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Development of Collision Avoidance Algorithms for the C-Enduro USV

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Abstract: This paper presents the development of the C-Enduro unmanned maritime surface vehicle (USV) and the collision avoidance algorithms for the sense and avoid system. The USV is designed to operate at sea for extended periods of time (up to 3-months) but also have the capability to transit for a short range at high speeds. The collision avoidance algorithms which also take COLREGS rules into account were validated in simulation.

Keywords: Autonomous surface vehicles; USV, collision avoidance, unmanned marine vehicles, obstacle avoidance, guidance and control.

1. INTRODUCTION

The development of unmanned surface vehicles spans several decades. The original radio-controlled boats were designed for damage assessment and dangerous mine clearance operations. Over the past two decades, the development of more advanced sensors and the increased capabilities of computational power and communication technology coupled with a reduction in cost have motivated the use of USV in new applications and more complex missions such as minesweeping, environmental data collection and monitoring, water survey, anti-surface, and submarine warfare.

Examples of those developed platforms include the Protector USV produced by Rafael Advanced Defense Systems Ltd, see Protector unmanned surface vehicle (2013), which is an independent remotely controlled vehicle capable of performing several tasks, such as intelligence, surveillance and reconnaissance missions, naval warfare and force protection. The Singapore-based Zycraft Independent Unmanned Surface Vehicle (IUSV) is another example, Lundquist (2013). The IUSV is designed for open ocean missions to support naval forces or provide merchant ships escort through pirate prone waters. The light hull and low fuel consumption enables the IUSV to carry out long endurance missions. Other examples include the ECA Robotics USVs for shallow water survey, oceanographic survey, detection and object classification.

Several other nations have also developed their own USV platforms, for example the Israeli project SeaStar in Aeronautics (2005), British Thales project Halcycon reconfigurable unmanned surface vehicle, see Harvey (2013) and Swedish unmanned surface vehicle Piraya in Iriszoom (2014).

As mentioned previously, USVs are finding their way into wider range of civilian applications as well. Currently there are a number of companies producing different types of USV not only for military establishments but also for industrial corporations, environmental institutions and government agencies.

ASV Ltd in the UK has produced a series of USVs for both commercial and academic use. One of the USVs is C-Cat, which is a lightweight, highly manoeuvrable multipurpose unmanned surface vehicle. The system is designed for water quality sampling, environmental assessments and hydrography in ASV unmanned marine systems (2014).

However, as USV are tasked with more complex missions and are expected to operate in different weather conditions, in order not to increase the operator work load and maintain high levels of safety, those platforms must have higher level of autonomy. Collision avoidance is an important part of such system and compromises a vital component of the self-navigation of the unmanned maritime surface vehicle.

Collision Detection and Resolution (CD&R) against incoming vessels would be an essential part of the USV higher level of autonomy. One of main issues with CD&R is whether the algorithm can guarantee collision avoidance by strict verification, since the CD&R algorithm is directly related to the safety of the vehicle.

A number of different approaches have been applied for CD&R problems. Larson *et al.* (2007) presented a two-tiered collision avoidance approach by accurately creating a world model based on various sensors such as vision and radar. This approach includes a far-field deliberative obstacle avoidance component and a near-field reactive obstacle avoidance component. Radar based collision avoidance detection was presented in Almeida *et al.* (2009). The algorithm was integrated in an operational autonomous surface vehicle and tested in different weather conditions to investigate the impact on radar performance. Naeem *et al.* (2012) proposed a strategy consisting of waypoint guidance by line-of-sight coupled with manual biasing scheme. Bibuli *et al.* (2012) presented a collision avoidance algorithm based on virtual target path following guidance technique, developed for USV multi-agent frameworks, which includes a basic integration with "Rules of Road". Zhuang *et al.*

(2011), presented an autonomous motion planning method based on the relative coordinated integrated with the standardised rules, COLREGs, defined by the International Maritime Organisation. Benjamin *et al.* (2006) applied a novel method of multi-objective optimization, interval programming, in a behaviour-based control framework for representing the navigation rules in a way that achieves simultaneous optimal satisfaction. The approach was experimentally validated using multiple autonomous surface craft. Loe *et al.* (2008) reviewed several approaches for collision avoidance, including the local methods and the global methods. The local methods include the Potential Field, Vector Field Histogram, and Dynamic Window approach. The global methods include A*, Rapidly-Exploring Random Tree, and Constrained Nonlinear Optimization.

2. ASV VEHICLE DESCRIPTION

C-Enduro (Fig.1) provides 'Persistent Presence' for the collection of offshore data. The advanced energy harvesting design can be used for a variety of research, military and commercial applications. C-Enduro has up to 3-months endurance, in excess of 4 knots for over 4000 miles range. The length of C-Enduro is 4.1m, the beam is 2.45m and the draft is 0.45m. The ASV vehicle is equipped with advanced mission planning and energy budget tools. In order to achieve long endurance, C-Enduro utilizes diesel, solar and wind energy. The control system of C-Enduro is based on the ASView control system, see ASV (2013). C-Enduro key parameters are given in Table 1.

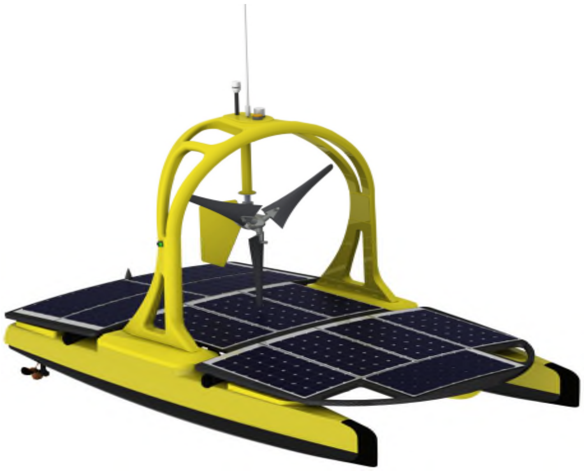

Fig. 1. C-Enduro unmanned surface vehicle in UST (2013)

Table 1. C-Enduro Technical Specifications

Length	4.1m
Beam	2.45m (road transportable)
Height	~2.8m (including antennae), 1.5m (mast off and placed on top)
Draft	0.45m
Weight	~350kg (lightship), ~450kg (fully loaded).
Primary propulsion	2 × DC brushless motors (1.4 kW each)
Speed	0 – 7 knots
Endurance	Up to 3 months utilizing solar / wind / diesel energy
Solar panel system	12 high efficiency panels generating a peak output power of 1200W
Diesel generator system	A peak charging power of 3.2KW
Wind turbine system	Generating a peak output power of 600W

As with regards to the sensor suite for navigation, the vessel is equipped with the following aids GPS, AIS transponder, radar reflectors, depth sounder and navigation lights. In addition, the vessels could be equipped with following sensor options depending on the type and mission requirements: Wetlabs Triplet Puck; CTD (lowered by winch to 250m+); Airmar Weatherstation; ADCP; PAM; CO_2; Camera (Stills / Video); Motion Reference Unit / Waves; Acoustic Modem; ASW Payload (Towed array or dipping); Electronic warfare; and Multibeam / Sidescan Sonar;

3. ALGORITHM DESCRIPTIONS

This section includes five parts: algorithm logic, inputs/ outputs of collision avoidance system, collision detection, implementation based on the rules of sea, collision resolution and resolution guidance.

3.1 Algorithm logic and inputs/outputs

a. Algorithm inputs

The algorithm logic is shown in Fig.2. The input of collision avoidance system is the Automatic Identification System (AIS) data. AIS is an automatic tracking system used on ships and by Vessel Traffic Services (VTS) for identifying and locating vessels by electronically exchanging data with other nearby ships. AIS system is required to be fitted aboard international voyaging ships that are more than 300 tons and all passenger ships regardless of size, see AIS (2013).

AIS data includes two types of data, dynamic data (position, speed etc.) and static data (vessel size, MMSI etc.). In the AIS data, the "MMSI" is the ID of the vessel. In the collision avoidance algorithm simulation, the MMSI, 'latitude', 'longitude', 'speed' and 'course' information will be used.

The ASV C-Enduro vehicle AIS system is capable of receiving information of other vessels that are in the range of at least 10 miles. In this study, a safety radius of 200 meters (0.108 nautical miles) around the intruder vessel is projected in order to ensure that any collision risk is avoided (cleared) by a safe distance, as shown in Fig.3.

The collision avoidance system is activated only when the intruders are in the filtering range of 0.75 nautical miles and the projection of the relative speed between the ownship and the intruder has intersection with the intruder safety circle.

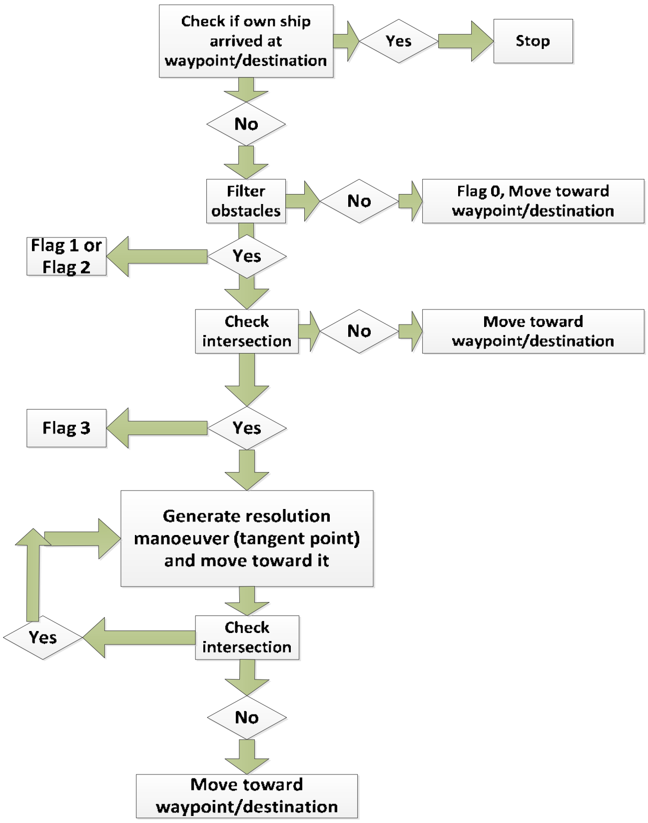

Fig. 2. USV collision avoidance algorithm logic

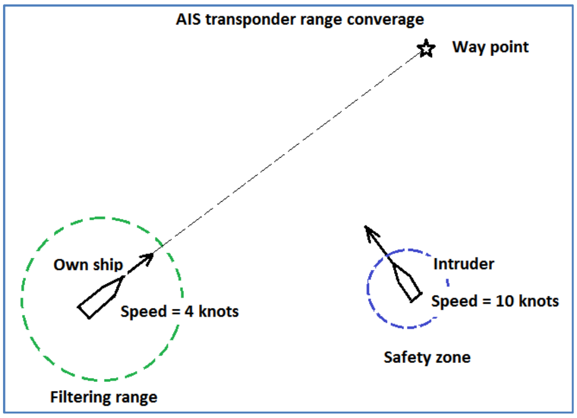

Fig. 3. Example of the first collision scenario

b. Algorithm outputs

The algorithm has three outputs, namely: the required course angle and speed; and the status flag. More specifically:

Required course angle: outputted by the CA algorithm only when status flag = 3 'AND' the intruder is approaching head-on or from the starboard side.

Required speed (assumed to be constant in the simulation) – outputted by the CA algorithm only when status flag = 3 'AND' the intruder is approaching head-on or from the starboard side.

In addition, to describe the C-Enduro status in different situations, four collision status flags are defined:

Status flag 0: No collision detected

Status flag 1: Traffic, the filtering range of the USV intersects with the safety zone of the intruder vessel.

Status flag 2: Caution, the intruder vessel is inside of the filtering range of the ownship.

Status flag 3: Warning, the intruder vessel is inside of the filtering range and there is collision risk.

3.2 Collision detection

In this section, geometric method will be used to compute the status flags and detect any collision risk. Table 2, below define the variables used in the algorithm.

Table 2. Variable list and description

Variables	Description
p_{u_x}, p_{u_y}	The position of C-Enduro
s_r	The filtering range
p_{f_x}, p_{f_y}	Final destination position / waypoint
p_{w_x}, p_{w_y}	The position of next waypoint
p_{obs_x}, p_{obs_y}	The position of the intruder vessel
r	The safety radius of the intruder vessel
r_d	The required distance from the destination /waypoint
v_{ux}, v_{uy}	The ASV C-Enduro vessel velocity in x and y directions
v_{obsx}, v_{obsy}	The intruder vessel velocity in x and y directions
v_{rx}, v_{ry}	The relative velocity between the ASV C-Enduro vessel and the intruder vessel in x and y directions
θ_u	The course angle of the C-Enduro vessel
θ_{obs}	The course angle of the intruder vessel
V_u	C-Enduro velocity scalar

Checking if the C-Enduro has arrived at destination:

$$f = \sqrt{\left(p_{u_x} - p_{f_x}\right)^2 + \left(p_{u_y} - p_{f_y}\right)^2} \qquad (1)$$

If $f > r_d$, it means C-Enduro has not arrived, otherwise, the USV has arrived;

Checking the status flags using (2):

$$g = \sqrt{\left(p_{u_x} - p_{obs_x}\right)^2 + \left(p_{u_y} - p_{obs_y}\right)^2} \qquad (2)$$

If $\mathrm{g} > \mathrm{s_r} + \mathrm{r}$, it means no collision detected and the status flag equal to 0;

If $\mathrm{s_r} < \mathrm{g} \leq \mathrm{s_r} + \mathrm{r}$, it means the filtering range of the USV intersects with the safety zone of the intruder vessel and the status flag equals to 1.

If $\mathrm{r} < \mathrm{g} \leq \mathrm{s_r}$, it means the intruder vessel is in the filtering range, and the status flag equals to 2. If the status flag equals to 2, the collision detection algorithm is triggered.

First, the relative velocity algorithm is reviewed. The speed of the ASV C-Enduro vessel is $\overrightarrow{\mathrm{v_u}}$, which can be described as $(\mathrm{v_{ux}}, \mathrm{v_{uy}})$. The speed vector of the intruder vessel is $\overrightarrow{\mathrm{v_{obs}}}$, which can be described as $(\mathrm{v_{obsx}}, \mathrm{v_{obsy}})$. The relative speed of the C-Enduro vessel with respect to the intruder vessel is $\overrightarrow{\mathrm{v_r}}$. The vectors relation is shown in Fig. 4.

The collision occurs only when the projected extension line of relative speed vector $\overrightarrow{\mathrm{v_r}}$ has intersection with the safety zone of the intruder vessel, as shown in Fig. 5.

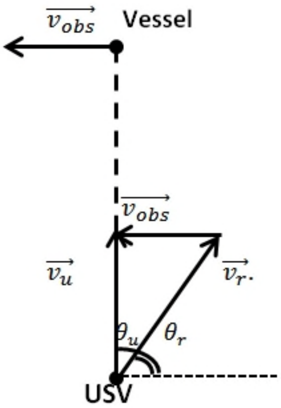

Fig. 4. Relative speed between the USV C-Enduro vessel and the intruder vessel

Checking the intersection requires the C-Enduro relative speed heading angle θ_r and the angle range $\Delta\theta$ between two half- lines, which are the lines between the USV position and the tangent points of the safety zone.

Therefore, the relative speed vector $\overrightarrow{v_r}$ should be calculated first. As AIS data only includes the velocity scalar and the course angle then all the vectors in Cartesian coordinates can be expressed in (v_x, v_y) format, thus the C-Enduro speed vector $\overrightarrow{v_u}$ and the intruder vessel speed vector $\overrightarrow{v_{obs}}$ are both converted into (v_{ux}, v_{uy}) and (v_{obsx}, v_{obsy}) to calculate relative speed (v_{rx}, v_{ry}).

v_{ux} and v_{uy} can be calculated by C-Enduro velocity scalar V_u and the USV course angle θ_u.

$$v_{ux} = V_u \times cos(\theta_u) \quad (3)$$
$$v_{uy} = V_u \times sin(\theta_u) \quad (4)$$

Similarly, v_{obsx} and v_{obsy} can be calculated by intruder velocity scalar V_{obs} and the course angle θ_{obs}.

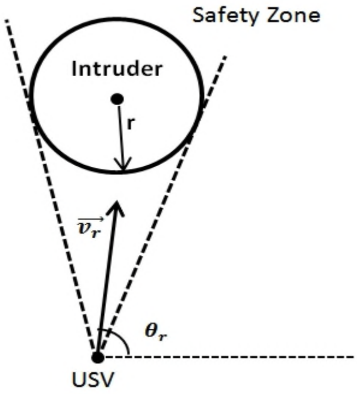

Fig. 5. Collision example, the projected line of relative speed vector $\overrightarrow{v_r}$ has intersection with the safety zone of the intruder

$$v_{obsx} = V_{obs} \times cos(\theta_{obs}) \quad (5)$$
$$v_{obsy} = V_{obs} \times sin(\theta_{obs}) \quad (6)$$

Thus the relative elements v_{rx}, v_{ry} can be calculated by using (7) and (8).

$$v_{rx} = v_{ux} - v_{obsx} \quad (7)$$
$$v_{ry} = v_{yx} - v_{obsy} \quad (8)$$

Relative velocity V_r and course angle θ_r can be calculated by using (9) and (10).

$$V_r = \sqrt{{v_{rx}}^2 + {v_{ry}}^2} \quad (9)$$
$$\theta_r = atan(v_{ry}/v_{rx}) \quad (10)$$

θ_r is derived using eqn.(3)-(10). However, θ_r calculated above falls in the range $(\frac{-\Pi}{2}, \frac{\Pi}{2})$, not the course range $[0, 2\Pi]$, therefore θ_r needs to be modified. The converting approach is given by:

$$if\ v_{rx} \geq 0 \& v_{ry} > 0$$
$$\theta_r = \theta_r \quad (11)$$
$$if\ v_{rx} \geq 0 \& v_{ry} < 0$$
$$\theta_r = \theta_r + 2\pi \quad (12)$$
$$if\ v_{rx} < 0 \& v_{ry} \geq 0$$
$$\theta_r = \theta_r + \pi \quad (13)$$
$$if\ v_{rx} < 0 \& v_{ry} \leq 0$$
$$\theta_r = \theta_r + \pi \quad (14)$$

To make it easier to visualize, the geometric graphical representation is shown in Fig.6. The next step is to calculate the collision angle range $\Delta\theta$.

The distance between C-Enduro and the intruder vessel is denoted by r_d.

$$r_d = \sqrt{(p_{ux} - p_{obsx})^2 + (p_{uy} - p_{obsy})^2} \quad (15)$$
$$\frac{\Delta\theta}{2} = asin(\frac{r}{r_d}) \quad (16)$$

The heading vector that starts from the USV to the intruder

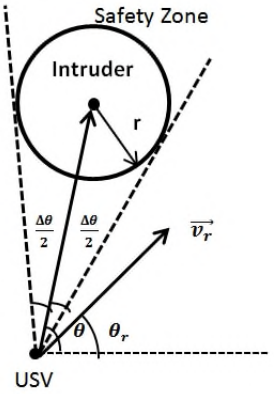

Fig. 6. Collision angle range $\Delta\theta$

can be denoted as $(p_{obsx} - p_{ux}, p_{obsy} - p_{uy})$. Thus, the heading angle θ can be generated.

$$\theta = atan(\frac{p_{obsy} - p_{uy}}{p_{obsx} - p_{ux}}) \tag{17}$$

If $\theta_r \in [\theta - \frac{\Delta\theta}{2}, \theta + \frac{\Delta\theta}{2}]$, the USV will move into the safety zone and the collision will occur. In this case, the status flag will equal to 3.

3.3 Implementation based on the rules of sea

Based on the International Regulations for preventing Collisions at Sea (COLREGS), 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 it. When two power-driven vessels are meeting head-on, both must alter course to starboard so that they pass on the port side of the other. An overtaking vessel must keep out of the way of the vessel being overtaken.

The method to distinguish crossing, heading-on and overtaking is presented in this sub-section.

When the status flag equals to 3, it means there will be potential collision risk. However, it does not mean the ASV ownship will take action to avoid the intruder. Only when the intruder is in the quadrant 1 of the C-Enduro, i.e. the starboard side of the vessel, the C-Enduro is in the crossing or head-on case then it will need to turn to starboard side. Quadrant 2 case means the intruder is in the port side of C-Enduro. Quadrant 3 and quadrant 4 mean that the intruder is in overtaking situation, in which case, C-Enduro does not need to take any action.

The method to check whether the intruder is in quadrant 1 is presented below.

Assume the course angle of the C-Enduro vessel is θ_u and the line-of-sight angle from the USV to the intruder is θ. As shown in the Fig. 7, when θ is in the range $[\theta_u - \frac{\pi}{2}, \theta_u]$, the intruder is in quadrant 1, However, the range of θ_u is $[0, 2\pi]$, the range of $\theta_u - \frac{\pi}{2}$ is $[-\frac{\pi}{2}, \frac{3\pi}{2}]$ and the range of θ is $[0, 2\pi]$. It is not correct to compare θ with $\theta_u - \frac{\pi}{2}$ and θ_u directly, so the situations are divided into two cases. When θ satisfies the equations below, the intruder is in quadrant 1 of the USV.

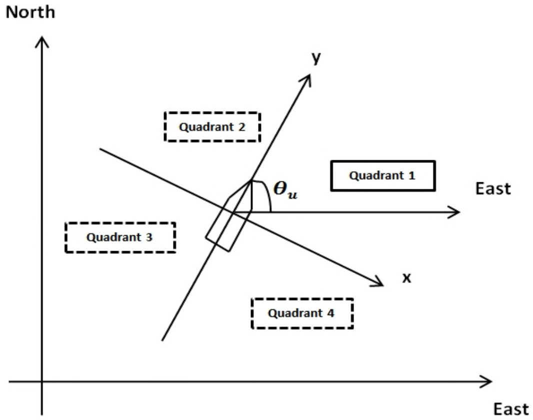

Fig. 7.Collision case analysis

Situation 1:

$$\theta_u - \frac{\pi}{2} \geq 0$$
$$\theta_u - \frac{\pi}{2} < \theta < \theta_u$$

Situation 2:

$$\theta_u - \frac{\pi}{2} < 0$$
$$\theta_u - \frac{\pi}{2} + 2\pi < \theta < 2\pi \ Or \ 0 \leq \theta < \theta_u$$

Only when the status flag equals to 3 and θ satisfies one of the two situations, the USV will only then take action to avoid the intruder.

3.4 Collision resolution

When the status flag equals to 3 and θ satisfies one of the two situations, the direction of the relative speed needs to be changed. Taking into consideration the maritime rules, the C-Enduro vessel needs to go to the right tangent point of the intruder safety circle.

From the C-Enduro position to the intruder safety circle, there will be two tangent points. Assuming the tangent point position is (x, y), we can use the equations below to find the solution.

$$(x - p_{obs_x})^2 + (y - p_{obs_y})^2 = r^2 \tag{18}$$

$$\left(y - p_{obs_y}\right) \times (y - p_{uy}) = -(x - p_{obs_x}) \times (x - p_{ux}) \tag{19}$$

Solving these two equations will give us two solutions, assuming those two solutions are (x_1, y_1) and (x_2, y_2), the approach for selecting the starboard side tangent point is given below.

Assuming the line-of-sight angles between the two tangent points and the C-Enduro vessel are θ_1 and θ_2, as shown in Fig. 8. It is worth mentioning that in the figure the starboard side tangent point can also be (x_2, y_2), the equations show how to determine which one of the two tangent points is the starboard side one.

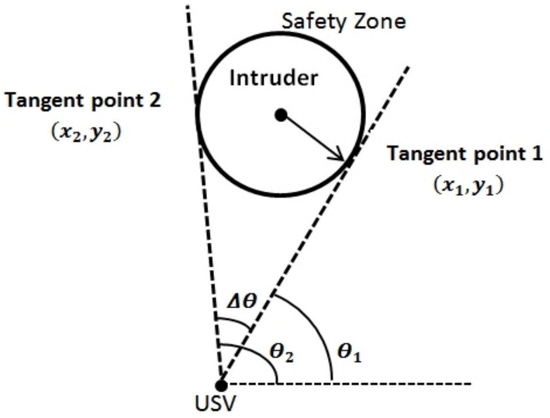

Fig. 8. Intruder safety zone tangent points

$$\Delta\theta = \theta_2 - \theta_1 \tag{20}$$

If $\Delta\theta$ satisfies the condition in eqn.(21), (x_1, y_1) is the starboard side tangent point, otherwise, the starboard side tangent point solution will be (x_2, y_2).

$$0 < \Delta\theta < \pi \text{ or } \Delta\theta < -\pi \tag{21}$$

3.5 Resolution guidance

Since the tracked tangent point (on the intruder safety circle, see Fig. 8) is moving, a guidance algorithm needs to be incorporated otherwise the proposed solution would be sensitive to disturbances. Any external disturbances (e.g. due to wind, waves or currents) might cause the USV vessel to demand large avoidance course angles which are not necessary. Hence an internal guidance loop had also to be included; a proportional navigation (PN) guidance method was implemented due to its simplicity.

In Fig. 9, $\overrightarrow{v_u}$ is the ASV ownship speed vector, $\overrightarrow{v_{obs}}$ is the intruder speed vector, which is the same as the tangent point speed vector; θ_3 is the line-of-sight angle between the USV and the tangent point; $\dot{\theta_3}$ is the line-of-sight angle changing rate; a_n is the acceleration perpendicular to the instantaneous line-of-sight. The C-Enduro velocity vector should rotate at a rate proportional to the rotation rate of the line-of-sight, and in the same direction.

$$a_n = N\dot{\theta_3}\, V_r \tag{22}$$

In (22), N is a proportional constant, which needs to be regulated in the implementation. In the simulation, N is set to be 6; $\dot{\theta_3}$ is the line-of-sight turning rate and V_r is the relative velocity between C-Enduro and the intruder tangent point, which approximately equal to the relative speed between the C-Enduro vessel and the intruder.

Thus the angular velocity of the C-Enduro vessel $\dot{\theta_u}$ can be obtained by:

$$\dot{\theta_u} = \frac{a_n}{V_u} \tag{23}$$

Where V_u is the C-Enduro velocity scalar.

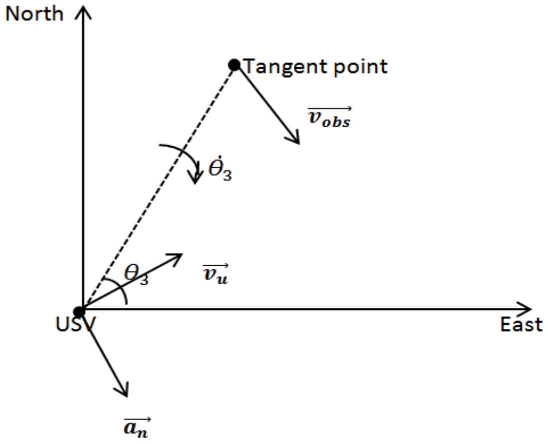

Fig. 9. PN Guidance

Thus the new required course angle for C-Enduro (θ_{u_new}) can be obtained:

$$\theta_{u\_new} = \theta_u + \dot{\theta_u} \times \Delta t \tag{24}$$

where Δt is θ_u update time interval, which is assumed to be 10 seconds, which is the same as the AIS data updating rate.

4. SIMULATION RESULTS

In the simulation scenario, five vessels were assumed to be detected in the 10 miles radius, (it is the estimated ASV AIS data receiving range). Only when the intruders enter the filtering range of the C-Enduro vessel, the status flag of C-Enduro will be updated.

All intruder vessels are assumed to have a constant speed of 10 knots. The C-Enduro vessel has a constant speed of 4 knots and the AIS data update is received every 10 seconds. True north coordinate is used for the C-Enduro course angle.

The parameters used in this simulation are summarised in Table 3, below.

Table 3. Parameters values used in the simulation

Parameter	Value
ASV vessel speed	4 knots
Intruder vessels speed	10 knots
Filtering range	0.75 nautical miles
Safety range	0.108 nautical miles, i.e. 200 meters
MMSI of the five intruders	1, 2 ,3 ,4, 5
AIS data updated rate	10 seconds

At time t = 100s, there are no intruders within the filtering range, the status flag remain at “0” and C-Enduro continue moving towards the destination waypoint, as shown in Fig. 10.

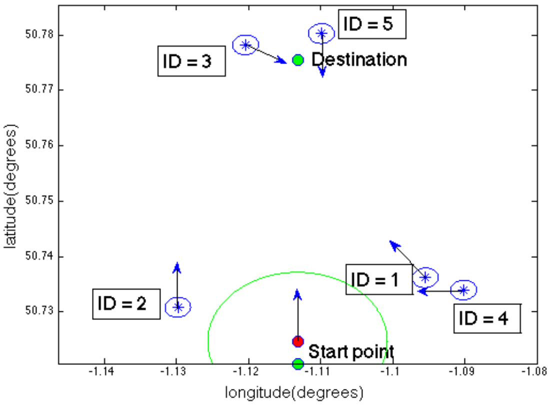

Fig. 10. All vessels detected within the 10 miles range

At time t = 460s, the intruder (ID=4) moved inside the filtering range from the starboard side (crossing case scenario). The algorithm calculated there will be collision risk, the C-Enduro guidance system will compute a new course to move to the tangent point of the safety zone of the intruder, until the ASV pass the tangent point, as shown in Fig. 11.

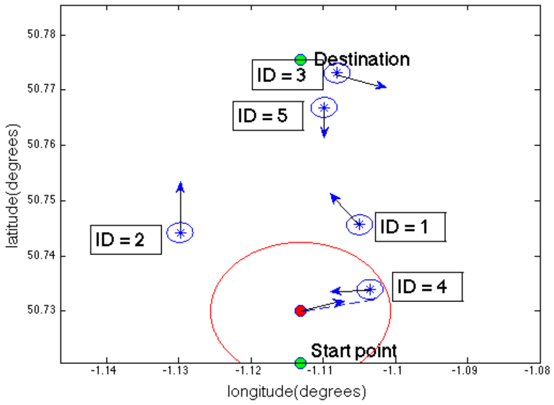

Fig. 11. Crossing case collision risk scenario (t=460s; intruder ID=4; status flag=3)

At time t = 800 s, the intruder (ID = 4) was avoided, the status flag was updated to '2' and the C-Enduro vessel would update its course to head towards the destination waypoint again; and at the same time another intruder (ID=5) is detected, as shown in Fig. 12. As the C-Enduro vessel start to navigate towards the final destination waypoint, there is a new head-on collision risk with the new intruder (ID=5) and the C-Enduro status flag remains at '2'.

At time t = 910s, see Fig.13, the new intruder (ID=5) enters the filtering range of C-Enduro and the collision avoidance algorithm is executed to avoid the head-on collision risk with intruder (ID = 5). The C-Enduro guidance system changes the heading course angle to the starboard side, in accordance with rules of the sea. The collision avoidance manoeuvre will continue until the tangent point of the safety circle is passed.

Fig. 14, shows the distances calculated between the C-Enduro vessel and intruder ID=4 (for the crossing case) and intruder

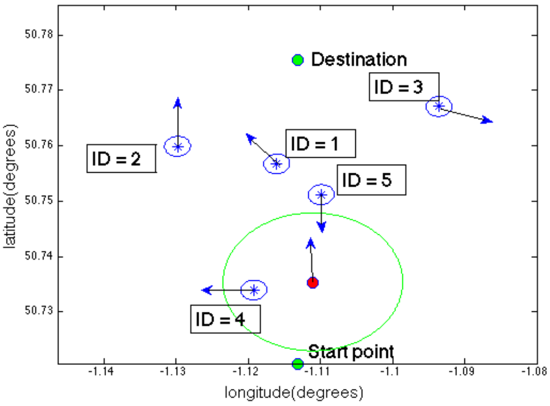

Fig. 12. Collision threat with intruder (ID=4) cleared. A new threat detected (ID=5); (t=800s; status flag=2)

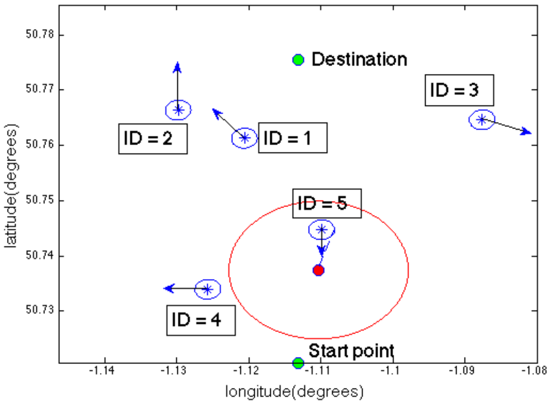

Fig. 13. Head-on collision risk case (t=910s; status flag=3)

ID=5 (for the head-on case) as calculated by the collision avoidance algorithm throughout the avoidance maneuver i.e. from the instance the collision avoidance algorithm was triggered till the end when the collision avoidance was completed and the C-Enduro vessel cleared the threat. As shown, the minimum distance between the C-Enduro vessel and intruders in both cases does not drop below the 200m safety zone radius. Hence it can be concluded that in the two scenaria the collision avoidance algorithm was successful executed the maneuvers.

Finally, the complete path of the C-Enduro vessel from the starting point till it reaches the final destination point is plotted in Fig. 15. The two course changes can clearly be seen, where the two maneuvers were executed in accordance with COLREGS rules to avoid the two collision risks.

5. CONCLUSUIONS

The paper presented the simulation results obtained from the implementation of the geometric collision detection and guidance methods for the ASV C-Enduro vessel. This validation is vital prior to carrying-out any sea trials. Initially, the planned sea trials will include the two test scenaria presented in this paper, namely the crossing and head-on cases. The collision avoidance algorithm successfully cleared both intruders and the minimum separation distance did not breach the assigned 200 meters safety zone. Furthermore, all collision risk manoeuvres were executed in accordance with the International Regulations for preventing Collisions at Sea. Due to the paper space limitation, the scenaria were the intruder was approaching from the left were not presented. However, the algorithms were also successful in these cases.

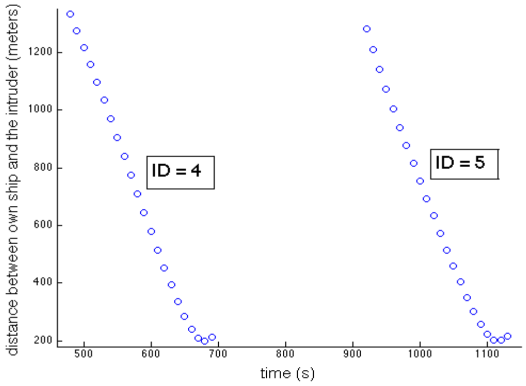

Fig. 14. Distance between the intruder and the ASV own ship

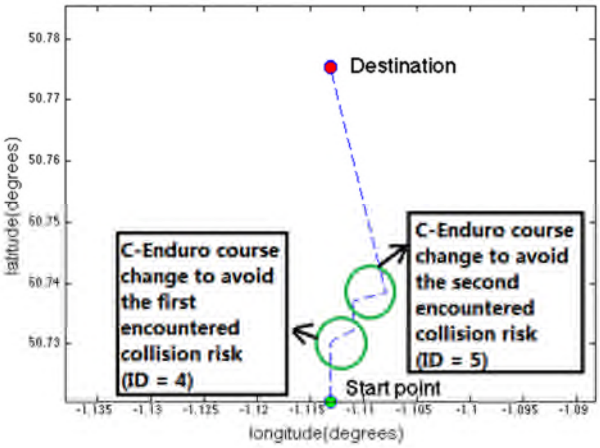

Fig. 15. The complete path of the ASV ownship from the starting point till it reaches the final destination point

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