221s)

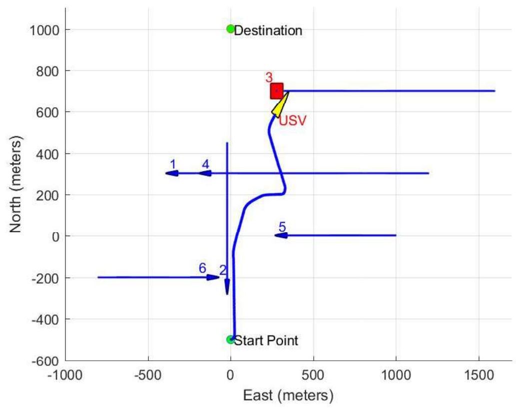

Fig. 14: Multiple dynamic intruders scenario (t = 330s)

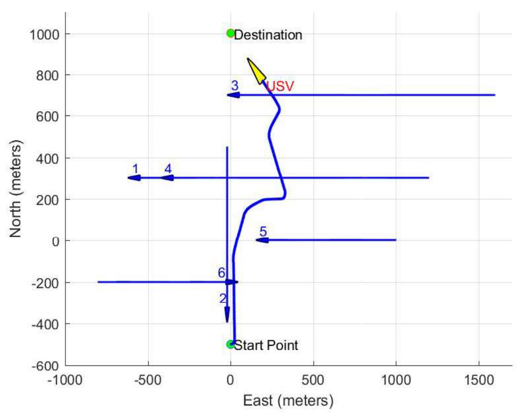

Fig. 15: Multiple dynamic intruders scenario (t = 387s)

(destination) before it arrives at the destination, the potential collision was calculated, the crossing intruder was No.3 and the USV altered course once again to avoid the collision, as shown in Fig. 14.

After the No.3 intruder was avoided, the USV can travel directly to the destination, as shown in Fig. 15. The Final path of the USV from start point to the destination is given in Fig. 16. For demonstrating the accuracy of the guidance algorithm, the distance between the USV and the intruder being avoided was also recorded, as shown in Fig. 17.

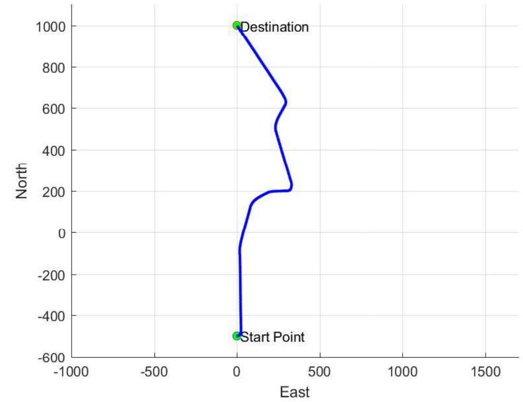

Fig. 16: Final path of Multiple dynamic intruders scenario

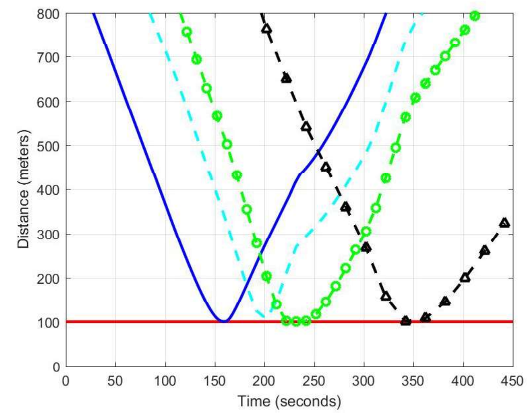

Fig. 17: Distance between the USV and the intruders (The distances between the USV and the No.2 intruder, No.1 intruder, No.4 intruder and No.3 intruder are represented by blue solid line, cyan dash line, green dash circle line and black dash triangle line respectively)

The intruders that have been avoided were No.2, No.1, No.4, and No.3 by time sequence. In Fig. 17, the distance between the USV and the intruders, the distances between the USV and the No.2 intruder, No.1 intruder, No.4 intruder and No.3 intruder are represented by blue solid line, cyan dash line, green dash circle line and black dash triangle line respectively. It can be seen that the distance between the USV and the intruder has been kept greater than 100 meters, which means the proposed algorithm can ensure the safety of the USV under multiple potential collisions scenarios while obeying the Colregs.

B. Multiple Static-Dynamic Mixed Intruders

In this scenario, multiple static intruders and multiple dynamic intruders were simulated to test the proposed algorithm, which is a common situation in the real life. The USV started from $(0, -500)$ and aimed to travel to destination $(0, 1000)$. The USV initial heading and speed is given as below:

$$\begin{cases} USV_\psi = 0 \\ USV_v = 4 \end{cases}$$

Seven intruders initial traffic information is given as below:

$$\begin{cases} intruder(1)_x = 100 \\ intruder(1)_y = 400 \\ intruder(1)_v = 0 \\ intruder(1)_\psi = \pi \end{cases} \quad \begin{cases} intruder(2)_x = -20 \\ intruder(2)_y = 0 \\ intruder(2)_v = 0 \\ intruder(2)_\psi = 1.5\pi \end{cases}$$

$$\begin{cases} intruder(3)_x = 1600 \\ intruder(3)_y = 700 \\ intruder(3)_v = 4 \\ intruder(3)_\psi = \pi \end{cases} \quad \begin{cases} intruder(4)_x = 1200 \\ intruder(4)_y = 500 \\ intruder(4)_v = 4 \\ intruder(4)_\psi = \pi \end{cases}$$

$$\begin{cases} intruder(5)_x = 500 \\ intruder(5)_y = 0 \\ intruder(5)_v = 0 \\ intruder(5)_\psi = \pi \end{cases} \quad \begin{cases} intruder(6)_x = -800 \\ intruder(6)_y = -200 \\ intruder(6)_v = 2 \\ intruder(6)_\psi = 0 \end{cases}$$

$$\begin{cases} intruder(7)_x = -1300 \\ intruder(7)_y = 500 \\ intruder(7)_v = 4 \\ intruder(7)_\psi = \pi \end{cases}$$

In this scenario, intruder No.1, No.2, and No.5 are the static vessels and the rest intruders are dynamic vessels. The dynamic vessels are represented by the small blue triangles and the static vessels are represented by the blue circles. In Fig. 18, at 103 seconds, the USV detected the potential collision with No.2 static intruder and it altered course to avoid this collision. After No.2 intruder was avoided, the USV detected potential collision with No.1 static intruder, it altered course to avoid No.1 intruder and soon it detected another two potential collisions with No.4 and No.7 intruders. Therefore, the multiple collisions resolution algorithm was triggered and the tangent point of safety circle of No.7 intruder was chosen as the collision resolution. The moment when the USV was avoiding No.1 intruder is shown in Fig. 19 and the moment, when the USV was avoiding No.4 and No.7 intruders, was shown in Fig. 20.

After the static No.1 intruder and dynamic No.4 and No.7 intruders were avoided, when the USV was planning to head back to the destination, a crossing potential collision with No.3 intruder was detected and the USV made an emergent turn to avoid No.3 intruder, as shown in Fig. 21. The final path is given in Fig. 22 and the distance between the USV and the intruders, when there was potential collision in 1 minute, was also recorded, as shown in Fig. 23.

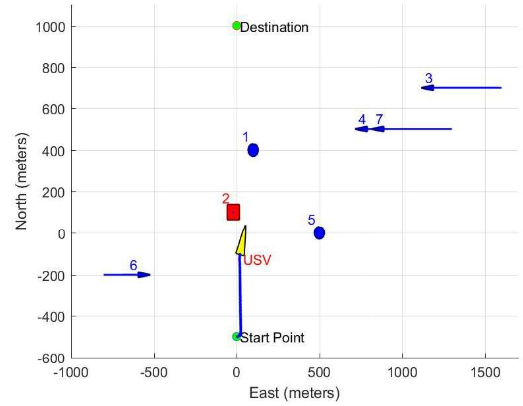

Fig. 18: Multiple static-dynamic intruders scenario (t = 103s, the USV is represented by the large yellow triangle, the dynamic vessels are represented by the small blue triangles, the static vessels are represented by the blue circles and the collision risk being avoided is represented by the red square)

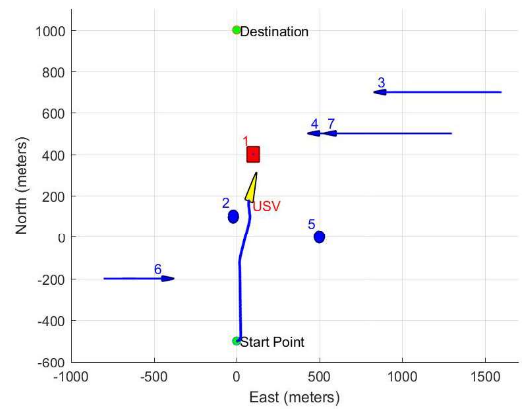

Fig. 19: Multiple static-dynamic intruders scenario (t = 175s)

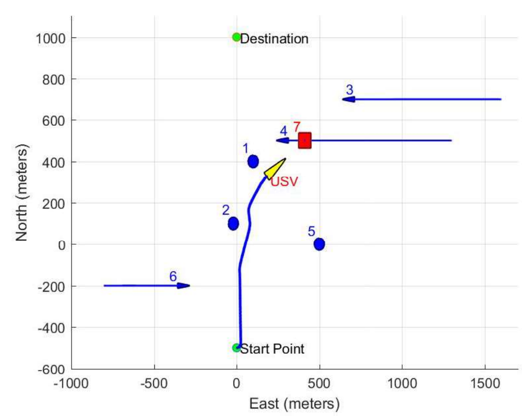

Fig. 20: Multiple static-dynamic intruders scenario (t =222s)

In Fig. 22, we can see that the intruders those have been

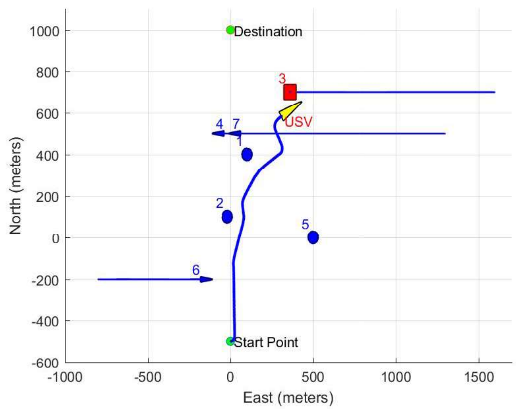

Fig. 21: Multiple static-dynamic intruders scenario (t = 310s)

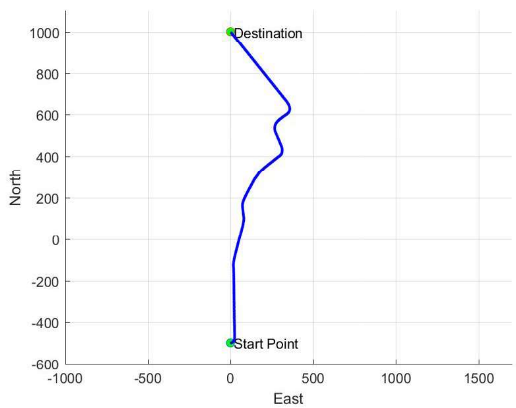

Fig. 22: Final path of multiple static-dynamic intruders scenario

avoided include No.2, No.1, No.4, No.7 and No.3 by time sequence. In Fig. 22, the distances between the USV and the No.2 intruder, No.1 intruder, No.4 intruder, No.7 intruder and No.3 intruder are represented by blue solid line, cyan dash line, green dash circle line, black dash plus line and black dash triangle line respectively. The recorded distances between the USV and these intruders were kept strictly larger than 100 meters, which proved that the proposed algorithm can ensure the safety of the USV while keep it obeys the Colregs.

VIII. Conclusion and Future Work

In this paper, a geometric collision avoidance was presented and validated in complex multiple collisions scenarios. The proposed algorithm takes into account Colregs and the generated collision resolution obeys these regulations. The resolution guidance algorithm ensures the USV maintain a constant clearance from the potential collisions. In the future work, the dynamic models and the control systems of the USV will be developed. Disturbances such as sea current,

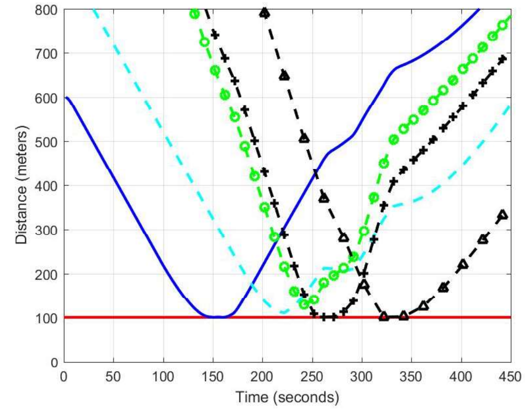

Fig. 23: Distance between the USV and the intruders (The distances between the USV and the No.2 intruder, No.1 intruder, No.4 intruder, No.7 intruder and No.3 intruder are represented by blue solid line, cyan dash line, green dash circle line, black dash plus line and black dash triangle line respectively)

waves and wind will also be taken into account.

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