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An automatic COLREGs-compliant obstacle avoidance system for an unmanned surface vehicle

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Abstract

Unmanned surface vehicles are becoming increasingly vital tools in a variety of maritime applications. Unfortunately, their usability is severely constrained by the lack of a reliable obstacle detection and avoidance system. In this article, one such experimental platform is proposed, which performs obstacle detection, risk assessment and path planning (avoidance) tasks autonomously in an integrated manner. The detection system is based on a vision-LIDAR (light detection and ranging) system, whereas a heuristic path planner is utilised. A unique property of the path planner is its compliance with the marine collision regulations. It is demonstrated through hardware-in-the-loop simulations that the proposed system can be useful for both uninhabited and manned vessels.

Keywords

Unmanned surface vehicle, obstacle detection, path planning, heuristics, COLREGs

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Introduction

Recently, there has been considerable interest in the development of unmanned surface vehicles (USVs) due to their increasing demand in a number of maritime applications. One of the main challenges for unmanned (and indeed manned) vessels is the simultaneous detection and avoidance of (static and dynamic) obstacles, which may appear *en route*. USVs are routinely being deployed in applications such as remote sensing, surveillance, coastal patrolling and the provision of navigation and communication support to unmanned underwater vehicles (UUVs). In many instances, they are remotely operated to perform a specific mission in open or confined waters. Fundamentally, the intelligence of these vehicles is determined by the navigation, guidance and control (NGC) system design. The vehicle should ideally operate without any human intervention. This means that the vessel's on-board control system must be self-reliant and able to maintain and supervise each on-board component. Nevertheless, even the most advanced NGC design is not sufficient for a craft to exhibit full autonomy without the presence of an obstacle detection and avoidance (ODA) system.[1] Studies have shown that in manned vessels, more than 60% of casualties at sea are caused by collisions.[2] In addition, it has been surmised that human error is a major contributing factor to those incidents. Suggested causes include reduction of manpower in order to economise and adding more responsibilities per crew member. A number of worldwide maritime incidents have occurred in the past year, including the grounding of the *Costa Concordia* and the collision between a cargo vessel and a passenger ferry in Belfast Lough.[3] Moreover, in October 2012, 38 people were killed in a collision between a ferry and another passenger vessel off Yung Shue Wan, Lamma Island, Hong Kong.[4] It appears from initial investigations that most, if not all, of these incidents occurred as a result of human error, such as failure to yield, and were therefore preventable. This provides a sound motivation for developing automatic collision detection and avoidance systems for both manned and unmanned vehicles. For uninhabited craft in particular, this cannot be

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overlooked as a collision with another manned ship could endanger human lives. Thus, a human operator would always be required to maintain a constant look-out for any potential obstacles, incurring added cost.

As UUVs operate underwater, they seldom pose a direct threat to ambient surface traffic. Despite this, there is a great deal of research in sonar-based ODA strategies being developed for UUVs in contrast to USVs (which are lesser investigated), primarily due to recent surge in underwater exploration.[1] As aforementioned, the autonomy of an unmanned vehicle depends on the design of a reliable NGC system. Of these, the navigation system acquires and processes data so that the guidance system can generate appropriate trajectories or waypoints to be followed by the vehicle. A well-designed control system or autopilot tracks the reference commands as closely as possible. The most common form of guidance law used in unmanned vehicles (marine or airborne) is line-of-sight (LOS) guidance.[5] In this method, the vessel's heading is equal to the LOS angle between the vehicle's current position and the target location. Several other guidance laws are also based on extensions of this methodology. In the absence of a collision detection 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 on-board components and, in the worst case, cause sinking. The presence of an on-board ODA system is therefore extremely important for the vehicle to become self-sufficient.

Unfortunately, the marine research community has predominantly focussed on advanced navigation and control system design and little attention has been paid to the area of collision avoidance. The usual strategy adopted to address this problem is simply by human intervention[1] via a radio control channel or a wireless link, adding to the operating cost in the form of a manned support boat. As a consequence, the usability and extent of the vessel is severely constrained. In Caccia,[6] it is argued that although USVs provide an excellent platform for fast experimentation and development of guidance and control algorithms, their use is limited due to the lack of a reliable ODA system.

The International Maritime Organisation (IMO) established the International Regulations for Preventing Collisions at Sea 1972 (COLREGs)[7] as a universal and definitive guide for executing standard avoidance manoeuvres. It is understood that all navigators shall comply with these guidelines. However, as highlighted in a recent survey,[8] the vast majority of research that has been conducted in the area of obstacle avoidance has failed to integrate these rules. In generic robotic obstacle avoidance, architectures typically adopt a deliberative approach (a global, offline approach, which finds an optimal path in a known environment) or a reactive approach (adapting online to avoid obstacles in a dynamic and unpredictable environment). Layered, hybrid approaches have also been proposed.[9] Path planning techniques that have been examined to date to execute COLREGs include Artificial Potential Fields,[10] Velocity Obstacles,[11] Fuzzy Logic,[12,13] and a heuristic A* method.[14] One significant study that employed Interval Programming to perform COLREGs avoidance with sea trials for verification[15] relied on a wireless link between encountering vessels. Heuristic methods are increasingly adapted to specific robotic path planning tasks for improved efficiency and flexibility. A description of some of the most common and successful algorithms developed, such as D*, D* Lite and ARA*, can be found in a survey by Ferguson et al.[16] However, as with all existing path planning techniques, further modifications are required to incorporate navigation regulations based on situational awareness. This proposed method aims to address some of the deficiencies with existing methods, that is, extending the application to multiple approaching vessels, minimum or no dependency on communication between vessels or automatic identification system (AIS) data, no complex layered reactive and deliberative architecture, effective handling of complex scenarios and real-time execution.

Motivated by the need of designing a reliable ODA system for USVs, this article describes such an experimental platform that can improve the USV's efficiency and safety, incorporating COLREGs into obstacle avoidance routines. The effect of reducing the incidence of human navigational error by automatically identifying threats and generating suitable avoidance action will serve to create a safer maritime environment. For the detection part of the proposed ODA system, a high-definition (HD) video camera and a laser sensor mounted on a pan and tilt platform were employed to provide the NGC system of the USV with a visual reference of the surrounding area. For a general class of marine vessels, it is common to use marine radar together with automatic radar plotting aid (ARPA) for detection and tracking. While this system is proven and provides an excellent range and other benefits, there are certain problems associated with it. A radar system may fail to detect those objects with a small signature above the water. For surveillance-type missions, for instance, this is an issue since a low-signature boat may not be tracked by the patrolling vessel. Also, for pop-up obstacles at a close range, the radar may not detect the obstacle at all. Moreover, the ARPA system only tracks moving objects, which limits the capability of the unmanned craft.

Other researchers have also successfully employed vision-based detection systems in their craft vehicles. For instance, Space and Naval Warfare Systems Center (SSC) San Diego has investigated the use of monocular vision for obstacle detection and range finding. The algorithm uses Earth's radius and the height of the camera above the water to measure the distance to the object. The same team of researchers have also adopted a stereo vision technique in their USV that was originally employed in NASA's Mars Rovers and some other unmanned ground vehicles.[17] In Gomes et al.,[18] a

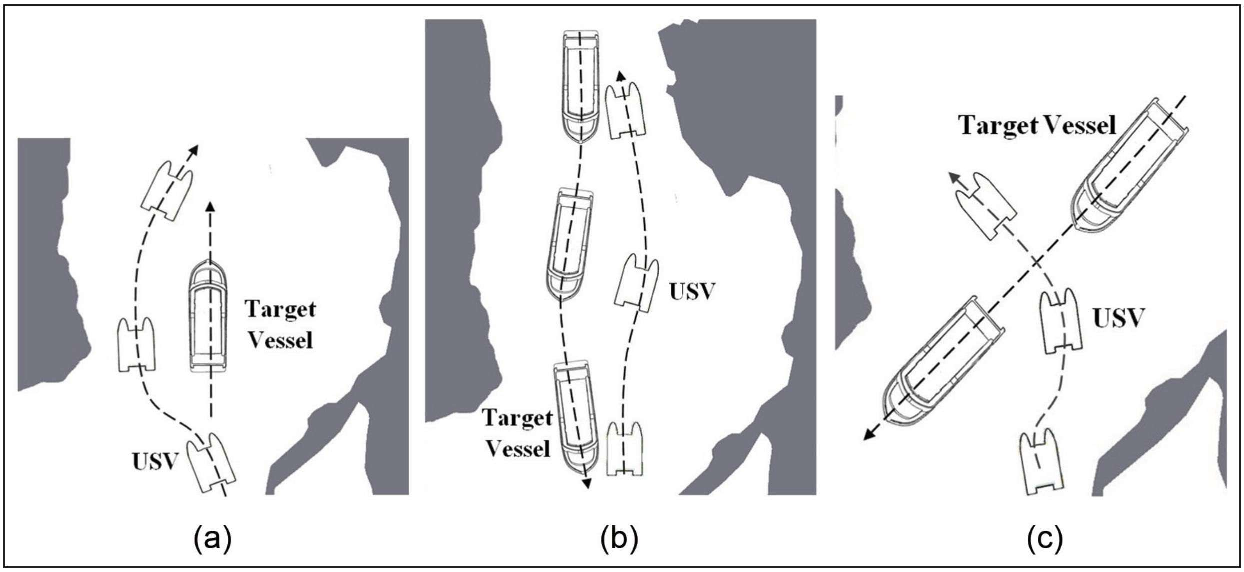

Figure 1. Primary COLREGs avoidance rules: (a) Rule 13: Overtaking, (b) Rule 14: Head-on and (c) Rule 15: Crossing.
USV: unmanned surface vehicle.

coastline following controller has been devised and implemented in the DELFIMx vehicle developed by the Instituto Superior Técnico, Lisbon, Portugal. The algorithm detects and tracks the coastline using an on-board laser range finder.

The novelty of the proposed framework lies in the integration of the detection unit with a COLREGs-compliant avoidance module. An introduction to the fundamentals of the COLREGs rules appears in section 'COLREGs', along with illustrations of the applicable avoidance guidelines. The ODA system is integrated with a risk assessment module, which identifies any potential threats and generates suitable actions in order to alleviate it. The detection system (described in detail in section 'The proposed ODA strategy') is paired with an online path planning algorithm (the Rule-based Repairing A* (R-RA*) described in section 'R-RA* Algorithm'),[19] which yields fast COLREGs-compliant paths for safe navigation in open seas. Simulations of the integrated system are presented in section 'Results', highlighting its effectiveness and the benefits of adopting this approach.

COLREGs

COLREGs consists of three parts, of which 'Part B: Steering and Sailing Rules' pertain to navigational practice. 'Part A: General' describes the applicability and responsibilities of the regulations, whereas 'Part C: Lights and Shapes' addresses the topics of various signals and use of lighting. The rules were issued by the IMO in 1972 but are still just as applicable today. They are paired with the Inland Navigation Rules, which exhibit similar protocols, with only marginal differences applying only to inland waters and lakes. Due to recent important advances in unmanned technology, the Navigation Safety Advisory Council (NAVSAC) has put forward a proposal for amending COLREGs to accommodate UUV and USV operations. Addressing the current deficiencies in automatic obstacle avoidance serves to support these additional amendments.

The three primary rules that must be incorporated in an effective ODA system are as follows: *Rule 13: Overtaking, Rule 14: Head-on* and *Rule 15: Crossing*. The rules are illustrated for clarity in Figure 1.[19] All avoidance actions must be obvious and taken well in advance. The overtaking rule (Figure 1(a)) stipulates that a vessel may pass on either the port (left) or starboard (right) side but must issue the appropriate signal. In a Head-on encounter (Figure 1(b)), when powered vessels approach each other, they must pass port to port by making respective starboard manoeuvres. When two vessels are crossing (Figure 1(c)), the powered vessel that has the other on its starboard side must give way by waiting until it has passed or by crossing abaft of (behind) the stand-on vessel.

It is no surprise that there is some sense of reluctance to hand over navigational duties solely to an autonomous system in favour of a skilled mariner. This is largely due to the fact that navigating requires intuition, common sense, experience and knowledge of when rules do not apply. An effective ODA system should not blindly implement COLREGs rules where exceptions occur. The rules state that collisions must be avoided at all cost and it is often necessary to breach the rules, for instance, it is mandatory to give way to a sailing vessel or a less manoeuvrable vessel at all times. This intelligent decision-making process should be incorporated into the automatic system, which should ensure that collisions can never occur, even when it is necessary to breach the rules.

The proposed ODA strategy

As previously stated, a reliable ODA system is a vital element for a fully autonomous craft. For manned

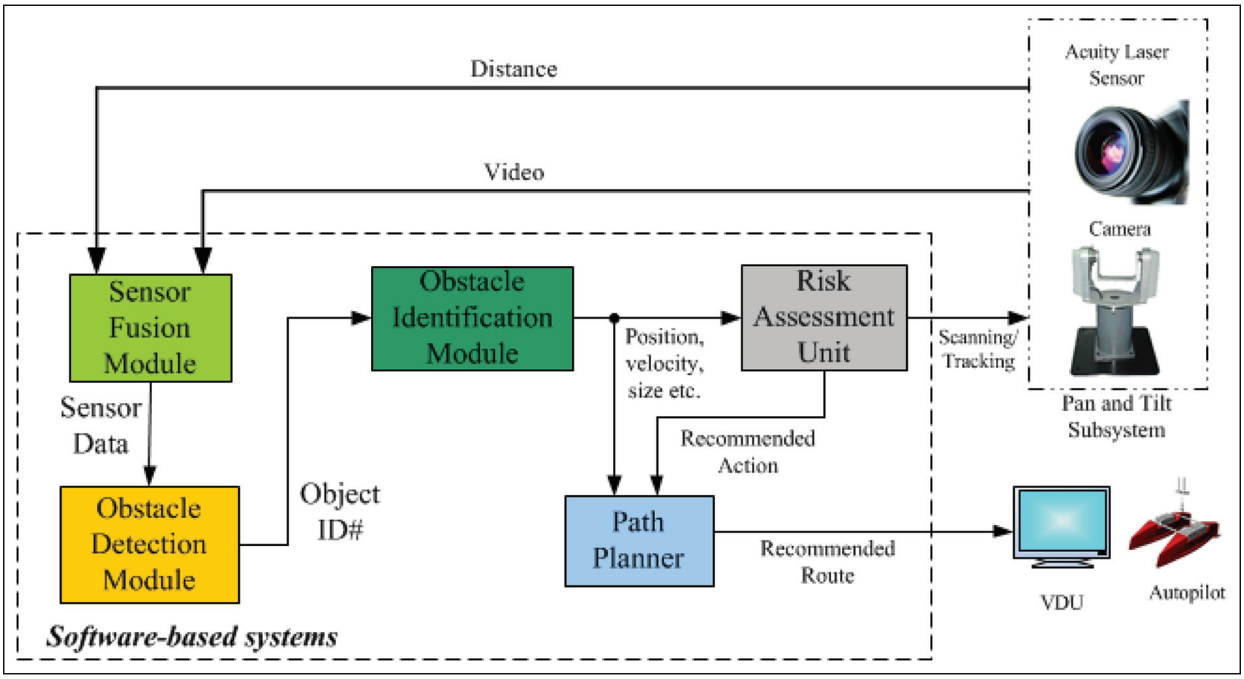

Figure 2. Individual elements of the proposed ODA system.
VDU: visual display unit.

vehicles, obstacle detection is generally accomplished by trained crew members with the aid of marine radar together with an ARPA as well as a manual lookout. For most USVs in existence, a trained operator remotely monitors the state of the vehicle with the help of an on-board camera and safely navigates around obstacles. The proposed system automates this procedure by generating safe routes for the autopilot with minimal or no supervision from a human operator. Figure 2 depicts the individual elements of the proposed ODA system, which are mostly software based except the pan and tilt subsystem. These are described in the following subsections.

The proposed system has been implemented using a *Googoltech* pan and tilt platform,[20] a Microsoft HD video camera for object detection and identification and an *Acuity* laser sensor[21] for accurate range measurements. Associated with these hardware devices, a wide range of software libraries have been used to control and analyse the acquired data. The *Googoltech C\C ++* library has been utilised to control the pan and tilt. Additionally, the *AForge.NET* computer vision library has been used to implement the obstacle detection/identification subsystem as depicted in Figure 3.

For testing purposes, a number of maritime scenarios have been created using the commercially available Virtual Sailor Simulator.[22] Indoor experiments have been carried out in a visualisation room at *Queen's University Belfast* equipped with multiple projectors and screens to emulate a panoramic view of the maritime environment. This set-up has two major disadvantages. The first issue is the lack of depth information, whereas the other is that the platform remains static, which is not practical. In practice, a laser range sensor is employed to obtain accurate depth information. In order to display the obstacles' information to the USV operator or the captain of the manned ship, a virtual map is developed using the .Net environment as shown in Figure 4. Here, the depth information is obtained from a data file for laboratory-based experiments (in simulation), while provision is made for a laser range sensor for outdoor trials (in practice).

The following hardware-in-the-loop simulation experiments aim to investigate the performance of the proposed ODA system in terms of detecting and identifying objects, assisting the risk assessment and recommending actions according to COLREGs rules. The results illustrate a scenario of two dynamic ships with paths, which are perpendicular to own ship's heading. Both the vessels are travelling in opposite directions at differing ranges from the own ship. Hence, the own ship becomes a give-way vessel to the ship on its starboard side, whereas it will act as the stand-on vehicle to the ship on its port side. The risk assessment unit will determine this appropriately.

Multiple dynamic obstacles detection scenario

The pan and tilt platform is adopted to periodically scan in the vicinity of the USV. Furthermore, the system is able to detect close-range obstacles, which may pose direct threat to own ship for which reactive path planning may become necessary. Figure 4(a) depicts the result of automatic visual tracking of two vehicles in the virtual environment, which is demonstrated in the form of bounding boxes around the craft. The proposed

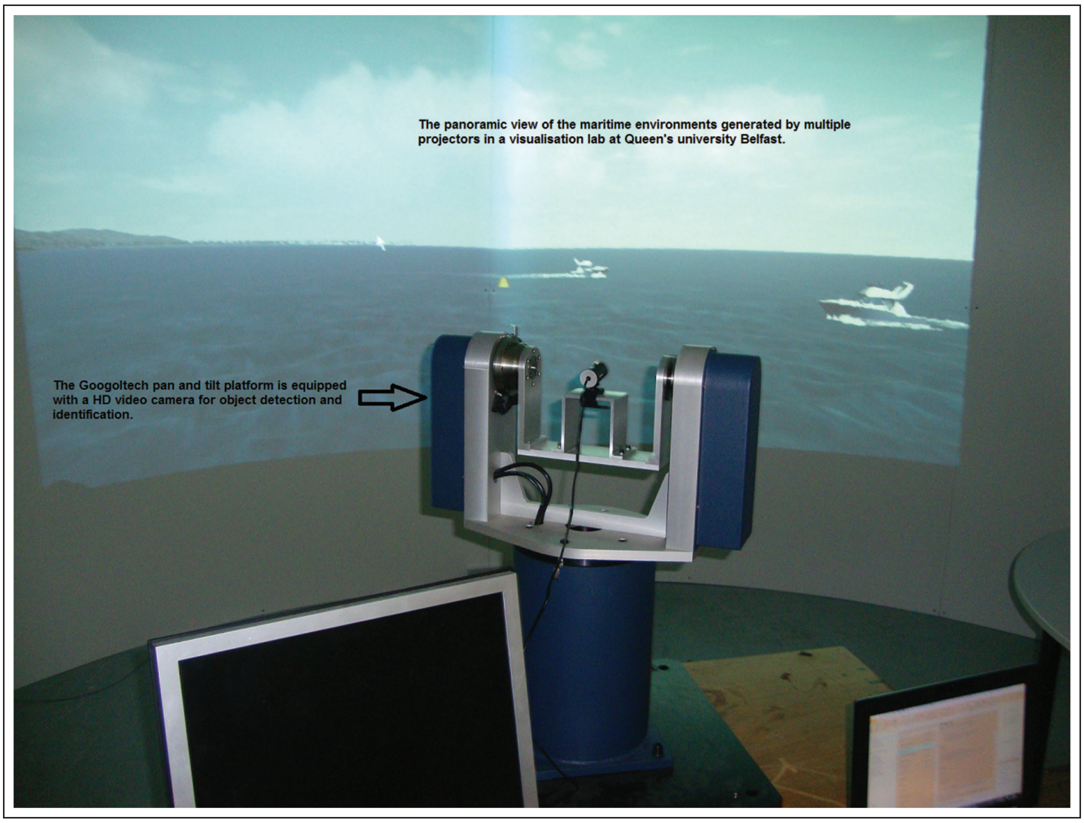

Figure 3. Pan and tilt platform and the virtual environment in the visualisation room.
HD: high definition.

system successfully ignored the waves and did not identify them as obstacles, by considering the height of the bounded box surrounding the waves and the dynamic nature of the waves, which subsides after a short time. Once an obstacle is detected and its state estimated, the information is displayed on a virtual map to assist the remote human operator or captain of a manned ship.

Figure 4(b) depicts a snapshot of the virtual map of the environment developed as part of the proposed system. This is analogous to a radar screen where information regarding any objects in the vicinity is continually updated and displayed. In Figure 4(b), there are three icons showing position of own ship and relative positions of two target ships. It is clear that the target ships are detected in sectors 1 and 3; however, since there is only one active area at a time, the other obstacle's position is being estimated by the prediction module. This means that the proposed system always keeps track of any previously detected obstacles and predicted their positions even if they are not visible directly by the camera. This means that the proposed system always keeps track of any previously detected obstacles and predicts their positions even if they are not directly visible by the camera.

In addition to scanning, the proposed system has the ability to further investigate a specific region to assist in determining potential collision threats. Figure 4(c) illustrates this scenario in which the detection unit requests the pan and tilt device to re-scan sector 2. The request can be seen at the top of the virtual map and will be highlighted for the operator.

Once the obstacle is identified as causing a potential risk of collision, the proposed system recommends suitable action to avoid it. Figure 4(d) displays system handling in one such situation. As shown, the proposed system recommends a port-side manoeuvre in addition to a reduction in speed in order to avoid collision with the nearby ship. Finally, Figures 5 and 6 provide a comparison between the actual and the estimated relative positions of the ships involved in the experiments using the prediction system. It is clear that the ODA system provides the path planner with the required information for all the obstacles in the vicinity, even if there is no direct LOS with the obstacle. However, some error accumulated by the estimation can be observed, which is corrected when the obstacle is directly seen once again by the vision system.

Pan and tilt mechanism

The first stage of any ODA system is to detect the presence of an object. Here, this is carried out using a HD camera along with a laser range finder mounted on a pan and tilt unit. Employing the video camera and the laser sensor will provide redundancy in the system and therefore fault tolerant capability. Additionally, the laser sensor will increase the obstacle detection range to 3000 m when reflective target boards are used on the target vessel. The pan and tilt mechanism increases the scanning range of the system while acting as a stabiliser for the vision sensor against sea waves. A scanning

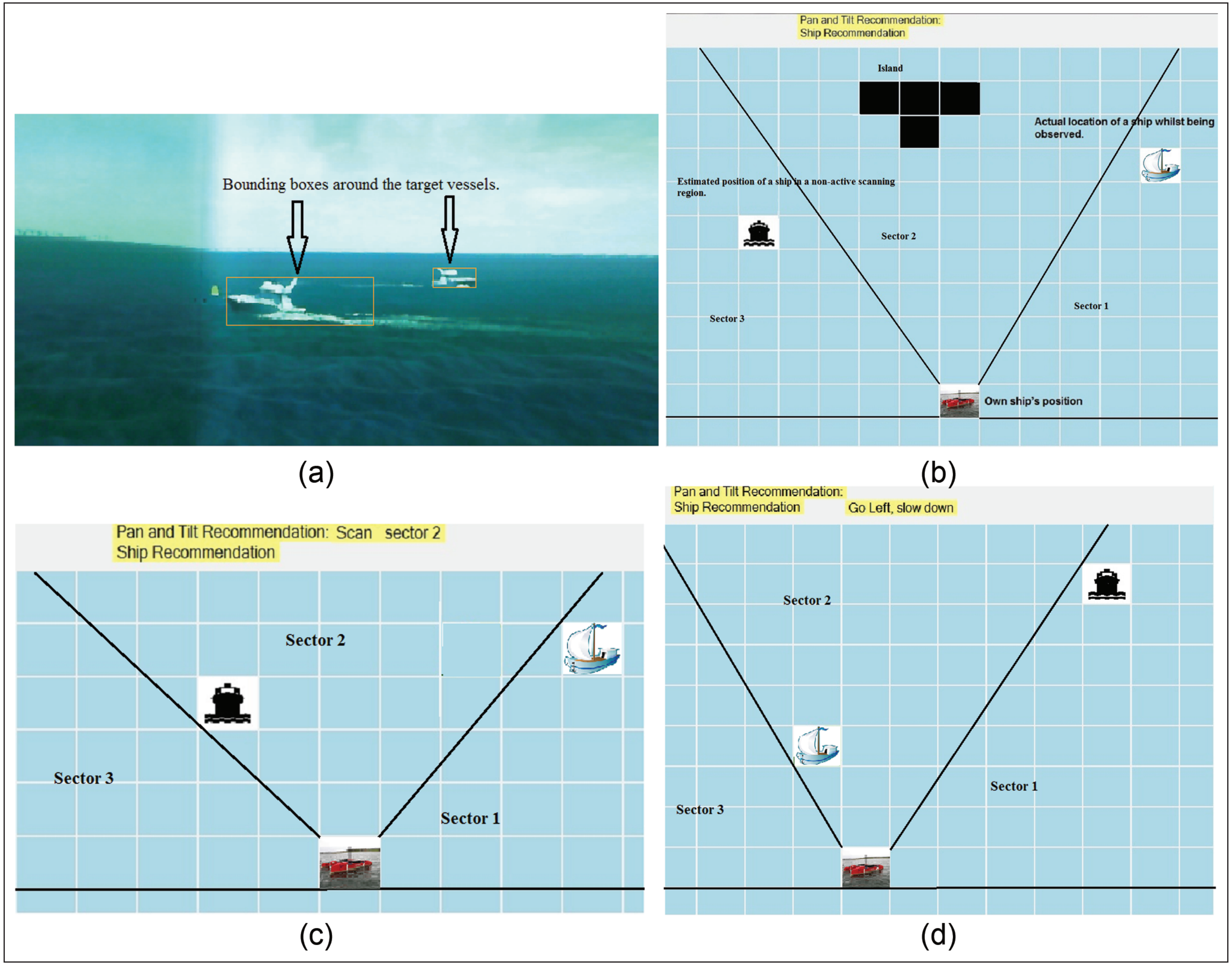

Figure 4. Multiple-obstacle encounter with COLREGs: (a) object detection, (b) real and estimated obstacle positions, (c) a snapshot of the maritime simulator showing the recommended action for the pan and tilt subsystem and (d) a snapshot of the maritime simulator showing the recommended action for the ship control subsystem.

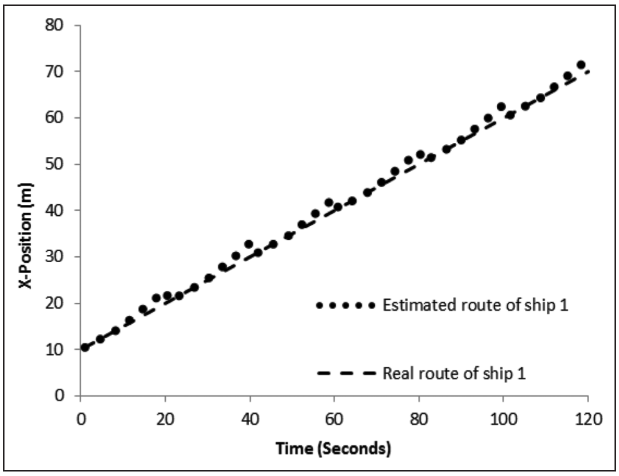

Figure 5. The real and estimated route of target ship 1.

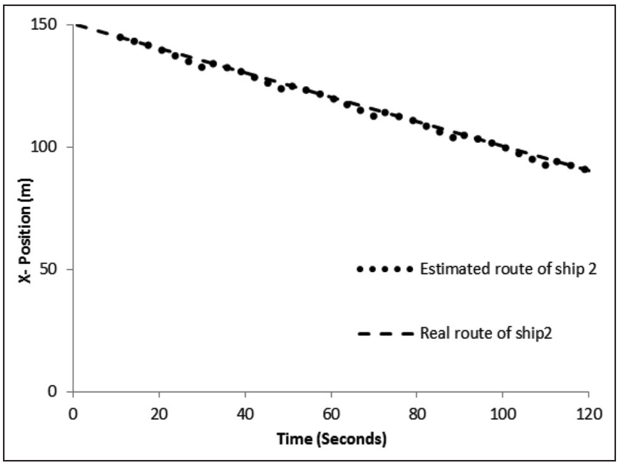

Figure 6. The real and estimated route of target ship 2.

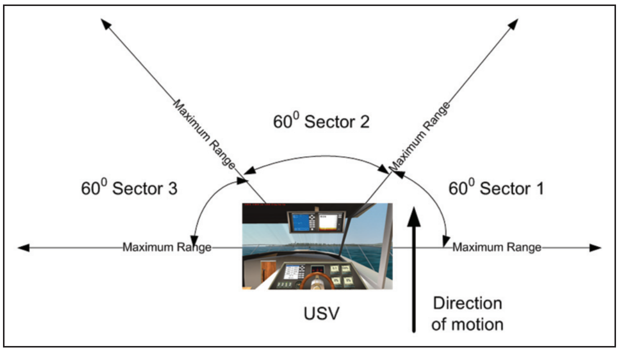

Figure 7. Vision system coverage.
USV: unmanned surface vehicle.

range of 180° is employed, which spans the area directly in front of the vehicle as well as both starboard- and port-side regions as shown in Figure 7. This was deemed sufficient as the path planner operates online and therefore only close-range or pop-up obstacles are dealt with in a reactive manner. Although vision systems are common in such detection systems, their use here with an automated panning and laser range finder is unique to a maritime environment.

Observations are made, stored and analysed for a period of time in each sector periodically according to predefined parameters or taking into account the velocity of the USV. However, if a threat has been identified in one of the sectors, the system is able to rescan/focus on that particular region until the threat is cleared and the situation is resolved. In the instance of having more than one threat in different sectors, the system will keep switching between the regions (while predicting the positions of the obstacles) until the situation is resolved. Additionally, the tilt part of the device works as a stabiliser for the system in the presence of wave disturbances. Tilt control is carried out by using feedback from a wave detection system comprising a compass, which will minimise the effect of wave movements on the platform and hence keep the camera and laser sensor in a lateral plane at all times.

Obstacle detection and identification subsystems

The camera and the laser sensor provide the obstacle detection subsystem with a visual reference of the surrounding area. The video feedback is analysed and processed using the widely used background subtraction technique to extract the information about any obstacles in the vicinity of the USV. It was found that the standard background subtraction algorithm was incorrectly tracking the sea waves, which are also dynamic in nature, as the algorithm detects any changes between the foreground and background images and thus tracks all moving objects including any ships in the vicinity as well as waves. This was resolved by modifying the algorithm by considering the two following characteristics: (a) the height of the bounded box of the waves and (b) the dynamic nature of the waves that will vanish after a small time. In addition to the camera system that is used to detect the presence of an obstacle, the laser sensor can provide accurate range measurements. The detection range of the laser sensor employed in this study is 300 m; however, this range increases to 3000 m with the use of reflective target boards.[21] Additionally, the laser sensor has an internal heating element to prevent any condensation on the lens. It may be possible that the sensor may incorrectly detect a large wave as an obstacle; however, this false alarm situation should be eliminated by periodically scanning the region and updating the map. Data from the camera along with the laser sensor are then used to extract the location, heading angle (if moving) and size of the obstacle, which are then transmitted to the motion planner.

Prediction module

Another vital element of the proposed ODA system is the prediction module, which forms part of the obstacle detection and identification subsystem. During the periodic scanning, since there is only one active region at a

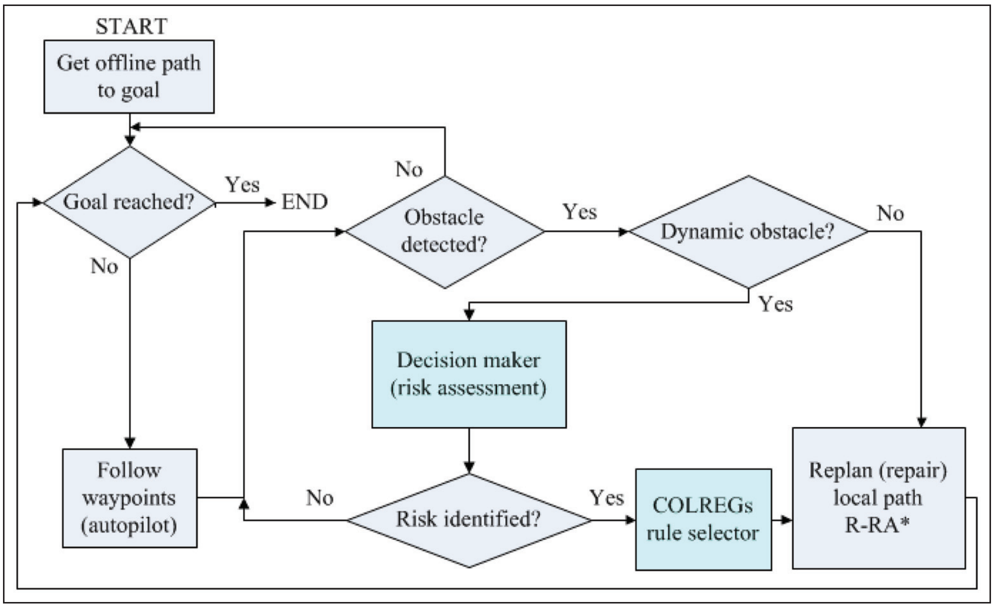

Figure 8. Path planning flowchart.
R-RA*: Rule-based Repairing A*.

time, the non-active sectors are dealt with using a prediction module to estimate the position of the obstacles (particularly the dynamic ones). The prediction module employs a linear forecasting technique to estimate the positions of the obstacles, which are not currently being observed by the vision sensor. This is to ensure that none of the obstacles within the current range are lost. The prediction unit will continue to provide the estimated position of known obstacles using equations (1) and (2) until it receives their actual updated positions when the system re-scans the corresponding region

$$X = X_p + \int V \cos(\psi) dt \tag{1}$$

$$Y = Y_p + \int V \sin(\psi) dt \tag{2}$$

where X and Y are the predicted coordinates of the target ship, X_p and Y_p are the last known coordinates, V is the velocity and ψ is the heading angle.

COLREGs-compliant path planning

It can be argued that COLREGs are easy to follow for a human navigator. However, there may be instances when confronted with multiple approaching vessels, where many simultaneous or conflicting COLREGs rules apply. In this case, a human navigator can find navigation very difficult, and captains of the respective ships often rely on radio communication to convey intentions and negotiate avoidance manoeuvres. Conversely, an automated navigational system can easily calculate the required manoeuvres, taking into account the real-time speed and heading information from each target. In order to achieve this, a R-RA* algorithm was developed for fast, iterative path planning online. The COLREGs rules are stored within the path planner and will be automatically selected where applicable upon the assessment of the encounter state.

The path planning process is illustrated by the flowchart in Figure 8, terminating when the final destination coordinates have been reached. An initial route is planned offline, using only a priori known map information. Then, the route is iteratively updated en route in real time when encounter scenarios occur. A key feature of the system design is a decision-making subroutine, which uses current information from the vision system (i.e. obstacle speed, heading and position) to carry out a risk assessment. This is to preserve the original route where it is safe to do so and not to expend computation when it is not mandatory. At all times, the system maintains situational awareness, receiving feedback from the Global Positioning System (GPS), gyrocompass and so on along with data at sampled intervals from the camera and laser range sensor.

Risk assessment

Risk assessment unit

The risk assessment unit is a discrete module, which works in conjunction with the path planner and is responsible for performing continuous collision risk assessment. Due to the fact that the detected obstacles may be dynamic in nature, the ODA system must assess the threat of these obstacles in a periodic manner. The closest point of approach (CPA) method[23] is adopted to find the closest distance between encountering vessels at any time in the future, assuming that they proceed at their current respective velocities (which are updated at each sampling interval). This is a feasible assumption, as the majority of surface vessels are neither highly manoeuvrable nor alter their speed rapidly within typical sampling times (a 10-s simulation time is selected,

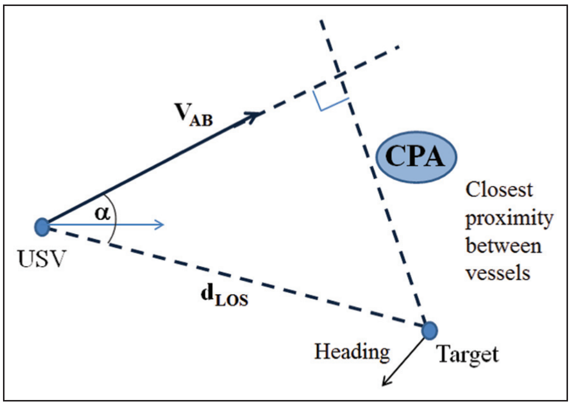

Figure 9. Closest point of approach for risk assessment.
USV: unmanned surface vehicle; CPA: closest point of approach.

which is the time taken to scan through the 180° range). If the closest predicted distance is less than the acceptable range, the module advises a change in direction as an approaching threat is confirmed. It is also linked to the pan and tilt subsystem in order to request further scanning of a specific region from where a threat is considered to be originating. Figure 9 illustrates how the CPA distance is calculated for two converging targets using the geometry of the projected relative velocity vector, V_{AB}, and the current distance between the USV and target, d_{LOS}. The shortest distance is found by equation (3), using Pythagorean theorem with the closed vector diagram, forming a right-angled triangle, where α is the angle indicated in Figure 9. Where vessels are currently diverging from their respective locations, the CPA shall be set equal to the current LOS distance between them. In the case of multiple approaching vessels, each target is analysed separately and categorised as an individual risk

$$CPA = d_{LOS} \sin(\alpha) \tag{3}$$

R-RA* algorithm

The R-RA* algorithm is proposed as an online extension of the standard A* algorithm, which is widely used in robotic path planning applications for two-dimensional problems. Like the A* algorithm, it performs a best-first search of the most likely paths leading to the goal by means of a cost function, which takes into account the cost of the path already travelled to the current node, $g(n)$, and the estimated cost of the remaining path to the target node, $h(n)$. The A* path planning method is a simple and fast one, which is well suited to this real-time application, and it can easily be extended to avoid multiple vessels. However, the R-RA* algorithm differs to the A* in that it is online in nature, only repairing the local, proximal path each time, as opposed to replanning the global path from start to finish at each loop, thus saving computation time.

The algorithm operates in a grid-based C-space, with binary occupancy in each cell, that is, either occupied by a ship or obstacle or unoccupied. The selection of grid size is key to the computational efficiency of the algorithm; however, due to the scale of large open sea areas, topological features (such as coastal land or islands) are usually large compared to the vessel's size. Another strategy is to create a map hierarchy or adopt sub-maps for particularly large courses. In this algorithm, constant speed is assumed and is updated at every sampled interval. The adjustment of speed is possible when the system is integrated with a robust controller, and the detection system is capable of making suitable recommendations.

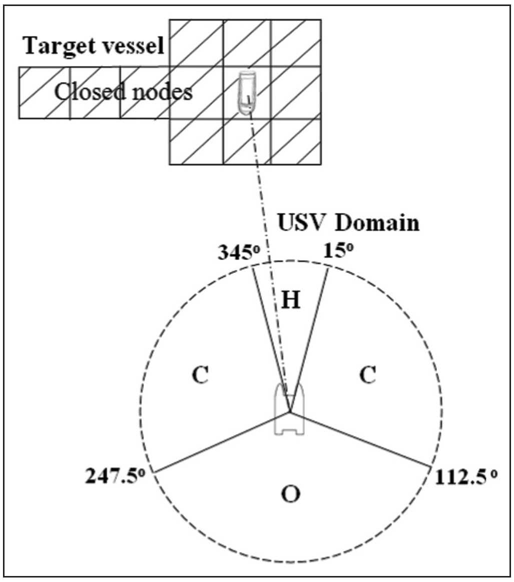

Figure 10. Head-on scenario adding forbidden nodes to closed list.
USV: unmanned surface vehicle.

After obtaining the offline, global path by using the standard A* algorithm, the R-RA* algorithm executes at each time interval in real time, responding to any changes along the current sub-path. If the static or dynamic obstacles pose a risk, the sub-path is recalculated, implementing any applicable COLREGs rule. This process is carried out iteratively, repairing the next segment of the route to prevent collisions by finding the least cost path, until the goal is reached.

One unique ability of this R-RA* method is the incorporation of the COLREGs rules by automatically identifying forbidden zones, which would breach COLREGs, and adding these regions to the closed list. Rule-based obstacle avoidance strategies are popular for grid-based path planning methods, for example, in the use of Bayesian occupancy[24] and collision cones,[25] and the placement of virtual obstacles.[14] This decision is based on the relative velocity of the approaching vessels, which in turn determines which encounter laws, if any, are applicable. For instance, in a Head-on scenario illustrated in Figure 10, both vessels are required to make starboard manoeuvres; hence, when another ship is heading directly towards the USV approximately parallel to the hull, the proximal nodes to the starboard side of the other ship are removed from the search nodes on the open list. This will prevent the USV from passing on the other vessel's proximal starboard, leaving sufficient clearance. This clearance represents a circular safety zone with a radius usually defined as 1.5–2 times the length of the USV. In this case, the safety zone has a radius 1.5 times the length of the smallest grid increment. In a non-standard scenario whereby the USV becomes the stand-on vessel, the path planner will simply implement standard avoidance procedures and always maintain this clearance. For safety reasons, the USV will never maintain its original course when the target vessel fails to give way as expected. This complies with COLREGs exceptions, which state that avoidance action should always be taken to avoid collisions, regardless of the standard manoeuvres in exceptional circumstances. Figure 10 shows a virtual safety zone in the form of a dashed circle around the USV. The sectors represent domains for Head-on (H), Crossing (C) and Overtaking (O) encounters. The international navigational rules deem overtaking to occur when another vessel is approaching from more than 22.5° of the ship's beam. There are currently no standards for defining Head-on or Crossing domains; however, both give-way situations require starboard manoeuvres regardless.

The main drawback with heuristic grid-based path planning methods is caused by the discretised nature of the C-space and that is the difficulty in incorporating vessel dynamics. A marine vessel is subjected to violent sea states with significant non-linear wind, wave and current disturbances. Even equipped with a robust speed and heading controller with state estimation, a USV cannot be treated like a holonomic robot. Its underactuation means it will experience drift (when stopping or turning) and roll and is also constrained by its inherent minimum turning radius. In order to address this, the waypoints are smoothed via a cubic hermite spline method, whereas Dubins[26] circles extend the path when a required turn has a radius smaller than the USV's capability. In addition, it is imperative to select an optimal side of occupancy grid squares to ensure safety within a safety margin, to allow for these inherent dynamic phenomena.

Results

The simulations which follow are designed to utilise information about the target, which is provided in real time by the detection system. These simulations use real discretised nautical map data based on a coastal area of Portugal (Sagres). The grid size is set to approximately 1:10 m, as 10 m is deemed sufficient clearance without sacrificing excessive optimality in terms of finding the shortest path to goal. A range of realistic COLREGs encounter scenarios are presented for single and multiple vessels, whose respective speeds are set arbitrarily, while the USV is assumed to be fixed at 2 m/s.

COLREGs-compliant route planning

In order to demonstrate the route planning algorithm, an Overtaking scenario is demonstrated first, as the USV receives position, speed and heading data from the vision system in real time. COLREGs states that a vessel may pass another either on the port or starboard side but must issue the corresponding signal to state its intention. In the following simulations, a target vessel's position with respect to time is indicated by a dot with a directional arrow. Figure 11(a)–(d) shows the original offline path and the updated paths as it receives new information about the target vessel and determines a risk. The R-RA* algorithm automatically plots a path to avoid the vessel, which is then smoothed to provide suitable waypoints for the autopilot. The local path is constantly updated until the threat of collision has passed, and the USV then resumes the original course. In this case, while overtaking on the port side would provide the most optimum route, a starboard overtake is desired so as not to pass too closely to the coast and risk grounding. Thus, the overtaking COLREGs rule is automatically selected, adding port nodes to the closed list. The final path shows the entire route taken by both vessels at the target destination. Figure 12(a) shows the CPA angle, which is calculated at each sample time throughout the simulation. When the magnitude of the distance falls below the stated boundary (of 100 m proximity), a risk is verified. It is observed in Figure 12(b) that the actual distance between vessels never reaches zero or near-zero and is always in excess of 15 m (the chosen safety zone radius). It is worthy to note that although AIS data are not necessary, if provided, it could serve as a support system to verify the other vessels' positions. For illustration purposes in these simulations, the vessels' positions are assumed to be known at all times; however, the path planner does not take corrective action until a risk is detected.

Figure 13 illustrates a Head-on encounter. Again, when the system detects the oncoming vessel, a risk assessment is performed, and when the CPA is less than the acceptable range, the local path is replanned. The relative angle of approaching vessels falls within the Head-on domain for COLREGs encounters, and thus, all nodes on the proximal starboard side of the oncoming ship are forbidden and added to the closed list. This forces the USV to make a port-to-port manoeuvre in accordance with COLREGs in order to take the shortest path to goal. The final avoidance path is shown to avoid the vessel, which also adopts port-to-port avoidance. The purpose of this simulation is to convey that the R-RA* algorithm offers more flexibility in choice of path. For instance, it may be preferable not to overtake vessels on the side of the most optimal path, perhaps due to undetected fishing nets or strong winds, which could increase the risk of grounding. The positions of the vessels are shown in Figure 13 at four different points in time, indicated by the numbers 1–4, respectively. Figure 14(a) shows that the target is

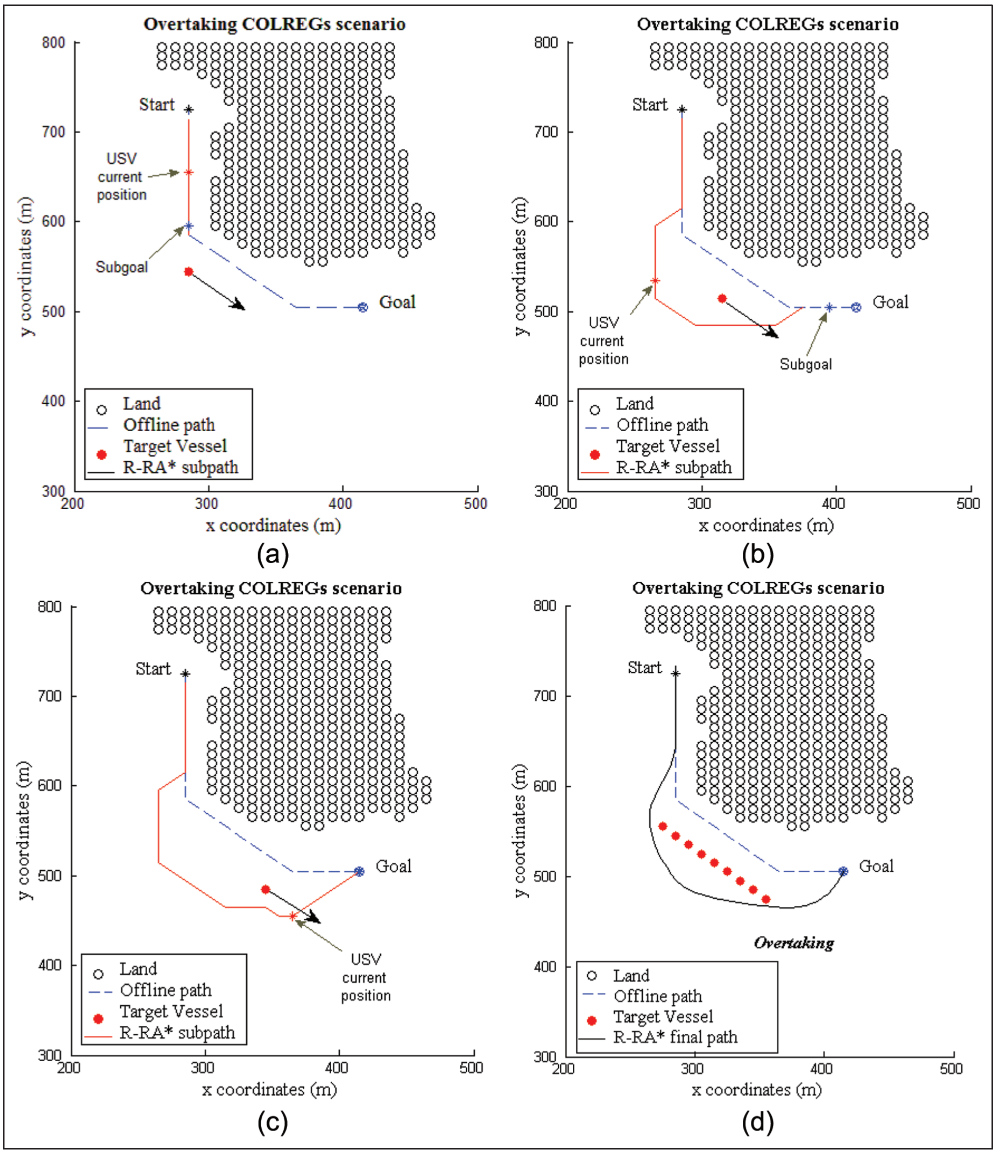

Figure 11. Overtaking encounter with COLREGs: (a) no risk of collision, (b) local path alteration for a starboard overtake, (c) starboard overtaking scenario and (d) final paths of encountering vessels.
USV: unmanned surface vehicle; R-RA*: Rule-based Repairing A*.

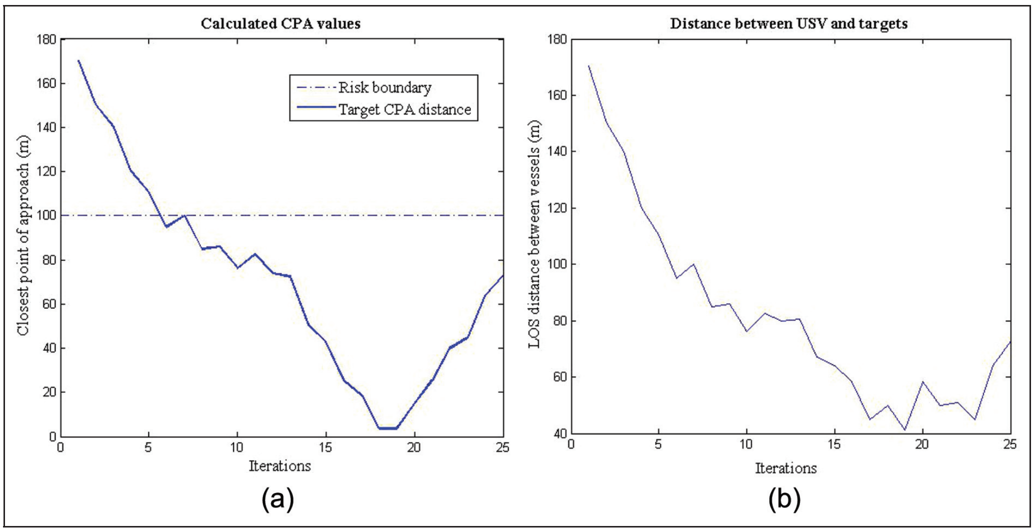

Figure 12. Overtaking encounter with COLREGs: (a) CPA angle as calculated; (b) Proximity between encountering vessels.
USV: unmanned surface vehicle; CPA: closest point of approach; LOS: line of sight.

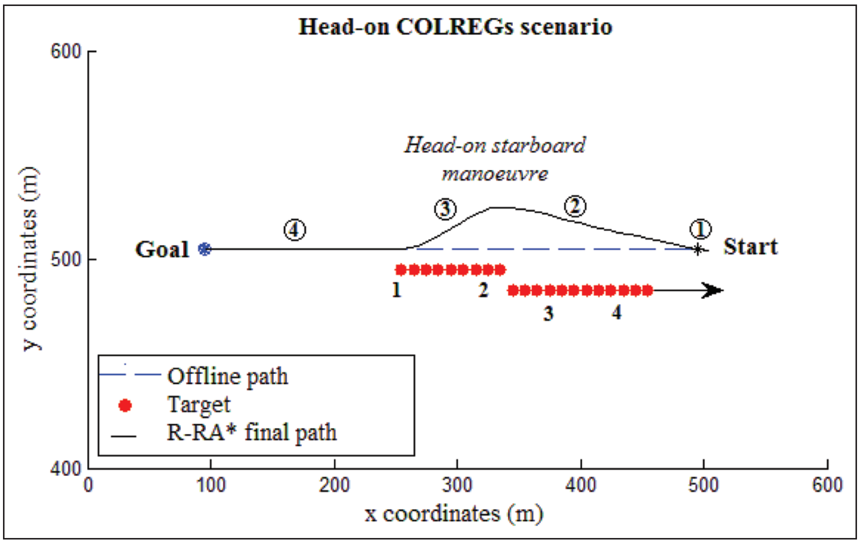

Figure 13. Head-on encounter with COLREGs.
R-RA*: Rule-based Repairing A*.

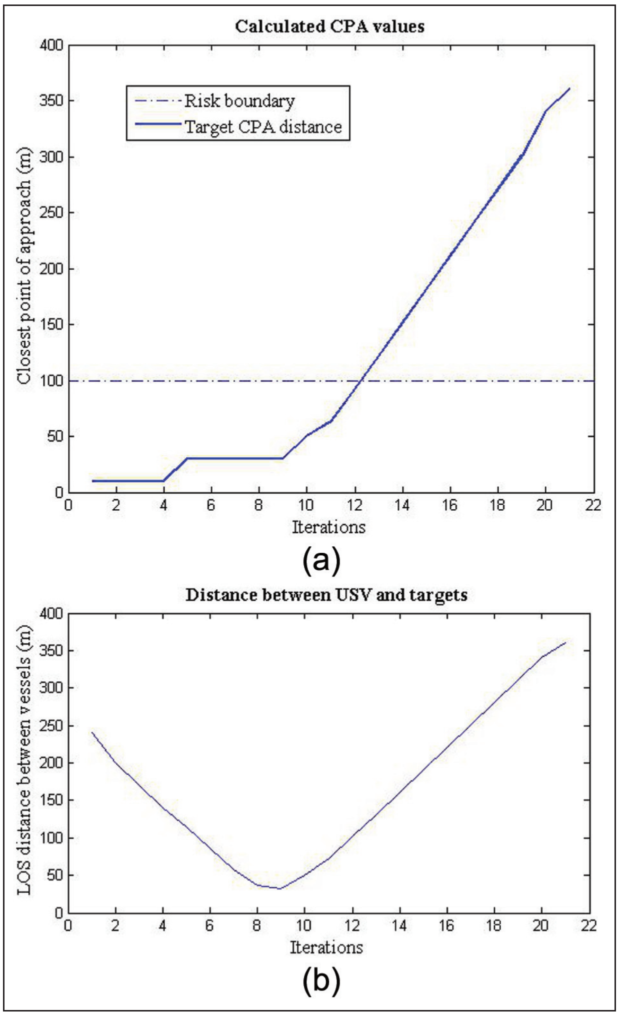

Figure 14. Head-on encounter with COLREGs: (a) CPA angle as calculated and (b) proximity between encountering vessels.
USV: unmanned surface vehicle; CPA: closest point of approach; LOS: line of sight.

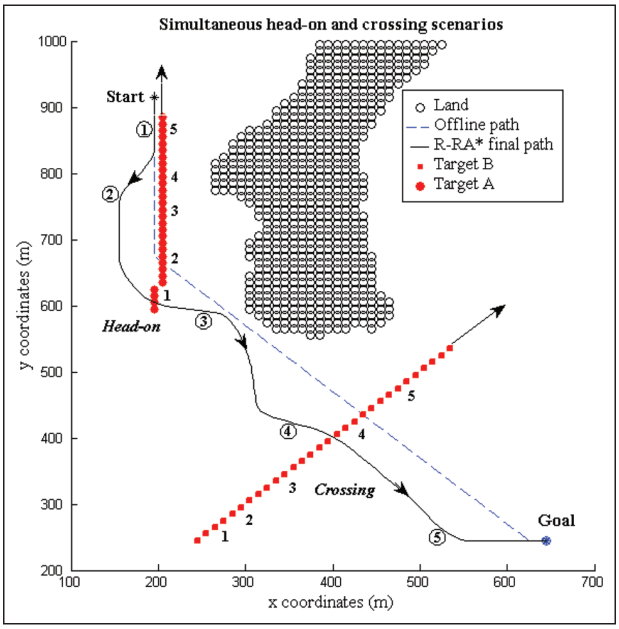

Figure 15. Multiple target COLREGs avoidance.
R-RA*: Rule-based Repairing A*.

present in the risk zone until the 114 s; however, Figure 14(b) verifies that it never collides with the USV due to suitable avoidance action.

One main advantage of the R-RA* method is that it can be easily extended for multiple-vessel encounters, as demonstrated in Figure 15. The USV sets out along the original global path, which was previously determined offline. *Target A* presents a Head-on scenario, and *Target B* poses a Crossing encounter further along the intended route according to the predicted locations. The vessels' simultaneous positions are annotated by the numbers 1–5. *Target A* is avoided by updating the

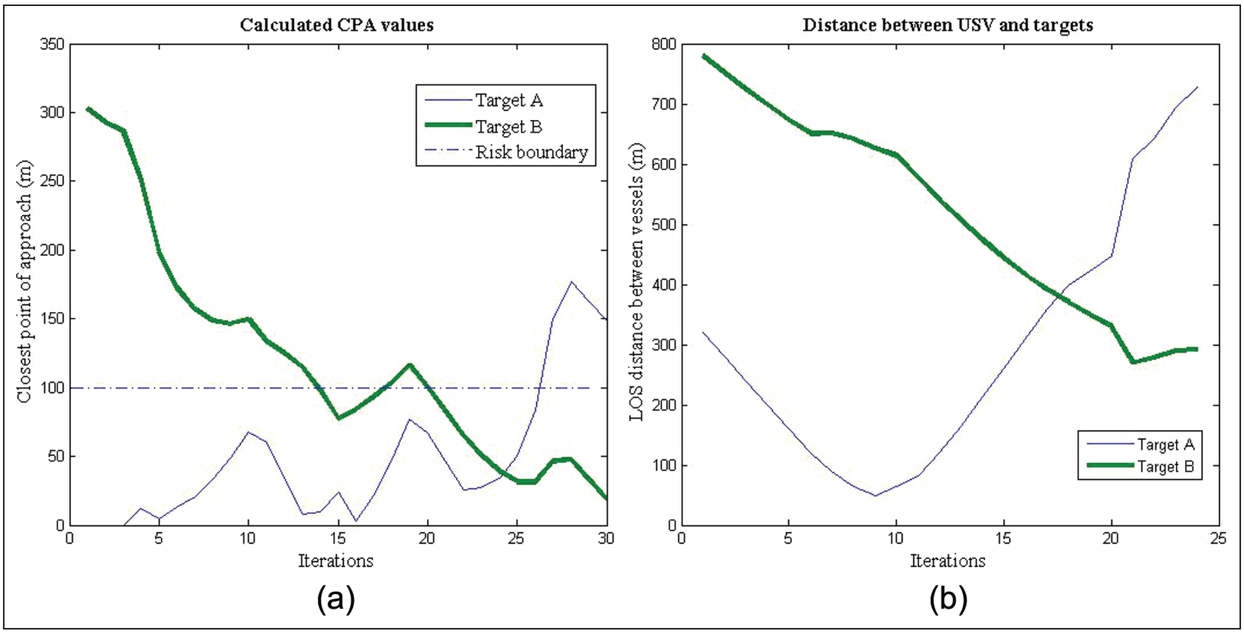

Figure 16. Multiple-vessel encounter with COLREGs: (a) CPA angle as calculated for each target and (b) proximity between encountering vessels and the USV.
USV: unmanned surface vehicle; CPA: closest point of approach; LOS: line of sight.

local path to perform a COLREGs manoeuvre until it is no longer a risk (as shown in Figure 16(a) at 304 s). On the new path, *Target B* is now approaching Head-on and initially enters the risk zone at 159 s, thus the R-RA* algorithm automatically steers the USV towards starboard. A breach of COLREGs could easily cause confusion and a risk of impact. The proposed integrated system ensures safe navigation without the need for operator intervention and decision-making. Finally, Figure 16(b) confirms that there is no collision.

Conclusion

This proposed integrated ODA system addresses the issue of navigational safety of USVs in operation at sea by automatically detecting and avoiding multiple, dynamic and pop-up obstacles in compliance with COLREGs, the Rules of the Road. It presents a fast, online solution without dependence on AIS data, wireless communication or radar for obstacle detection. Improvements to the current system include incorporation of optimal speed assignment in addition to the recommended spatial path for more efficient avoidance trajectories. This will present an effective solution for highly complex multiple-vessel encounters where conflicting routes exist. Furthermore, vessel dynamics may be considered by using information about the sea state and exploiting the direction of ocean currents or wind to optimise the route. The current testing platform can then be integrated within a full NGC system and USV model for verification.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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