Proceedings of the 18th World Congress
The International Federation of Automatic Control
Milano (Italy) August 28 - September 2, 2011

Evasive Decision Making in Uninhabited Maritime Vehicles

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Abstract: Unmanned surface vehicles (USVs) are able to navigate in hazardous environments without jeopardising human life. In order to eliminate the human factor altogether, a reliable onboard collision detection and avoidance system is mandatory. This would improve a vessel's self reliance and aid in accomplishing complex missions for extended periods. In addition, the evasive manoeuvres are required to be compliant with coastguard regulations (COLREGs) defined by the International Maritime Organisation. This paper reports the preliminary investigation of such collision avoidance manoeuvres by employing a biased waypoint guidance scheme and genetic algorithms. The paper deals with reactive collision avoidance for objects in the near field. In addition, the dynamics of a USV called *Springer* is incorporated which provides a realistic setting for the proposed strategies. Simulation results demonstrate that the adopted schemes are able to generate safe and viable reference trajectories.

Keywords: Unmanned surface vehicles; guidance and control; collision avoidance; COLREGs; genetic algorithms.

1. INTRODUCTION

Research and development in unmanned surface vehicles (USVs) has gathered pace over the last few years, though the majority of development is still within the defense sector. As more unmanned systems are being deployed world wide for economic and safety reasons, researchers have began to realise the importance of this vital tool for oceanography, data collection in hazardous environments, environmental monitoring or testing new navigation, guidance and control (NGC) strategies. Another unique research area is the use of USVs in conjunction with underwater vehicles to carry out various studies, for instance to investigate hydrothermal vent activity [Pascoal, 2000]. The problem with these uninhabited craft lies with their inability to operate for extended periods without constant or regular human supervision. One of the key reasons is the lack of an onboard collision detection and avoidance system. Currently, the usual approach involves human intervention [Corfield and Young, 2006] through observation with the naked eye or via a constant stream of video data to a remote operator. The latter requires a radio control channel or a wireless link thus adding to the operating cost in the form of a manned support platform. Consequently, the usability and operational extent of the vessel is severely constrained. In Caccia [2006], it is argued that although USVs provide an excellent platform for fast experimentation and development of NGC algorithms, their use is limited by the lack of an obstacle detection and avoidance (ODA) system. Having a reliable automatic ODA module is thus fundamental to a fully autonomous system. Studies have shown that, in manned vessels, over 60% of casualties at sea are caused by collisions [Jingsong et al., 2008]. In addition, it has been found that human error is a major contributing factor to those incidents. This could be due to ever-decreasing numbers of crew adding more responsibilities to those left. For uninhabited craft, this issue cannot be overlooked, as collisions with other manned ships could endanger human life.

To operate USVs, a robust and reliable NGC system is therefore required that would need minimum or no human intervention. A generic block diagram of the NGC system is depicted in Fig. 1. The inner loop forms the feedback control system whereas the outer one is essentially the guidance loop.

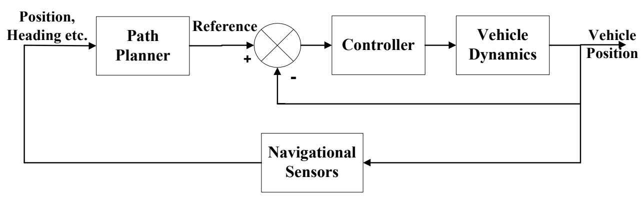

Fig. 1. Navigation, guidance and control of a dynamic vehicle

Many guidance laws designed for unmanned vehicles (marine or airborne) involves line-of-sight (LOS) estimation [Naeem et al., 2003]. Thus, a LOS angle is formed and followed between the vehicle's current position and the target location. In the absence of an ODA system, the unmanned vehicle will follow the reference path regardless of the presence of any intermediate objects. This could lead to catastrophe as the vehicle may run into an obstacle thus damaging the onboard components and in the worst case, even cause it to sink. The presence of an onboard

ODA module is thus extremely important for the vehicle to become self-sufficient. Unfortunately, the marine research community has been mainly focussed on advanced navigation and control systems design and little attention is paid to the area of collision avoidance. There are few reported studies of the use of automatic collision avoidance systems on maritime vehicles. These will be highlighted in Section 2.

In order to seamlessly integrate unmanned vehicles with the rest of marine traffic, a solution is needed that is capable of producing standardised manoeuvres by the USV such that the ambient traffic does not perceive it as a threat in any way. To resolve this problem, coastguard regulations (COLREGs) on prevention of collision at sea defined by the International Maritime Organisation (IMO) [Commandant, 1999] can be adopted. These suggest particular manoeuvres in response to various obstacle encounter settings. Although COLREGs are defined for a diverse range of collision scenarios, they are highly subjective. This has resulted in some controversial decisions and hence collisions between vessels. It is noted that 56% of collisions at sea include violation of COLREGs Statheros et al. [2008]. The infamous *Titanic* tragedy was in fact as a direct result of the unwillingness of the crew to change the speed of the vessel [Lord, 1955] as required by the rules of obstacle encounter at that time.

This paper reports preliminary research results on autonomous path planning for uninhabited marine craft based on COLREGs rules. Two methodologies are investigated and described below. The first scheme incorporates LOS guidance and a manual bias in the heading angle to avoid an obstacle in accordance with these regulations. The addition of the bias angle is carried out only when the vehicle is at the boundary of the safety zone of the obstacle. By comparison, the second strategy employs genetic algorithms (GAs) to generate near optimal evasive manoeuvres that are both safe and COLREGs-compliant. This generates avoidance paths without violating the safety margin and is dependent only on the location of the waypoints and the detected obstacles. The emphasis is placed on following IMO guidelines and optimality is less favoured. It is also vital to integrate the dynamics of the vehicle into path planning as a feasible trajectory for one vessel may be impractical for another. The dynamic model of a USV named *Springer* [Naeem et al., 2008] is thus utilised to determine the feasibility of the adopted approach.

The organisation of the paper is as follows. Section 2 presents a review of COLREGs-based path planning strategies for marine vehicles including a brief outline of IMO regulations. Section 3 highlights the *Springer* dynamics followed by the problem formulation in Section 4. Simulation results are presented in Section 5. The paper ends with concluding remarks in Section 6.

2. REVIEW OF COLLISION AVOIDANCE

Collision avoidance systems have been investigated and developed for a number of land-based robotic applications. In addition, most if not all commercial aircraft are equipped with an automatic collision avoidance module commonly known as ACAS. For application to underwater vehicles, sonar-based ODA systems are common. By comparison, research into ODA systems for USVs, despite their importance, is surprisingly limited and only a few programs have considered developing obstacle avoidance systems let alone those based on COLREGs. For instance, Benjamin *et al.* at MIT [Benjamin et al., 2006, Benjamin and Curcio, 2004] have investigated COLREGs-based navigation using multi-objective optimization and interval programming to generate a behaviour-based control algorithm. The proposed strategy was implemented on two kayak-based SCOUT vehicles each with the capability to communicate its position to the other. Experimental results are reported for a single obstacle only. The Space and Naval Warfare Systems Center in San Diego have employed a voting technique that is also COLREGs-compliant [Larson et al., 2006, 2007]. Another collision avoidance method using fuzzy logic with reference to COLREGs was devised for vessel traffic service (VTS) [Kao et al., 2007], but no experimental results have been reported. More recently, research on COLREGs-based automatic collision avoidance for manned vessels was conducted by researchers in the Universities of Glasgow and Strathclyde [Xue et al., 2009]. They employed artificial potential field and speed vector for trajectory planning and collision avoidance. Simulation results were presented to demonstrate path planning for various obstacle encounter scenarios.

In contrast, this paper employs two simple mechanisms to generate obstacle avoidance paths for single, multiple and dynamic obstacles. A circular safety zone is defined around each obstacle which is not considered in any of the above references. For simulation analysis, both the proposed schemes were tested for a head-on collision scenario (COLREGs rule 14) similar to other studies. A brief outline of COLREGs regulations also commonly termed as marine 'rules of the road' is now presented.

2.1 COLREGs

The coastguard regulations or COLREGs provide a general set of guidelines for the type of action that must be taken by the ship (navigator) in order to avoid a collision. In some instances, there are similarities with automobile driving regulations such as the "right of way" rule. In a head-on scenario, both the own ship [1] and target vehicle are required to turn to their respective *starboard* sides which would certainly avoid collision between the vessels. The rules also state that any movement of the ship must be such that it is visibly evident by the ambient sea traffic. However, there is no mention of the amount of course change in those situations and it is left to the captain/navigator to make such a decision. From a captain's viewpoint, there is absolutely no difference whether the starboard heading manoeuvre is say 28^0 or 30^0 as long as it is avoiding the collision. Also, for optimal navigation, the ship is required to closely follow the assigned path and deviate only when necessary, e.g. for obstacle avoidance tasks. Moreover, the craft would need to return to its assigned seaway as soon as it is safe to do so. Achieving this automatically would entail an intelligent motion planning strategy capable of providing an optimal and safe path based on the dynamics of the given vessel. COLREGs rules also suggest constant lookout and communication between nearby vehicles as is normally carried out by the VTS

[1] Own ship refers to the vessel being controlled.

in the vicinity of a harbour. Nonetheless, situations arise where there is no communication between own ship and other sea traffic making it even more important for the USV to strictly adhere to the COLREGs at all times.

A brief introduction to the *Springer* USV is outlined next, including its steering mechanism and the dynamic model. This model is employed in the subsequent closed-loop simulation studies. Hence a basic understanding of its operation is required.

3. *SPRINGER* USV

The *Springer* USV is a medium water-plane twin hull vessel primarily designed to carry out pollutant tracking and environmental and hydrographic surveys in rivers, reservoirs, inland waterways and coastal waters, particularly where shallow waters prevail. It is a low cost vessel which was also intended for use as a test bed for researchers involved in environmental data gathering, designing alternative energy sources, sensor and instrumentation technology and control systems engineering.

Each hull of the catamaran shaped vessel is divided into two watertight compartments containing the onboard sensors and instrumentation including battery packs. Pelicases are placed within the bay areas between the two cross beams, as shown in Fig. 2, which house the computers and onboard electronics and control circuitry. A wireless router and GPS unit are also installed on the mount shown in Fig. 2. The onboard computers are all linked through a wireless network. This provides an external intervention capability in the case of erratic behaviour or allows the system to simply reset, if required. For the interested reader, the detailed hardware development of the *Springer* USV is described in Naeem et al. [2008].

Fig. 2. *Springer* USV during trials in Devon, UK

Although *Springer's* steering mechanism is based on differential thrust, this can be manipulated to generate the following single-input single-output state space model linearised at a speed of 4 knots:

$$x(k+1) = \mathbf{A}x(k) + \mathbf{B}u(k) \quad (1)$$

$$y(k) = \mathbf{C}x(k) + \mathbf{D}u(k) \quad (2)$$

where $u = n_d$ is the differential thrust in rpm given by Eq. 3 in terms of the individual thruster velocities, n_1 and n_2. The controlled variable, $y = \psi$, is the heading angle of the USV in radians.

$$n_d = \frac{n_1 - n_2}{2} \quad (3)$$

The state matrices are given by:

$$\mathbf{A} = \begin{bmatrix} 1.002 & 0 \\ 0 & 0.9945 \end{bmatrix}, \ \mathbf{B} = \begin{bmatrix} 6.354 \times 10^{-6} \\ -4.699 \times 10^{-6} \end{bmatrix}$$

$$\mathbf{C} = [\, 34.13 \ \ 15.11 \,] \text{ and } \mathbf{D} = [0]$$

The above model was obtained by applying system identification (SI) techniques to the input-output data acquired through experiments [Naeem et al., 2008]. Note that, in the absence of external disturbances, the sway variable can be ignored. The speed was kept constant by maintaining the common mode thrust velocity n_c given by

$$n_c = \frac{n_1 + n_2}{2} \quad (4)$$

n_d was then used as the excitation signal to generate the output heading data. This input/output data pair was utilised to yield the above model using SI.

4. PROBLEM FORMULATION

The overall obstacle avoidance problem is generally accomplished by employing two architectures; (a) deliberative and (b) reflexive or reactive. In the deliberative scheme, obstacles in the far field are considered which are known *a priori* to the mission. This includes shoreline, pontoons and other infrastructure commonly present around a sea port. On the other hand, reactive obstacle avoidance generally deals with (pop-up) objects in the near field that are too close to cause collision with the own vessel. In this scheme, real-time evasive trajectories need to be computed on-the-fly to avoid running into an obstacle. For instance, in the vicinity of a harbour, there is normally a great deal of movement and so the reflexive part of the algorithm will have to generate appropriate manoeuvres to obtain a collision-free path. In what follows, the reactive part of obstacle avoidance is planned with the assumption that an onboard detection system reliably detects any obstacles in the vicinity of the own ship.

It is common to define virtual safety zones around own ship as well as around each of the obstacles and waypoints. In addition, the dynamics of the vessel dictates that a reasonable safety margin be maintained between own ship and the obstacle. Ships dynamics differ greatly, hence a suitable path for one ship may be totally infeasible for another. It is therefore essential to incorporate the dynamics into path planning. The terminology 'circle of acceptance' or COA is generally used for the zones around the waypoints. When the vehicle arrives within the COA of a waypoint, the next waypoint is selected by the mission planner. By contrast, the marked region around an obstacle will be called a 'circle of rejection' or COR which should not be breached unless essential.

In order to test the effectiveness of the adopted approaches, static as well as mobile obstacles have been considered. Two strategies are investigated and simulated for generating evasive paths for both types of obstacles. The first scheme avoids objects by manually biasing the current heading angle towards the starboard side in order to comply with COLREGs. If the own ship enters the

COR, the addition of bias in the heading angle will push the craft away, therefore maintaining a safe distance from the obstacle as well as not deviating unnecessarily from the assigned route. The second strategy for generating feasible trajectories is to employ genetic algorithms (GAs). These are evolutionary search techniques based on survival of the fittest hypothesis. In this paper, the GA search-space consists of cartesian coordinates in two dimensions. In contrast to the biasing LOS guidance, the GA-based methodology generates an overall trajectory depending on the position of waypoints and the detected obstacles. The evasive manoeuvres are independent of COR violations. Another GA-based collision avoidance algorithm for surface vehicles was proposed in Ito et al. [1999] but COLREGs rules were unfortunately not incorporated. The objective functions employed in GAs are problem dependent. Here, the following minimisation function is proposed:

$$\min J = J_{waypoints} + J_{COR} \tag{5}$$

$$J_{waypoints} = \sum_{i=1}^{n} dist(P_{usv}, P_{waypoint_i}) \tag{6}$$

$$J_{COR} = \left(\sum_{j=1}^{m} dist(P_{usv}, P_{obstacle_j}) \right)^{-1} \tag{7}$$

The first term in Eq. 5 minimises the distance between the current USV position and the waypoints; n being the number of waypoints. By comparison, J_{COR} is a penalty factor which penalises those paths which are too close to any of the obstacle's COR, where m is the total number of detected obstacles.

For COLREGs compliance, the GA population is scanned for illegitimate manoeuvres. Those paths (coordinates) in the search-space that violates the IMO regulations are assigned an infinite cost which precludes their selection at the next generation. This will generate an adequate trajectory without (or minimally) breaching the safety zones. It will also bring the vessel back to the original seaway as soon as the obstacle is avoided.

5. SIMULATION RESULTS

The simulation experiments were carried out in closed-loop and a simple PID controller was implemented to follow the generated trajectories as closely as possible. The feedback to the path planner is the latest vessel position which allows the dynamics of the vessel to be integrated in the overall scheme. Simulation results are presented below for the two strategies proposed in this paper. In order to track the guidance commands, a simple PID controller was utilised which was tuned heuristically and integrated with the path planner. The PID gains are selected as 750, 10 and 10 respectively.

Path planning through manual biasing Firstly, the evasive performance of the biased-LOS guidance scheme was investigated for single, multiple and moving obstacles. Fig. 3 depicts the USV trajectory along all the waypoints around a single fixed object. The large dashed circular region is the COR which should not be entered. Through experimentation, a bias angle of 75^0 was introduced when the vessel enters the COR. The amount of change in heading is dependent on the dynamics of the vehicle being controlled but should be large enough to be identified by other ships in the vicinity. It is clear from the figure that the bias in the heading has modified the assigned route towards the starboard side in order to avoid the obstacle in accordance with the regulations. The vessel almost always points towards the direct LOS route between the vehicle and the waypoint but deviates from this route when the no-go zone is breached.

A similar simulation analysis for multiple stationary obstacles is demonstrated in Fig. 4. Some of the waypoints are chosen to be very near the obstacle boundary which makes it impossible for the own ship to avoid entering the COR. In those cases, the breach is unavoidable albeit minimal due to the dynamics of the own vessel.

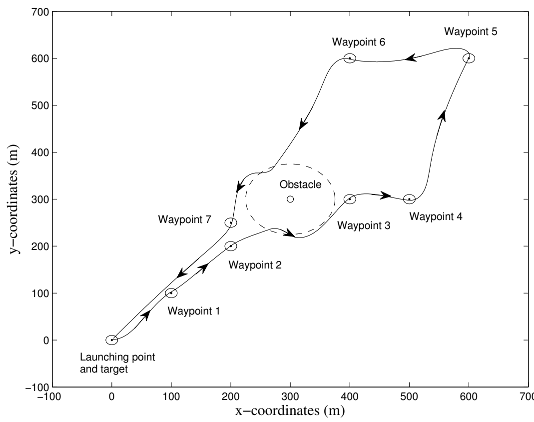

Fig. 3. COLREGs-based collision avoidance for a single static obstacle using the biased LOS guidance scheme

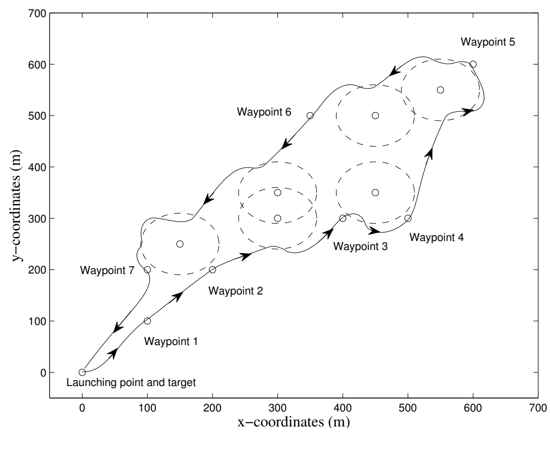

Fig. 4. COLREGs-based path planning for multiple static obstacles using the biased LOS guidance scheme

Finally, the performance of the proposed scheme was investigated for a mobile obstacle moving towards the vessel at 0.3 m/s as shown in Fig. 5. Between waypoints 1 and 2, the own ship is still at a safe distance from the obstacle, hence a straight line route is obtained. On the course to waypoint 3, the own vessel is on a collision course with the obstacle and hence an evasive manoeuvre is needed. This is shown by the starboard turn between waypoints 2 and 3. The remaining trajectory until waypoint 6 consists of straight LOS paths and no evasion is required. However, as the vessel approaches the final waypoint, it repeatedly breaches the COR causing the path planner to generate COLREGs compliant manoeuvres.

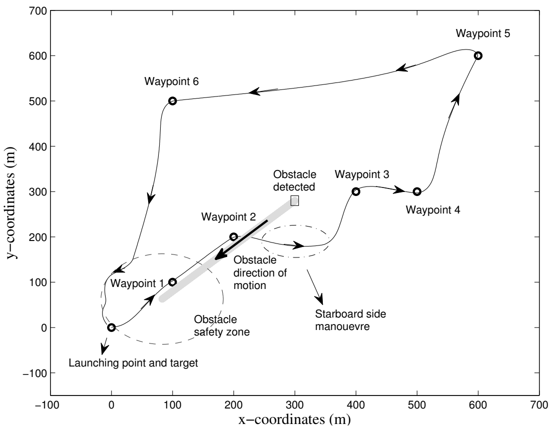

Fig. 5. COLREGs-based collision avoidance for a single dynamic obstacle using the biased LOS guidance

GA-based path planning The GA-based path planner was next simulated and the performance again analysed for multiple and mobile obstacles. Initially, for multiple obstacles case, the ship dynamics were ignored and the objective function in (5) was utilised without the addition of the COLREGs penalty term. The simulation result depicted in Fig. 6 demonstrates that the GA-based ODA system now prevents any section of the resulting path to be within the COR. Since no COLREGs are taken into account, the own ship always takes the shortest possible route to arrive at all the waypoints. Fig. 7 demonstrates the affect of including the USV dynamics and COLREGs penalty term in the objective function; the waypoints and obstacles being located in the same locations as before. In this case, all manoeuvres follow the COLREGs guidelines as the vehicle passes from the starboard side of all the obstacles. The figure also shows the direct LOS route if no obstacles were present in the path.

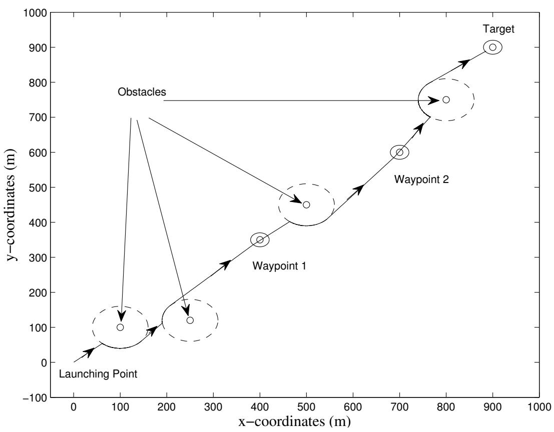

Fig. 6. GA-based collision avoidance simulation for multiple static obstacles without COLREGs

Fig. 8 presents another obstacle avoidance trajectory for multiple obstacles which is COLREGs-compliant. The figure clearly demonstrates that, although the port side manoeuvre between waypoint 2 and target would result in

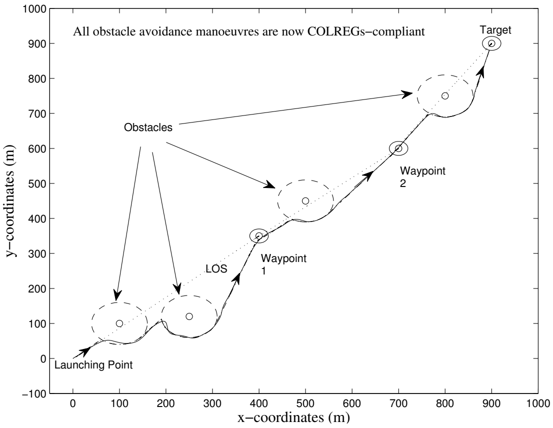

Fig. 7. COLREGs-based collision avoidance simulation for multiple static obstacles using the GA path planner

a much shorter route, the regulations must be adhered to which produced a longer but safe and viable route.

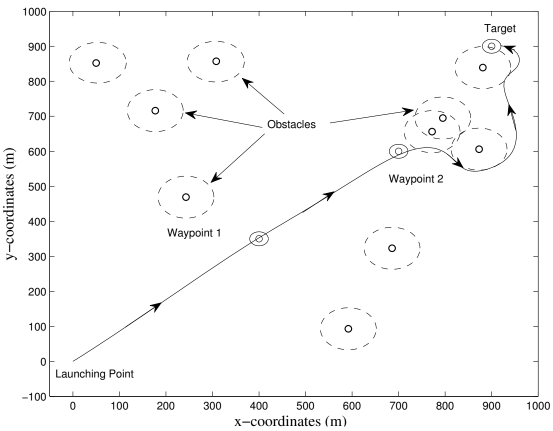

Fig. 8. COLREGs-compliant GA-based path planning for multiple static obstacles

Finally, a mobile obstacle such as a ship was considered which is assumed to be travelling in a straight line towards the USV. The resulting route generated by the GA-based ODA system is depicted in Fig. 9 showing the starboard side manoeuvre required to evade the oncoming ship. In order to analyse the performance of this system, the obstacle avoidance manoeuvre is plotted in detail in Fig. 10. It can be observed that the own vessel breached the COR minimally before turning to the starboard side and then maintaining a constant distance from the obstacle by keeping its path along the CORs boundaries. When the obstacle was fully avoided, the USV continued on the LOS angle towards the target.

6. CONCLUSION

Preliminary results on the development of obstacle avoidance strategies for uninhabited surface vehicles are presented in this paper. The uniqueness of the proposed strategies lie with the inclusion of standardised rules defined by the IMO. Two alternative schemes are presented. The first is a LOS based path planning with the addition of a bias in the heading angle to avoid the obstacle. The second technique uses GAs to generate evasive paths that are safe and compatible with the marine 'rules of the

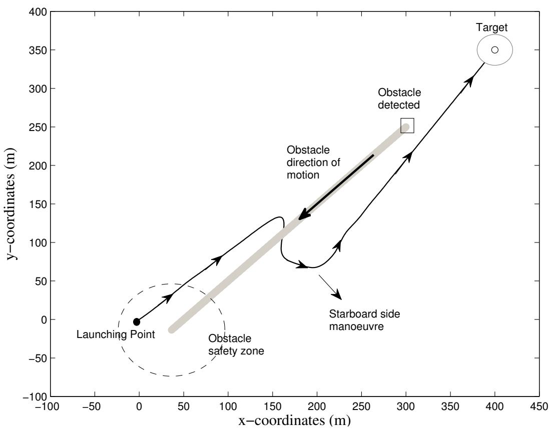

Fig. 9. COLREGs-based collision avoidance simulation for a mobile obstacle using the GA path planner

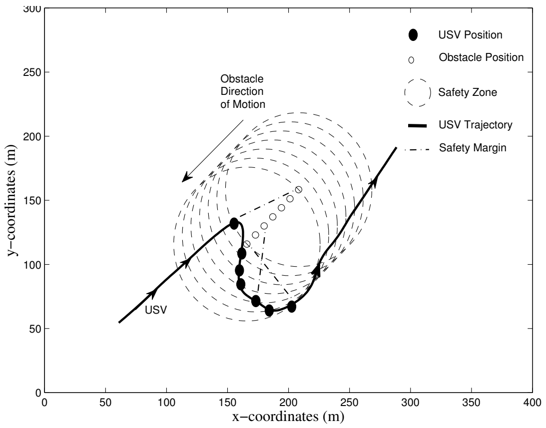

Fig. 10. Detailed analysis of the evasive manoeuvre in Figure 9

road'. The simulation results presented in the paper also incorporated the dynamics of a USV to provide realistic trajectories. The first technique almost always breaches the COR since the addition of the bias angle is dependent on the distance of own ship to the obstacle. In contrast, the GA-based methodology achieves obstacle avoidance by *a priori* considering the location of all the waypoints and the detected obstacles. It should be noted that manned vessels could also benefit from autonomous path planning, thus helping to eliminate the subjective nature of human decisions, thereby safeguarding the onboard personnel. In the future, other motion planning strategies such as using particle swarm optimisation will be investigated for COLREGs compliance. The affect of sea disturbances on the performance of the proposed approaches will also be analysed.

ACKNOWLEDGMENT

The authors would like to acknowledge the EPSRC, UK for funding the project. The *Springer* USV model was kindly supplied by the MIDAS Research Group at the University of Plymouth, UK for this study.

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