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COLREGs-based collision avoidance strategies for unmanned surface vehicles

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A B S T R A C T

The aim of this paper is to report the preliminary development of an automatic collision avoidance technique for unmanned marine craft based on standardised rules, COLREGs, defined by the International Maritime Organisation. It is noted that all marine surface vessels are required to adhere to COLREGs at all times in order to minimise or eliminate the risk of collisions. The approach presented is essentially a reactive path planning algorithm which provides feedback to the autopilot of an unmanned vessel or the human captain of a manned ship for steering the craft safely. The proposed strategy consists of waypoint guidance by line-of-sight coupled with a manual biasing scheme. This is applied to the dynamic model of an unmanned surface vehicle. A simple PID autopilot is incorporated to ensure that the vessel adheres to the generated seaway. It is shown through simulations that the resulting scheme is able to generate viable trajectories in the presence of both stationary and dynamic obstacles. Rules 8 and 14 of the COLREGs, which apply to the amount of manoeuvre and to a head-on scenario respectively are simulated. A comparison is also made with an offline or deliberative grid-based path planning algorithm which has been modified to generate COLREGs-compliant routes.

1. Introduction

Automatic unmanned systems are an integral part of everyday life, normally employed to perform repetitive chores quickly and efficiently which are too tedious for humans. Most are designed to operate in structured environments where the surroundings do not vary considerably. This enables the uninhabited system to continuously recalibrate itself using fixed *a priori* known locations. Developing a fully autonomous system which can work in any unstructured or unpredictable environment is a challenging task that requires robust guidance and control strategies. For unmanned mobile systems operating in fast changing surroundings, such as an automobile, aircraft or a humanoid robot, the automatic guidance system or path planner plays a central role in bringing autonomy to the whole system. The guidance or mission commands are normally sent through a wired or wireless channel by a remote operator whose responsibility is to constantly oversee the system and act accordingly. The guidance system is thus essential to determine "reasonable" and safe actions that are required to accomplish a mission.

Fig. 1 depicts a block diagram of a navigation, guidance, and control system for a dynamical system such as an unmanned vehicle. The inner loop is the standard feedback control system, while the outer guidance loop acquires and processes the information from onboard sensors.

In what follows, a guidance system, or more precisely, an obstacle avoidance system (path planner) is developed for an unmanned (maritime) surface vehicle or USV. USVs are useful tools in tasks such as oceanography, remote sensing, weapons delivery, force multipliers, environmental monitoring, surveying, and mapping and providing navigation and communication support to unmanned underwater vehicles. There are several worldwide USV programs both in the defence and civil sectors such as the *Delfim* USV for mapping applications [16] and *Protector* USV [17] for maritime assets protection. Most of these rely on remote operator guidance for sending mission commands and to constantly overlook the vehicle's status either by direct observation or via a wireless video link [6]. This adds to the operating cost of each mission and is not practical for extended periods of time.

In order to fully benefit from this technology, a reliable obstacle detection and avoidance (ODA) system is thus mandatory, a fact confirmed by leading researchers and industrialists in the field [3,6]. Besides developing a system that generates evasive manoeuvres to avoid an object, it is important that the USV behaves in a manner that is discernable by other ships in the vicinity. This attribute would aid in integrating the USVs with the rest of the marine traffic. The coastguard regulations on prevention of collision at sea (COLREGs), defined by the International Maritime Organisation (IMO) [5,4], can usefully be incorporated for this purpose. It should be noted that all manned vessels are required to adhere to these

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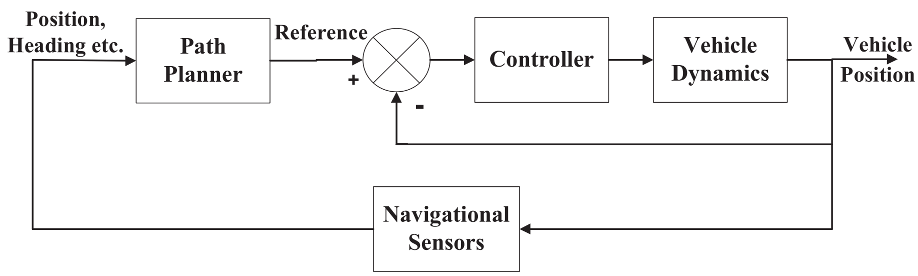

Fig. 1. Navigation, guidance (path planning) and control of a dynamic vehicle.

regulations at all times in order to avoid a collision. Section 2 highlights the basis of this work and existing research in this area.

The proposed approach employs a simple waypoint by line-of-sight (LOS) guidance strategy [8] coupled with a manual biasing scheme. This is tested in simulations on the *Springer* USV dynamic model described in Section 3. To this end, several mission waypoints are selected between the USV launching position and the destination. The vehicle is normally guided to stay on the direct LOS route between successive waypoints when no obstacles are found. Assuming that a vision-based detection system is present onboard, a bias is added to the current reference heading angle should an object is found posing a threat. This manual bias deviates the course of the USV and thus the obstacle is evaded. Once the threat is passed, the craft is again commanded to follow the direct LOS angle between its current position and the next waypoint. It will be demonstrated that the addition of the bias angle generates evasive manoeuvres that satisfy the IMO requirements. Simulation results are presented showing USV trajectories between all the waypoints for the case of both single and multiple stationary objects as well as a single dynamic obstacle. For comparison purpose, an A*-based algorithm, DPSS (Direction Priority Sequential Selection) [20] is also applied that has been modified to generate safe and feasible routes in accordance with COLREGs. The novelty of this work thus includes the modification of waypoint-by-LOS and DPSS algorithms to generate COLREGs-compliant routes. In addition, the dynamics of the vehicle are incorporated which produces realistic trajectories that can be followed by a given vehicle.

The organisation of the paper is as follows. Section 2 explains the motivation of this research including a brief description of IMO regulations. The *Springer* USV dynamic model used in the simulation study is briefly described in Section 3. The problem formation is then outlined in Section 4 along with a brief description of the DPSS technique. Section 5 presents simulation results whilst concluding remarks follow in Section 6.

2. Motivation and background

Recent statistics have shown that 60% of casualties at sea are caused by collisions [9]. It has also been found that human error is a major contributing factor to such incidents. Furthermore, it is reported in Statheros et al. [18] that 56% of collisions at sea include violation of COLREGs. The infamous *Titanic* tragedy was in fact as a result of the unwillingness of the crew to change the speed of the vessel [14] as required by the rules of obstacle encounter at that time. Although these studies are compiled for manned ships, unmanned vessels without any form of onboard intelligence could even be more vulnerable. Insurance companies are generally reluctant to provide cover for these types of vessels for this very reason. A review of related research has revealed that very few USVs are equipped with an onboard detection and avoidance system. In addition, only a handful of research programmes have considered developing COLREGs-based avoidance systems. For instance, Benjamin and others at MIT [1,2] have investigated COLREGs-based navigation using a multi-objective optimisation 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. The Space and Naval Warfare Systems Center in San Diego (SSC San Diego) have developed an ODA system which provides optimal trajectories based on the COLREGs. The distance to the object is measured using an onboard camera system mounted on a SEADOO Challenger 2000 sport boat [12,13]. Another collision avoidance method using fuzzy logic with reference to COLREGs is devised for vessel traffic service (VTS) [10], however, no experimental results have been reported. A simulation study of COLREGs-based automatic collision avoidance for manned vessels at the Universities of Glasgow and Strathclyde [19] employed an artificial potential field and a speed vector for trajectory planning and collision avoidance. Results were presented to demonstrate path planning for various obstacle encounter scenarios. More recently, the US Defense Advanced Research Projects Agency has announced the development of a USV capable of carrying out anti-submarine warfare. A key part of the programme is to provide the vessel with the capability to safely navigate at sea within the framework of IMO regulations [11].

In the absence of obstacles, a waypoint guidance scheme generally works very well. However, in practice, the real-world is full of unpredictable situations, so it is not possible to leave the unmanned vessel unattended during a mission. This paper introduces a straightforward, yet effective, technique for obstacle avoidance based on IMO regulations. A brief account of these regulations now follows.

2.1. Coastguard regulations

Consider an unmanned vehicle *en route* to an environmental monitoring operation which has encountered a manned ship in a head-on scenario. It is clear that there cannot be any verbal communication between the two vessels. Hence it is important that both the USV and the manned vessel abide by some pre-defined rules. Fortunately, the coastguard regulations or COLREGs on prevention of collision at sea have been defined by the IMO [5,4]. These rules suggests particular manoeuvres in various obstacle encounter settings. For instance, in the head-on collision scenario presented (Rule 14), both the vessels involved must turn towards their respective starboard sides as demonstrated in Fig. 2. Also, Rule 15 defines the crossing situation, which is akin to right-of-way precedence in automobile driving.

The difficulty with the COLREGs is that they were written for humans and thus are subjective in nature. For instance, Rule 8(*b*) states that any change in the vehicle's course should be discernable by the ambient traffic and must not include a series of small changes. For a human captain, it does not make any difference whether the obstacle avoidance manoeuvre is say 28° or 30° as long as it is avoiding the collision. However, for optimal navigation,

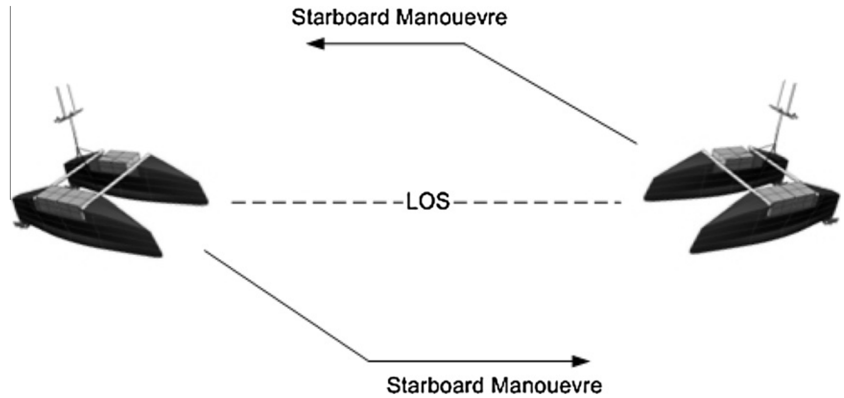

Fig. 2. Head-on collision scenario (COLREGS – Rule 14).

the ship is required not to deviate unnecessarily from the assigned path, while following the IMO guidelines. Hence any automatic path planning system may also prove useful for (the captain of) a manned vessel. COLREGs rules also suggest constant lookout and communication between nearby vehicles which is normally carried out by the VTS in the vicinity of a harbour. Nonetheless, there are situations where there is no communication between own ship[1] (such as an uninhabited vehicle) and other sea traffic and therefore additional complications will arise. It is therefore even more important for the USV to stay on track and strictly adhere to the COLREGs at all times.

For simulation purposes, rules 8 and 14 of the COLREGs are selected. These apply to the amount of manoeuvre and to a head-on scenario respectively. The new COLREGs-based collision avoidance system is based on waypoint guidance coupled with a manual biasing scheme. Here the current course of the USV is biased towards the starboard side to avoid running into the obstacle. Although this strategy is clearly not optimal as it is simply emulating human behaviour, it demonstrates that the regulations can indeed be automated and successfully applied to unmanned vehicles. Indeed, any evasive strategy complying with COLREGs will generate safe but not necessarily optimal trajectories as safety is the primary concern. The simulation study is carried out using a model of the *Springer* USV which is presented in the next section.

3. *Springer* USV [15]

The *Springer* USV is a catamaran-shaped research vessel which was primarily designed to carry out pollutant tracking and environmental and hydrographic surveys in rivers, reservoirs, inland waterways and coastal waters. It is a low cost vehicle which was also intended to be used 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 *Springer* is divided into two watertight compartments containing some of the onboard sensors and electronics including battery packs. Pelicases are placed within the bay areas between the two cross-beams, as depicted in Fig. 3. These house the computers and the remaining onboard electronics and control circuitry. A GPS receiver and wireless router were also installed on the mount shown in Fig. 3. The onboard computers are all linked through an *ad hoc* wireless network providing an external intervention capability in the case of erratic behaviour or simply for monitoring purposes. Some hardware specifications of the vehicle are provided in Table 1. For the interested reader, the detailed hardware development of the *Springer* USV is described in Naeem et al. [15].

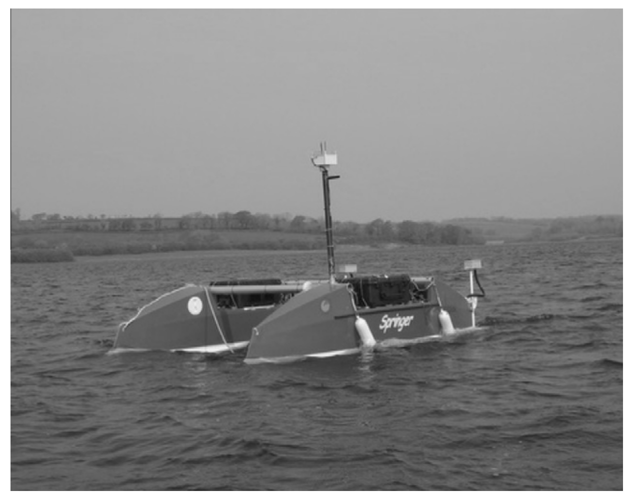

Fig. 3. *Springer* USV during trials at Roadford Reservoir, Devon.

Springer's steering mechanism is based on differential thrust and the dynamic equations can be manipulated to generate the following single-input single-output state space model, where bold case letters represent matrices:

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

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

where $u = n_d$ is the differential thrust input 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 output heading angle of the USV in radians.

$$n_d = \frac{n_1 - n_2}{2} \tag{3}$$

Table 1
Springer USV specifications.

Parameter	Value
Length	4 m
Width	2.3 m
Weight	600 kg
Operating speed	4 knots
Minimum turning radius	25 m

[1] Own ship refers to the vessel being controlled. All other vehicles posing a collision threat will be referred to as target ships.

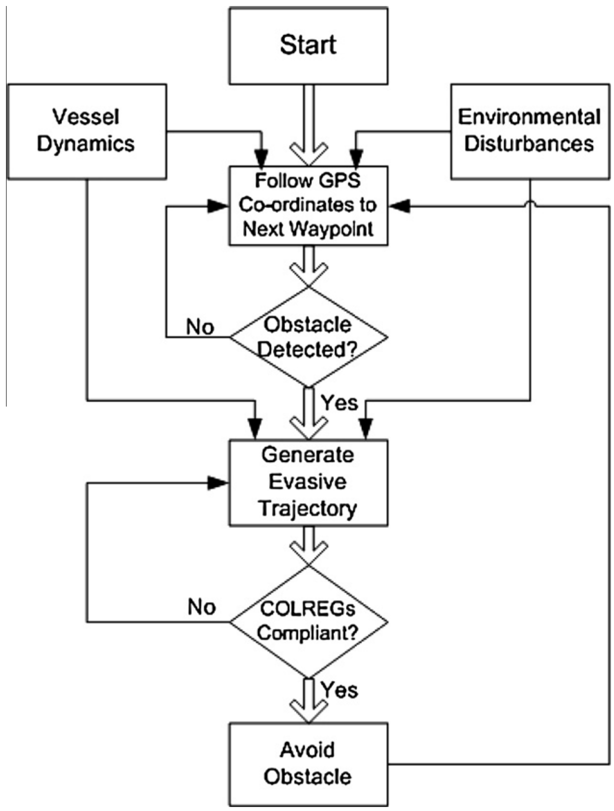

Fig. 4. Proposed COLREGs-based obstacle detection and avoidance strategy.

It is obvious that when $n_d = 0$ i.e. $n_1 = n_2$, the vessel traverses in a straight line in the absence of external disturbances. The state matrices are given by:

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

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

The above dynamic model was obtained by applying system identification techniques to the input–output data acquired through trials carried out at a fixed speed of 4 knots. This was maintained by preserving the common mode thrust velocity n_c in Eq. (4):

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

Here n_d was then used as the excitation input to generate the corresponding output heading data. Note that a second-order discrete transfer function model was originally identified which was converted to a state-space model for implementation.

4. Problem formulation

In order for the automatic collision avoidance to work, a reliable detection system is mandatory. This is responsible for keeping track of any changes in the vicinity of the vessel and reporting to the avoidance (guidance) module. For many reported applications including this paper, it is normally assumed that the location of the obstacles is known in advance. A map of the environment is also available which defines the location of all the fixed infrastructure present around a sea port or a harbour.

Designing an obstacle avoidance system entails two architectures; (a) deliberative and (b) reflexive or reactive. The deliberative architecture includes all the fixed known obstacles or objects which are in the far field. By contrast, the reflexive architecture deals with (pop-up) objects that are too close to cause collision with the vehicle being operated. In this paper, the reactive obstacle avoidance problem is mainly investigated i.e. with undetected objects or obstacles that are in the vicinity of the vehicle. It is assumed that a camera and LIDAR (light detection and ranging) system is present onboard which can reliably detect any such obstacles and provide their distances and bearings from the USV. The vision processing software detects the vertices of an object whose distance from the ship is accurately calculated using a LIDAR. Although this method of detection has some obvious disadvantages, such as false alarm rate, it is only being used in this paper to demonstrate the functioning of the proposed approach.

It is common to employ a virtual safety zone around the obstacles as well as the ship being controlled. These zones must not be breached at any time unless strictly necessary. Their sizes depend on the dynamics of the vessel but should be at least twice that of the vehicle's minimum turning radius. Here a circular safety zone[2] called the circle-of-rejection (COR) is assumed around each obstacle. Note that the proposed algorithm is independent of the shape and size of the static object. A circle-of-acceptance (COA) is also assumed around each waypoint which flags the arrival of the ship at each one. When the vehicle enters the COA of a waypoint, the mission planner selects the next waypoint and the vehicle is guided towards it. The COA is normally taken to be twice the length of the vessel being commanded [8].

The methodology adopted here has two distinct planning stages. Firstly, the vehicle must never enters the safety zone around the obstacle. Secondly, in order to comply with COLREGs, the vehicle must pass by from the starboard side of the obstacle. This is true for both stationary and mobile obstacles. As explained earlier, the proposed approach employs a simple waypoint guidance by LOS [8] coupled together with a manual biasing scheme. This strategy changes the current heading angle of the vehicle towards the starboard side when the distance of the ship to the obstacle is less than or equal to, the radius of COR as shown below:

$$\begin{array}{l|l} \text{heading} = LOS + \text{bias angle}, & distance(USV, obstacle) \leqslant COR \\ \text{heading} = LOS, & \text{otherwise} \end{array}$$

This strategy would then avoid the obstacle as well as complying with coastguard regulations. The flowchart shown in Fig. 4 illustrates the concept. It is noted that Rule 8 of the IMO regulations requires any change in the heading angle of the vehicle to be visually distinguishable by other marine traffic.

The following subsection outlines a brief description of the DPSS algorithm highlighting the modifications made to generate COLREGs-compliant paths.

4.1. DPSS algorithm

The DPSS algorithm is essentially a modified version of the A* method which has been developed by Yang et al. [20] to enhance its performance in terms of improved trajectories and computational cost. The A* algorithm is a classical grid-based methodology which has been widely applied in different shapes and forms. It uses a heuristic method to focus the search towards the goal position. Using an edge cost and a heuristic based on the Euclidean distance, the A* algorithm can find the shortest paths [7]. For the classical A* algorithm, its scalability is limited by its memory requirements. It stores all explored nodes of a search graph in the memory, using an Open List to store nodes on the search frontier and a Closed List to store already-expanded nodes.

[2] Elliptical-shaped zones are also common.

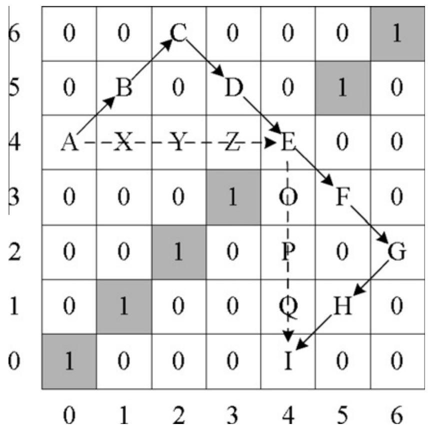

Fig. 5. Effect of Path Fin Cutting function to the raw path generated by DPSS.

Depending on the size of the grid map, a large number of nodes may have to be searched at any given time. Thus, repeatedly searching through these lists can slow down the application significantly. Hence, it is not suitable for real-time engineering applications requiring on-the-fly computations.

On the other hand, the DPSS method is based on a Goal Direction Vector and results in search time reduced by up to 50%. However, due to its inherent search nature, it is also mainly suited for offline applications. The DPSS strategy produces waypoints around obstacles that forms a smoother path with less jagged segments than A*. This scheme consists primarily of two functions: a Node Sorting Search (NSS), similar to A* and Path Fin Cutting (PFC). The NSS function is based on a direction priority sorting and can be used to achieve a feasible path with minimum number of steps. The route obtained at this step is termed as the raw path. Next, PFC function is used to optimise the raw path. Since the focus of the NSS function is on the steps rather than the length/cost, it is necessary to develop some measures to generate smoother paths with less jagged segments and to improve the quality of the raw path. Fig. 5 demonstrates the outcome of applying the PFC function to the raw path given by $A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F \rightarrow G \rightarrow H \rightarrow I$. The optimised path is calculated to be $A \rightarrow X \rightarrow Y \rightarrow Z \rightarrow E \rightarrow O \rightarrow P \rightarrow Q \rightarrow I$. It is clear that although the number of steps in both cases are the same, the path length is considerably reduced.

For COLREGs-compliant paths, a simple modification is introduced to the DPSS algorithm. In order to implement Rule 14 (head-on scenario), the grids to the port (left) side of the vehicle are not searched. This is done by placing a virtual obstacle in each of the port-side grid. Hence the algorithm is forced to explore only the starboard (right) side of the grid thus generating manoeuvres that are based on COLREGs.

The proposed biased-LOS strategy is very well suited for real-time (reactive) applications as it calculates the LOS angle at every step (iteration). On the other hand, the DPSS algorithm generates a trajectory offline making use of all available knowledge about the environment thus can be termed as a deliberative search technique. Because of this, the DPSS scheme cannot handle mobile obstacles without some further modification. In addition, the DPSS technique require the obstacle shape to be rectangular/square which is not a constraint in the biased-LOS strategy. However, for a fair comparison, a square-shaped region is assumed for each obstacle with edge length equal to twice the COR in all DPSS simulations. Finally, the dynamics of the system are incorporated in both biased-LOS and DPSS schemes that will produce realistic trajectories.

In order to track the guidance commands, a simple PID controller was utilised which was tuned heuristically and integrated with the path planner. The controller or autopilot ensures that the vehicle stays on course as required by the guidance system. The parameters of the PID autopilot are provided in Table 2:

Table 2
PID parameters used in the simulation study.

PID parameter	Value
Proportional gain (K_p)	750
Integral gain (K_I)	10
Derivative gain (K_D)	10

5. Simulation results

Simulation experiments have been carried out both for static and dynamic obstacles. Based on the waypoint guidance strategy, the vessel follows the LOS angle between its current position and the next waypoint. If there is a breach of the COR, the added bias in the current heading angle alters the course of the vessel towards the starboard side in order to avoid the impact as well as complying with the COLREGs. When the obstacle is fully avoided, the vehicle returns to the current LOS to the next waypoint. The parameters used in all simulation studies are provided in Table 3.

Initially, a single stationary object located at (300,250) was considered. The vehicle was launched at the origin and was required to visit the waypoints listed in Table 4. The vessel finally returned to the launching position.

The simulation run is depicted in Fig. 6 showing USV trajectory through all the waypoints. The effect of vessel dynamics is evident from this plot. The craft continuously follows the LOS angles between successive waypoints until an obstacle is encountered. In that case, there is a visible shift in the vehicle's current heading angle towards the starboard side to avoid the collision which is clearly COLREGs-compliant. Once the obstacle is passed, the USV headed towards the next waypoint by tracking the current LOS angle.

The trajectory generated by the DPSS algorithm is also superimposed on Fig. 6. The difference between the two schemes is mainly evident when the obstacle is encountered. The algorithm calculated two extra waypoints between waypoints 2 and 3 at (301,196) and (357,245) which are just outside the boundary of the COR. This is shown as black-faced circles in Fig. 6. The vehicle is then commanded to follow that additional waypoint to avoid the collision. The trajectory appears to be superior to that of one generated by the proposed strategy as the COR is never beached. However, it should be kept in mind that this path was obtained through offline calculations resulting in complete avoidance of the COR. The proposed strategy, on the other hand, works on-the-fly and deviates only when the obstacle is detected or when at the boundary of the COR.

Table 3
Simulation parameters.

Simulation parameter	Value
COR	50 m
COA	10 m
Bias angle	−75°

Table 4
Waypoint coordinates for the static obstacles case.

x (m)	100	200	400	500	600	400	200
y (m)	100	200	300	300	600	600	500

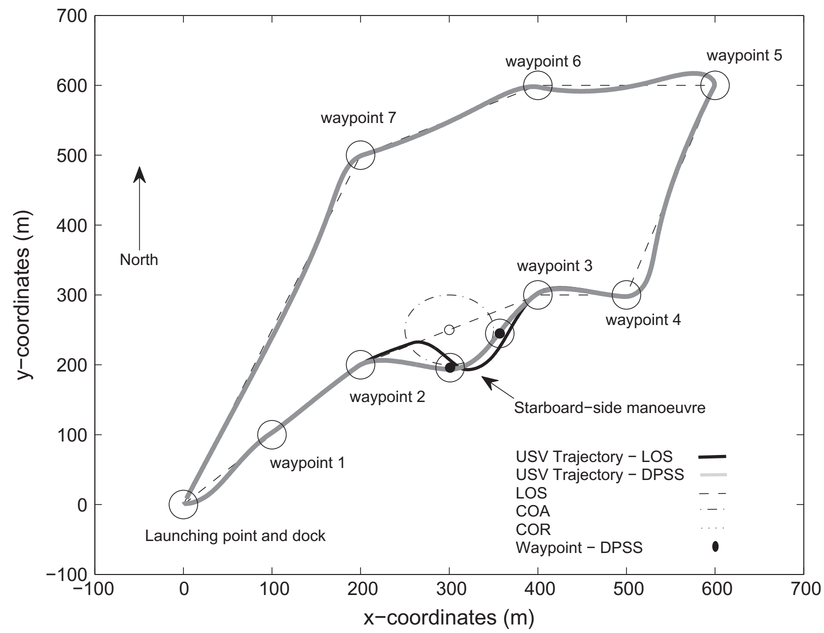

Fig. 6. COLREGs-based collision avoidance simulation for a single static obstacle using the biased-LOS scheme and DPSS.

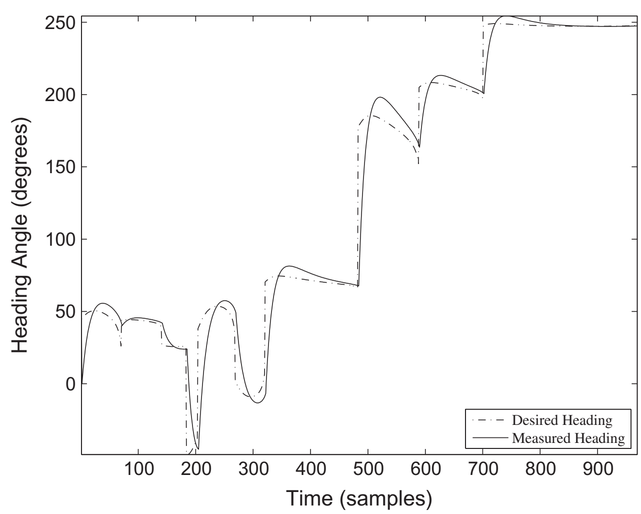

Fig. 7. COLREGs-based collision avoidance simulation for a single static obstacle using the manual biasing scheme showing the heading angle.

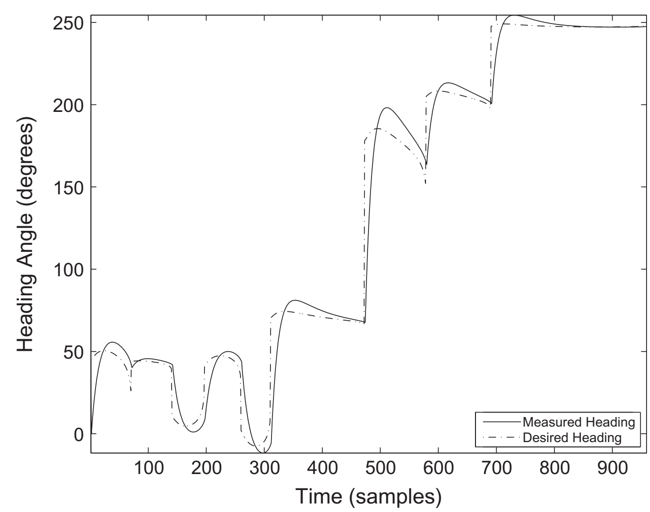

Fig. 8. COLREGs-based collision avoidance simulation for a single static obstacle using the DPSS strategy showing the heading angle.

Figs. 7 and 8 illustrates the heading angle tracked by the controller for biased-LOS and DPSS techniques respectively. The change in course angle to avoid the obstacle, generated by the two schemes, is evident at 200 and 150 samples respectively. Note that the LOS is calculated at each iteration which varies according to the current position of the USV.

For completeness, the standard DPSS trajectory is also plotted in Fig. 9. The black-faced circles represent the extra waypoints generated by the standard DPSS algorithm on the boundary of COR. It is clear that without modification, the DPSS will generate the shortest route between the two waypoints when avoiding the obstacle. In this case, this is not COLREGs-compliant as the vehicle passes through from the port-side of the obstacle.

The next scenario involved multiple stationary obstacles of different shapes and sizes whose vertices are estimated using an onboard detection system. Again, the USV was assumed to have been launched at (0,0) where it eventually docked after completing the mission. In this case, there were seven waypoints and four obstacles (three rectangle and one triangle-shaped) in a field of 700 by 700 m. The co-ordinates of the waypoints provided in Table 5 were randomly chosen with no waypoint located within any of the obstacle boundary.

The obstacle avoidance simulation is presented in Fig. 10 which shows the USV's trajectory through all the waypoints. Several evasive actions have evidently been generated by the path planner. From waypoint 1 to 2, the craft had to navigate away from the obstacle twice before arriving at the waypoint. There was a starboard side turn *en route* to waypoint 3, whereas the trajectory from waypoint 5 to 6 consisted of several avoidance manoeuvres, including a very sharp starboard turn. The path taken by the USV from waypoint 6 to 7 also contained COLREGs-compliant manoeuvres to avoid running into the obstacle. Note that waypoints 2, 3 and 6 are very close to the boundary of the COR and hence a breach was unavoidable. The vehicle finally docked at the launching point.

There are obvious problems with this type of strategy. Although the vessel seems to be keeping away from all the collisions, the evasive actions depend on breaching the COR. The craft must hence

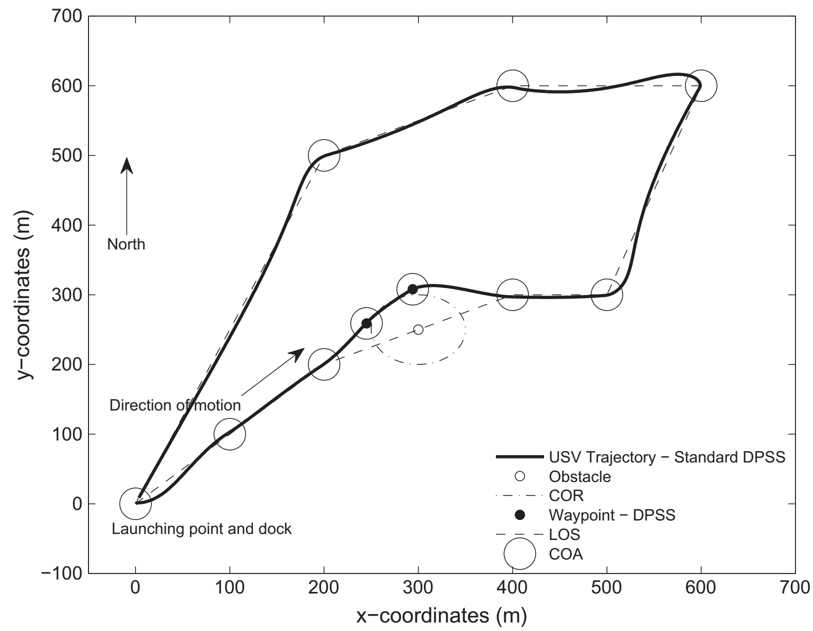

Fig. 9. Collision avoidance simulation for a single static obstacle using the standard DPSS.

Table 5
Waypoint coordinates for the static obstacles case.

x (m)	100	400	520	600	450	200	50
y (m)	100	300	400	600	550	575	400

always enters the COR before it is pushed away by the manual biasing scheme. Also, detecting only the obstacle vertices means that the craft may run into an obstacle if two of its vertices are separated by more than twice the radius of COR. An edge detection system would therefore be more appropriate.

Fig. 10 also shows the additional waypoints generated by the DPSS algorithm and the resulting USV trajectory. In this case, several waypoints were inserted between the original waypoints in Table 5. The new waypoint coordinates are listed in Table 6 and are also depicted in Fig. 10 as black-faced circles.

It is noted that the overall USV trajectory appears to be much smoother as compared to the proposed one, however, this is due to the offline calculations made by the DPSS scheme. In Fig. 11, the USV trajectory is shown for the standard DPSS algorithm. The main difference in the path can be observed between waypoints 6 and 7 where the DPSS has chosen the shortest path (from the port side) and therefore not COLREGs-compliant.

The performance of the proposed scheme was investigated next for a mobile obstacle moving towards the vessel at 1 m/s. Six waypoints, provided in Table 7, were chosen which were sparsely located in an area of 700 m^2. It is clear that the initial USV

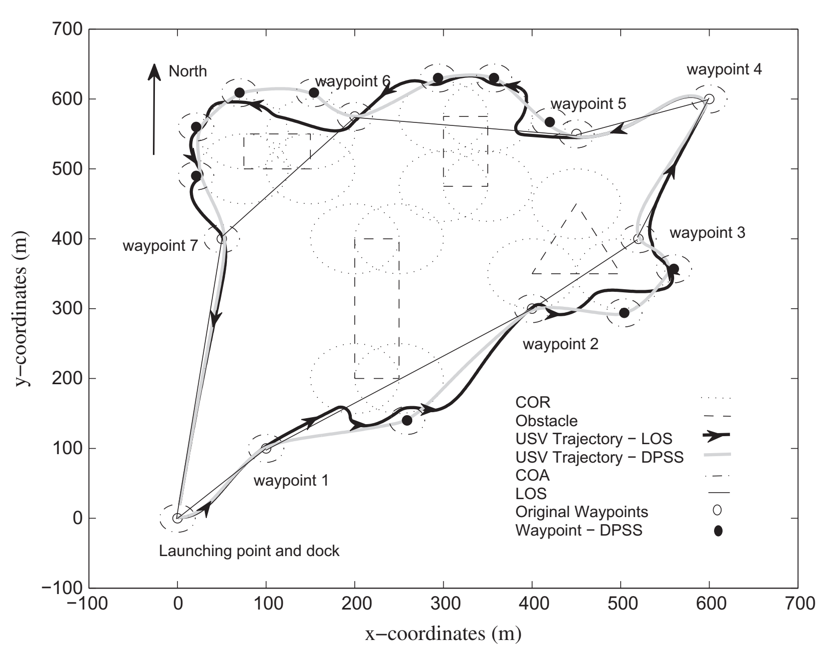

Fig. 10. COLREGs-based collision avoidance simulation for multiple static obstacles using the biased-LOS scheme and DPSS.

Table 6
Additional waypoint coordinates generated by the DPSS algorithm for the static obstacles case.

x (m)	259	504	560	420	357	294	154	70	21	21
y (m)	140	294	357	567	630	630	609	609	560	490

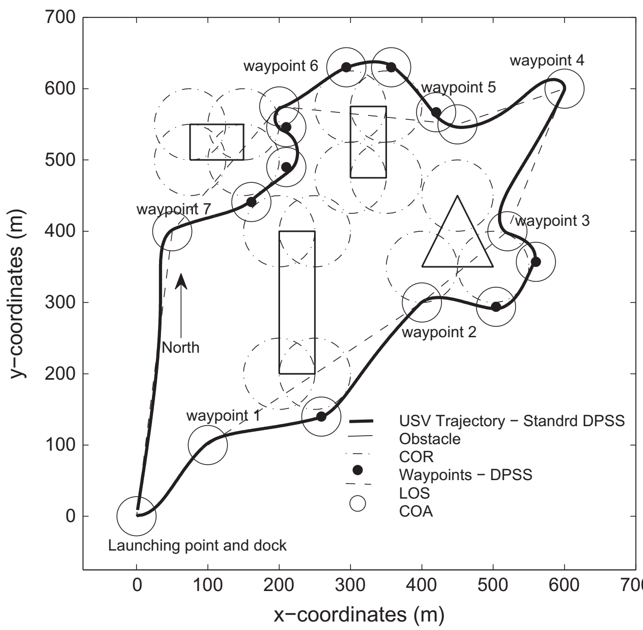

Fig. 11. Collision avoidance simulation for a multiple static obstacle using the standard DPSS.

orientation would have been towards the North–East direction and therefore on a direct collision course with the oncoming ship. In this type of ship encounter scenario, both vessels are normally required to turn towards their respective starboard sides in order to avoid the collision. However, it is assumed here that the oncoming

Table 7
Waypoint coordinates for missions with a dynamic obstacle.

x (m)	100	200	400	500	600	100
y (m)	100	200	300	300	600	500

ship is heading straight towards the own vehicle without changing its course.

The resulting USV trajectory is depicted in Fig. 12. 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 tar-

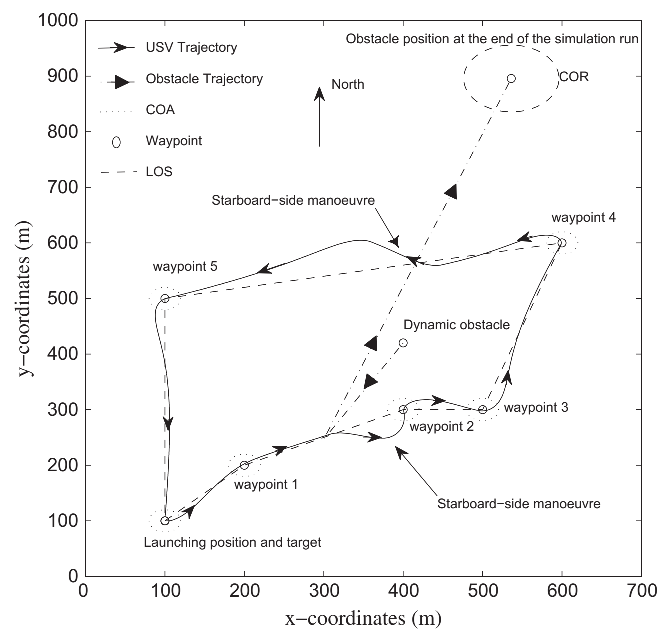

Fig. 13. Collision avoidance trajectory for a dynamic obstacle using the manual biasing scheme.

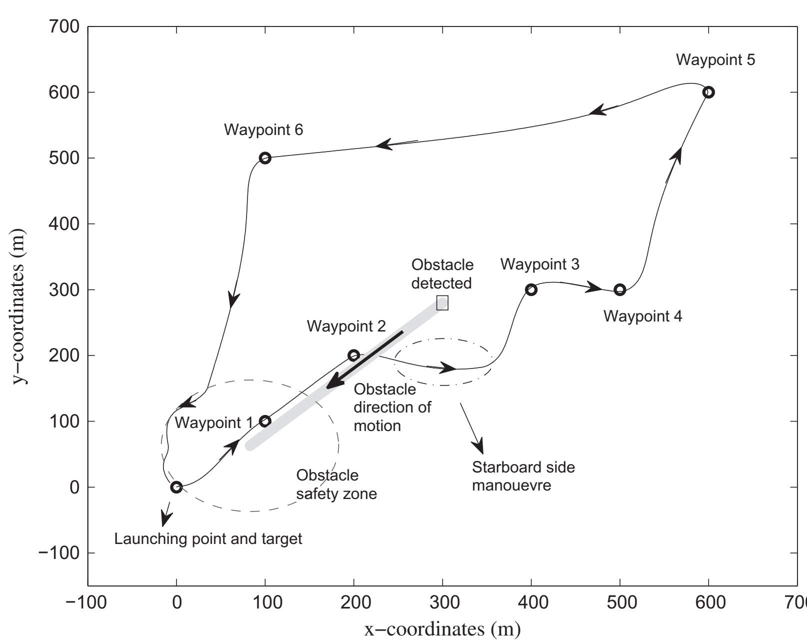

Fig. 12. COLREGs-based collision avoidance simulation for a single dynamic obstacle using the LOS guidance with manual bias.

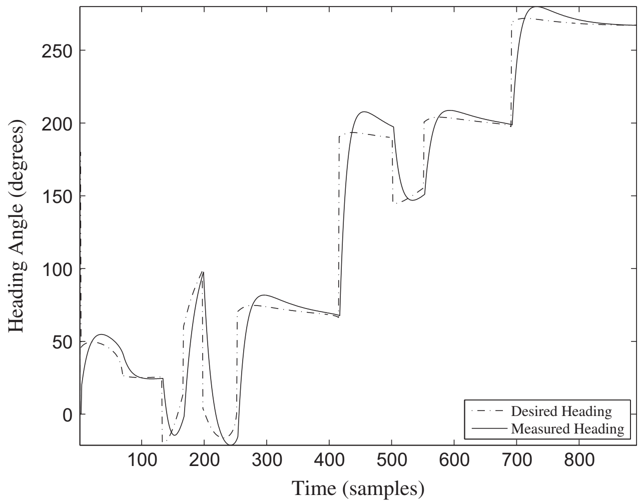

Fig. 14. Collision avoidance trajectory for a dynamic obstacle using the manual biasing scheme.

get ship 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 dock, it repeatedly breaches the COR causing the path planner to generate COLREGs compliant manoeuvres.

Finally, a single mobile obstacle, comprising a ship initially considered to be moving in the South-Westerly direction[3] at a fixed speed of 1 m/s was examined. Again, a COR of radius 50 m was assumed around the obstacle. The same mission coordinates provided in Table 7 were selected apart from the first which is assumed to be the launching point and destination.

In order to create an interesting scenario, the direction of the target ship was altered towards the North-East after the USV evaded its first encounter. This provided a practical situation or could also be regarded as two dynamic obstacles encountered during a mission. The complete USV route depicted in Fig. 13 shows two evasive actions from waypoint 1 to 2 and from waypoint 4 to 5. In both cases, the USV passed on from the right-hand side of the moving ship and avoided the collision. The remaining trajectory consisted of approximately straight line or LOS paths. The relative speed limitation of the USV with the obstacle is a potential problem with this simulation as it may require a large COR so that appropriate action can be taken well in advance.

The desired and actual heading angles of the craft are also shown in Fig. 14. Here two evasive actions are evident at 150 and 500 sample times. All other step changes in heading are, in fact, LOS angles measured between the USV current position and the next waypoint.

6. Concluding remarks

This paper has presented preliminary simulation results on the development of an obstacle avoidance strategy for uninhabited marine craft. A simple manual biasing scheme was implemented together with the waypoint by LOS guidance technique. The highlight here is the integration of standardised IMO regulations or COLREGS in the path planning. The dynamics of an actual USV were also incorporated, providing realistic trajectories which are closely followed by the autopilot. An offline grid-based path planning scheme was also modified to produce COLREGs-compliant paths and both results are shown to be comparable. In the proposed reactive strategy, the USV must enter within the COR before the heading bias is introduced which diverts its heading towards the starboard side. It was assumed that the position of the obstacles was unknown and were detected on-the-fly by an onboard vision-based system. It should be noted that manned vessels could also benefit from autonomous path planning, thus helping to eliminate the subjective nature of human decision making and safeguarding the onboard personnel. The IMO, which has defined the COLREGs, may also want to necessitate the use of automatic ODA systems as standard on all marine craft. Note that an automatic collision avoidance system or ACAS is now installed as an integral part on all commercial aircraft and therefore similar legislation is required for maritime vessels as well.

More advanced motion planning strategies are currently being investigated for COLREGs-compliance using evolutionary algorithms such as genetic algorithms and particle swarm optimisation. This is being carried out under an Engineering and Physical Sciences Research Council, UK, grant [21]. Furthermore, automation of additional IMO rules will be carried out and the performance analysed in the presence of sea disturbances.

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