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A Rule-based Heuristic Method for COLREGS-compliant Collision Avoidance for an Unmanned Surface Vehicle

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Abstract: With an increasing demand throughout industry for autonomous vehicles with more intelligent decision-making features, the issue of Unmanned Surface Vehicle (USV) navigation is addressed with respect to automatic obstacle avoidance. This Obstacle Detection and Avoidance (ODA) system design approach addresses the primary concern, the safety of a USV in operation. Due to the desire for improved autonomy and thus reduced human interaction, it is essential to incorporate vessel avoidance protocols into the ODA architecture for operation amongst maritime traffic, implementing the marine *Rules of the Road*. A heuristic Rule-based Repairing A* (R-RA*) algorithm is proposed, which is integrated within a decision-making framework. The integrated system has proven effective in simulations for path planning in real-time, in accordance with the International Regulations for Preventing Collisions at Sea.

Keywords: Autonomous vehicles, marine surface vessels, path planning, collision avoidance, COLREGs, heuristics, guidance

1. INTRODUCTION

USV research and development has been largely overshadowed in the past by that of Unmanned Underwater Vehicles (UUVs) due to implications for the oil and gas industry, and also by Unmanned Aerial Vehicles (UAVs) which have become a vital tool in modern military strategies. In 2007, the Defence Advanced Research Projects Agency (DARPA) announced that 3 billion US dollars is required in fiscal 2012 for projects involving ASV development for submarine tracking as part of the Navy USV Master Plan (Doyle (2011)). Further advances in artificial intelligence, advanced smart sensors, wireless networks and optimisation, in addition to DARPA's announcement, have triggered the escalating focus on improving the autonomy of marine surface vehicles. Besides the utilisation of USVs in military applications such as minesweeping, surveillance, reconnaissance and intelligence missions, e.g. the *Israeli Protector* (Rafael Advanced Defense Systems Ltd. (2010)), they are particularly prevalent in marine research, primarily for acquiring oceanographic data (bathymetry, pollution monitoring, etc.). Such prototypes include the autonomous catamaran, *Charlie* from the Institute of Intelligent Systems for Automation in Genova, Italy (Bibuli et al. (2008)), which collected samples during the XIX Italian expedition to Antarctica, and in the UK, the *Springer* from the Marine & Industrial Dynamic Analysis Research Group (MIDAS) at the University of Plymouth, which conducts environmental and hydrographic surveys in coastal waters (Naeem et al. (2006)).

In order for a USV to exhibit full autonomy, it must be capable of operating in a marine environment without intervention from a human operator. This encompasses motion planning, obstacle evasion and more specifically collision avoidance with moving marine traffic in accordance with the International Regulations for Preventing Collisions at Sea (COLREGs)(Commandant (1999)), thus differentiating it from a generic robotic pathfinding task.

The International Maritime Organisation (IMO) established modern COLREGs in 1972 as a set of guidelines for vessel encounters at sea, i.e. *Rules of the Road*. All vessel operators are expected to comply with these regulations, which outline protocols for determining right of way and correct avoidance manoeuvres. Whilst motion planning has been investigated in detail by the research community, relatively little attention has been dedicated to COLREGs compliance with the exception of a few studies. Reasons for this lack of interest include the absence of legal regulations pertaining to USV operation. Hence, until now industry has sought manned vehicles in preference to USVs, largely due to deficiencies in their decision-making capabilities.

Human error, both active and latent, are said to cause marine collisions in an estimated 89-96% of cases (Rothblum (2000)), for instance the catastrophic *MV Doña Paz* ferry collision with the *MT Vector*. An intelligent Obstacle Detection and Avoidance (ODA) system can potentially eliminate the issues caused by poor judgement or failure to react promptly. This concept could prove vital, not only for unmanned vehicles, but also as an assist to human navigators when selecting an appropriate course.

Several noteworthy attempts have been made to integrate COLREGs into an obstacle avoidance system, with each adopting a unique approach. Potential field methods are

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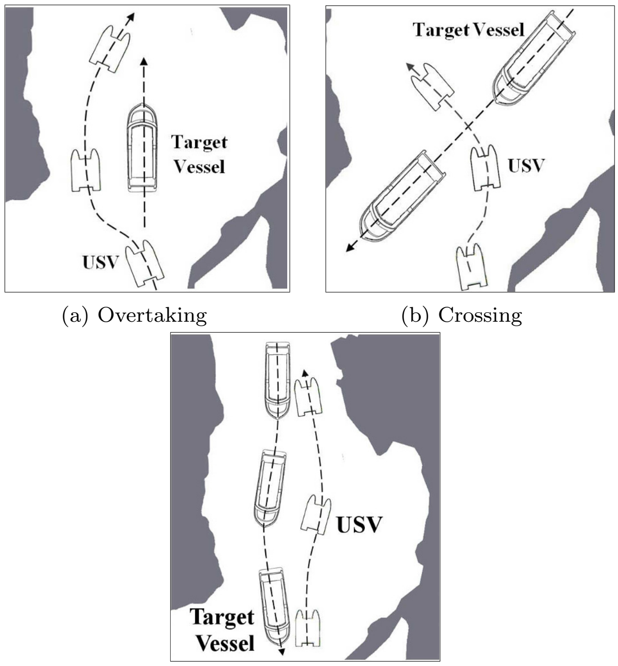
generally very popular for obstacle avoidance problems and have been implemented by Lee et al. (2004), where Modified Virtual Field Forces (MVFF) combined with fuzzy expert rules were applied. A more recent study by Xue et al. (2011) employs potential fields for multiple vessel encounter simulations, adhering to COLREGs. Evolutionary methods have not been widely explored for COLREGs path planning, due to the real-time nature of the problem, however one study successfully uses Ant Colony Optimisation (ACO) for e-navigation support on manned vessels to plan safe routes (Tsou and Hsueh (2010)). Benjamin et al. (2006) conducted sea trials to test several COLREGs encounter scenarios with two *SCOUT* vessels communicating wirelessly. The behaviour-based architecture uses Interval Programming with action averaging selection for more complex behaviours.

There are several deficiencies with the methods explored to date. The nature of these issues range from real-time implementation (because the planning phase takes too long or an indeterminate or inconsistent amount of time), to infeasible paths. For instance, potential field avoidance is prone to becoming trapped in local minima. Many of these methods also exhibit unpredictable behaviour, especially the reactive avoidance methods. The resulting path to goal may vary completely from the original intended path, which is considered to be poor navigational practice. Whilst some of these studies have considered multiple vessel encounters, most have not. In addition, many of the vessels simulated do not exhibit any type of complex behaviour, i.e. changes in speed.

Heuristic methods are suited to this spatial path planning task, as it can be considered two-dimensional in nature. For instance, a study by Casalino et al. (2009) consisting of a three layer obstacle avoidance system architecture (offline, deliberative online and reactive) includes a modified heuristic A* search for dynamic obstacle avoidance online, but without consideration of COLREGs protocols. Another recent heuristic-based example executed UUV motion planning using HA* which searches homotopy classes for topological paths, however traffic regulations obviously do not apply underwater (Hernández et al. (2011)). This study introduces a Rule-based Repairing A* (R-RA*) method operating in a suitably defined C-space which is governed by a decision maker. The primary advantage of R-RA* is the enhanced safety resulting from the generation of COLREGs-compliant paths, which is absent from other similarly fast and computationally efficient heuristic techniques. The proposed algorithm is capable of implementing the IMO regulations in real-time, generating consistent paths unlike most other methods, preserving the original course where possible.

This paper's content is comprised of the following topics. Section 2 outlines fundamental COLREGs theory and how these rules are integrated within the decision making framework. Section 3 presents the R-RA* approach, complete with pseudocode. Simulation results are presented in Section 4, implementing of some of the most vital COLREGs rules using the R-RA* path planning method. The paper concludes with Section 5, highlighting the benefits of employing this unique heuristic approach and mentioning future work.



(a) Overtaking (b) Crossing

(c) Head-on

Fig. 1. (a) A vessel may pass on either port or starboard, but must issue the appropriate signal. (b) The powered vessel which has the other on its starboard side must give-way by waiting until it has passed or crossing abaft of the stand-on vessel. (c) When powered vessels approach each other head-on, they must pass port to port by making respective starboard manoeuvres.

2. COLLISION AVOIDANCE REGULATIONS

COLREGs consists of three main sections; *General (Part A)* outlining the applicability and responsibilities of the regulations, *Steering and Sailing Rules (Part B)* and *Lights and Shapes (Part C)* which addresses the issue of various signals and use of lighting. *Part B* is the most applicable section to this study and the main rules are described with illustrations in Fig. 1; *Rule 13: Overtaking* (Fig. 1a), *Rule 15: Crossing* (Fig. 1b) and *Rule 14: Head-on*(Fig. 1c).

2.1 Practical Implementation

Although vessels are most likely to engage in close encounters with others in narrow channels, it could happen anywhere at sea. COLREGs state that all actions to avoid collision should be substantial, obvious and made in advance. These protocols should be abided by unless the target vessel does not comply, then general avoidance action must be taken. Although these laws are simple for a human to comprehend, their quantification is complex. There are also many exceptions to these rules which a USV must take into account, for instance, one must always give way to sailing vessels, and large vessels constrained by their draft or those whose manoeuvring is restricted. An oil tanker with a large turning radius is unlikely to deviate from its course to give way to a smaller vessel. This decision making system shall be incorporated into the ODA architecture.

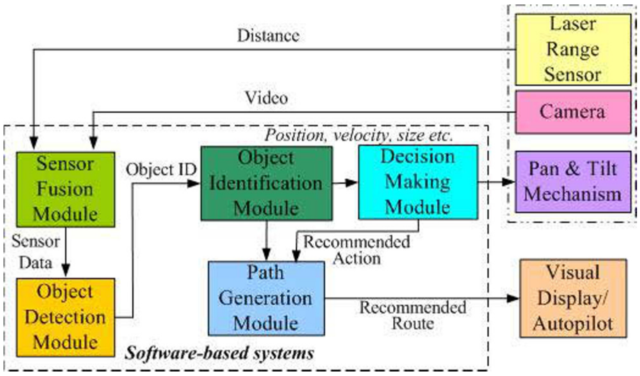


Fig. 2. Block diagram showing the ODA subsystems.

2.2 Decision Making Framework

Fig. 2 illustrates the assumed ODA architecture which incorporates the decision making framework and path planning system. Vision sensors (including laser-based) or Automatic Identification System (AIS) data provide the necessary information to identify other vessels present via the Object Detection and Identification Modules and determine their speed, acceleration, heading, size and type. A pan and tilt platform enables camera rotation, providing a large viewing range. When in range, the Decision Making Module projects a target vessel's estimated future position, determining if the Closest Point of Approach (CPA) distance is acceptable and, if required, commands the path planner to generate a new course to avoid collisions. The decision maker within this module must determine which COLREGs rules apply according to the relative angle of approach and adjust the speed as necessary (otherwise constant) for stand-on or give-way roles whilst traversing the spatial avoidance path. The situation assessment is a continuous process and must be equipped to deal with emergency evasive scenarios, in the instance that COLREGs are breached by the other vessel. It is assumed that avoidance path is generated iteratively by the R-RA* method within the Path Generation Module to provide waypoints for the Autopilot.

3. RULE-BASED REPAIRING A* ALGORITHM

The standard A* algorithm is widely used for robotic path planning in known environments due to its fast, efficient, optimal and simplistic nature. It performs a best-first search of the most probable paths leading to the goal via 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, $h(n)$. Many variations and extensions of the A* algorithm are now in existence for autonomous path planning tasks and the computer games design industry for improved efficiency and flexibility. A description of some of the most common and successful algorithms developed such as D*, D* Lite, ARA* etc. can be found in a survey by (Ferguson et al. (2005)). However, as with all existing path planning methods, further modifications are required to incorporate navigation regulations based on situation awareness.

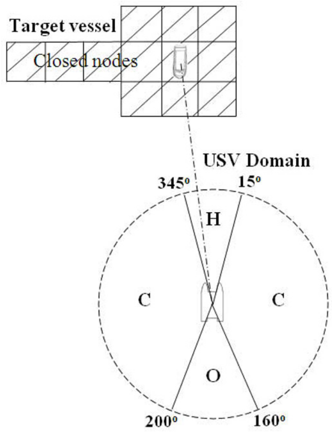


Fig. 3. USV domain for COLREGs behaviours, showing the addition of starboard-side nodes to the closed list for a head-on encounter denoted by H.

3.1 Modified Algorithm for Collision Avoidance

The proposed R-RA* algorithm relies on additional navigational decisions, governed by rules formulated for COLREGs compliance. These decisions are made based on the relative states of the approaching vessels and determine which areas of the map should be considered out of bounds for the heuristic search depending on the encounter type. For instance, the proximate starboard region of a vessel approaching head-on will be added to the closed list for the A* search to prevent resulting paths crossing this area which would breach COLREGs, as illustrated in Fig. 3. The domain region labelled H activates head-on behaviour, whereas O represents the overtaking region and C for a crossing scenario. The algorithm operates in a grid-based C-space, with binary occupancy in each cell, i.e. 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 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.

For each of the three primary COLREGs protocols (overtaking, head-on and crossing) the first step is to plan an offline path from the start position to the global target using the standard A* algorithm, avoiding all stationary obstacles such as land features and ships (with COLREGs) according to the present map information (Algorithm 1.2). All moving ships within sensor range during this first step are considered to be stationary at their current coordinates. During the next step, the R-RA* algorithm begins searching along the next offline global path segment (Algorithm 2.2). If no ships are in this vicinity, i.e. no map information has changed along this path then the USV proceeds along the current path. At each time interval during which updated map data is received, another search is performed for the next segment of the path from the current location. When a target vessel is identified and its velocity is established, the decision maker assesses the requirement for specific collision avoidance protocols and subsequently adds any affected map regions to the closed list. A new repaired sub-path is then generated to perform COLREGs avoidance techniques before resuming

Algorithm 1. Offline Global Path by A* with COLREGs

```
Closed ← {b} ▷ Initialise map and add obstacle nodes to Closed list
call Encounter ▷ Adds forbidden nodes to Closed for COLREGs compliance (see Algorithm 2.9)
Open ← {n}    ▷ Add empty nodes to Open list
procedure HEURISTIC PLANNER($n_{start}$, $n_{goal}$)
    $g(n) \leftarrow 0$
    $f(n) \leftarrow g(n) + h(n)$    ▷ Heuristic cost function
    while Open≠ 0 do
        Get node $n$ in Open with smallest $f(n)$
        Insert $n$ into Closed
        if $n_{goal} = n$ then
            ▷ Backstep via pointers to find path
            Return path to goal
        else
            ▷ Get successors of current node
            Expand $n \leftarrow \{n'\}$
            for all $n'$ do
                ▷ Find Manhattan estimate of cost to goal
                Get $h(n')$
                ▷ If node not yet expanded
                if $n' \in$ Open then
                    ▷ Get $w(n, n')$, cost of traversing between $n'$ and parent node
                    if $g(n) + w(n, n') < g(n')$ then
                        procedure UPDATEPARENT
                            ▷ Set backstepping pointer
                            $n'_{parent} \leftarrow n$
                            ▷ Update key with minimum-heap
                            $f(n') \leftarrow g(n)+w(n, n')+h(n')$
                            ▷ If $n' \notin$ Open, insert into Open
                        end procedure
                    end if
                    ▷ If node has already been expanded
                else if $n' \in$ Closed then
                    if $g(n) + w(n, n') < g(n')$ then
                        UPDATEPARENT
                    end if
                else
                    ▷ New node encountered
                    UPDATEPARENT
                end if
            end for
        end if
    end while
    return ∅    ▷ No path exists to goal
end procedure
```

along the original route. This loop is repeated until the destination is reached.

3.2 Vessel Dynamics

The resulting grid-based path does not inherently incorporate ship dynamics. Simply smoothing the jagged path with a spline method may not prove sufficient for generating feasible waypoints. Dynamics such as turning radius, maximum speed, drift etc. are unique to each ship's design, so it is not possible to implement a universal solution. It is assumed that the vessel's speed remains constant or is externally controlled by the decision maker. The issue of incorporating turning radii, e.g. in excess of $500m$ for a large

Algorithm 2. Online R-RA* Path Planning

```
▷ Current node, c obtained from GPS data
while $c \neq n_{global}$ do
    ▷ Define risk zone in vessel proximity
    procedure DECISION
        ▷ Assesses risk and need for replanning
        if $CPA < CPAlimit$ then
            Get relative approach angle
            ▷ Encounter determines COLREGs rule which applies and forbidden nodes
            call Encounter
            Get closed regions ← {o}
            Open ← {n}
            ▷ Add forbidden nodes to Closed list
            Closed ← {b} + {o}
            ▷ Vessel's current node is the start node
            Set $c \leftarrow n_{start}$
            ▷ New goal node is a defined subgoal
            Set $n_{subgoal} \leftarrow n_{goal}$
            ▷ Repair path locally
            call Heuristic Planner
            update path locally
        else
        end if
    end procedure
end while
```

draft vessel, is solved by Dubins circles (Dubins (1957)) applied after spline smoothing to non-conforming curve sections. Where the angle between consecutive smoothed waypoints is less than permissible, the path is altered. Assuming constant speed, the discontinuous region of the path is replaced by an arc of radius r_{min}, calculated by simple geometry for the circle which intersects both LOS tangents at a single point. It would also be ensured that the end pose is pointed towards the next waypoint.

After the new waypoints have been generated, a feasibility check ensures that the final path still conforms to the avoidance specifications.

4. SIMULATION RESULTS

The R-RA* algorithm was tested in a number of MATLAB simulations for a range of vessel encounter scenarios where COLREGs rules apply. Its performance is compared with that of a standard A* algorithm, modified to work online. It is assumed that GPS or AIS information is available at sampled time intervals to communicate own-vessel and target-vessel positions and to allow projections of future estimated positions. Real nautical map data was acquired of a $2.5km^2$ coastal region near Montijo, Portugal and scaled for demonstrative purposes. For the resulting path, the vessel dynamics are incorporated for a hypothetical vessel with a specific turning radius using Dubins curves.

4.1 COLREGs Simulations

It is assumed that the unmanned vehicle is a small, powered and highly manoeuvrable boat and that the stand-on vessel is a sailing vessel or fishing trawler of maximum length $25m$. Thus, a nautical map grid square size of approximately $25m$ was selected based on the maximum size of either vessel. For each planned path, the

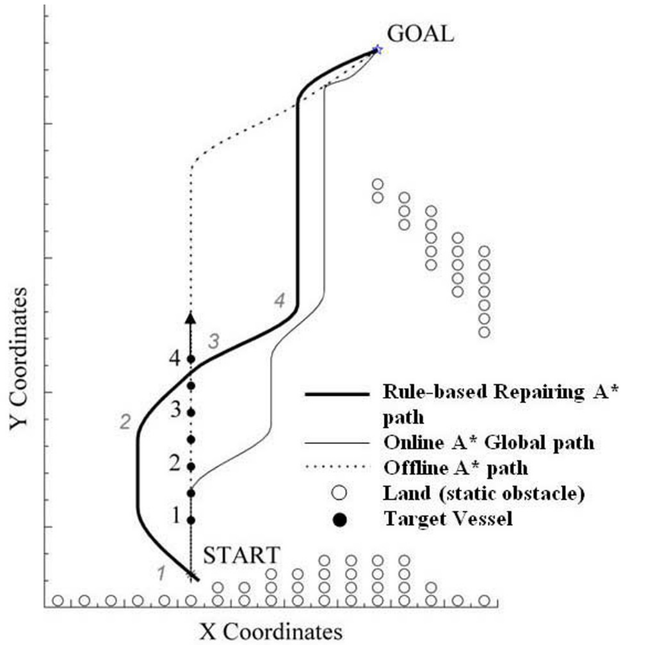


Fig. 4. Comparison of A* and the Rule-based Repairing A* for Rule 1: Overtaking situation with a stand-on vessel.

minimum clearance between the vessel and any obstacle is always equal to one square, i.e. maximum ship length.

Fig. 4 illustrates *Rule 13*, the Overtaking situation, for example bypassing a sailing vessel which is travelling at a constant velocity as indicated by the direction of the arrow. The path of the stand-on vessel follows the chronological annotations, beginning at 1 and the same numbers denoted on the modified path indicate the corresponding USV locations at that time. The offline path provides the most direct, optimal route to the goal, taking account of the necessary clearances. Although a ship may pass on the port or starboard side of another provided sufficient clearance is given, it is necessary to be able to predetermine the course of action in order to give the correct signals. The standard A* algorithm successfully avoids the vessel being overtaken, however it will always overtake on the side which will provide the most optimal route. The proposed R-RA* method makes an informed decision and is capable of performing overtaking manoeuvres on either side. This flexibility makes the method more appropriate for strategic missions.

A typical Head On scenario is illustrated in Fig. 5. The stand-on vessel in this case takes no evasive action around the oncoming USV, as it is assumed to be large and not easily manoeuvrable. In reality, marine vessels do not intentionally come within close proximity of each other before implementing avoidance manoeuvres, but instead take early and substantial action. The online A* algorithm takes early evasive action, but directly violates COLREGs *Rule 14* by passing the target ship starboard to starboard. The R-RA* path conforms to this rule by planning a spatial path passing port to port. When the threat has passed at point 4, the original path is resumed.

The final scenario in Fig. 6 represents a Crossing encounter with a ship approaching from starboard. According to *Rule*

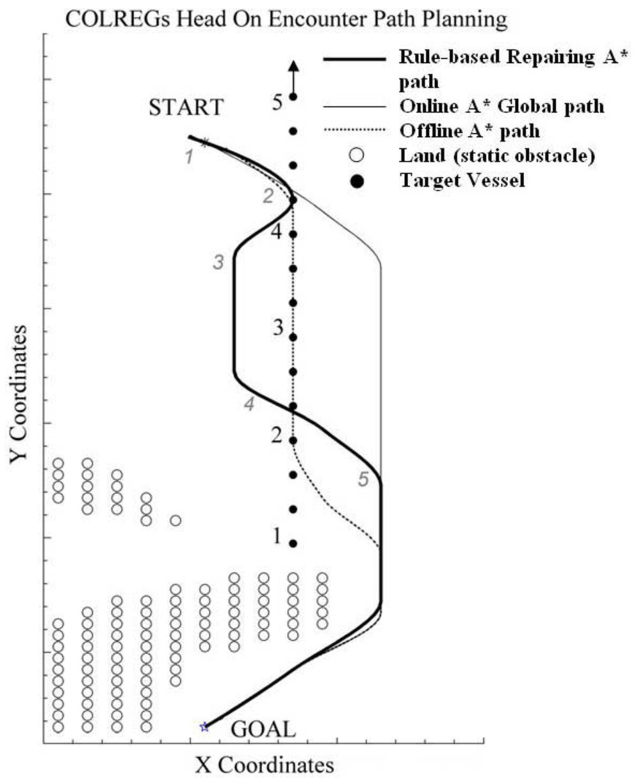


Fig. 5. Comparison of A* and the R-RA* for Rule 14: Head-on situation with a stand-on vessel.

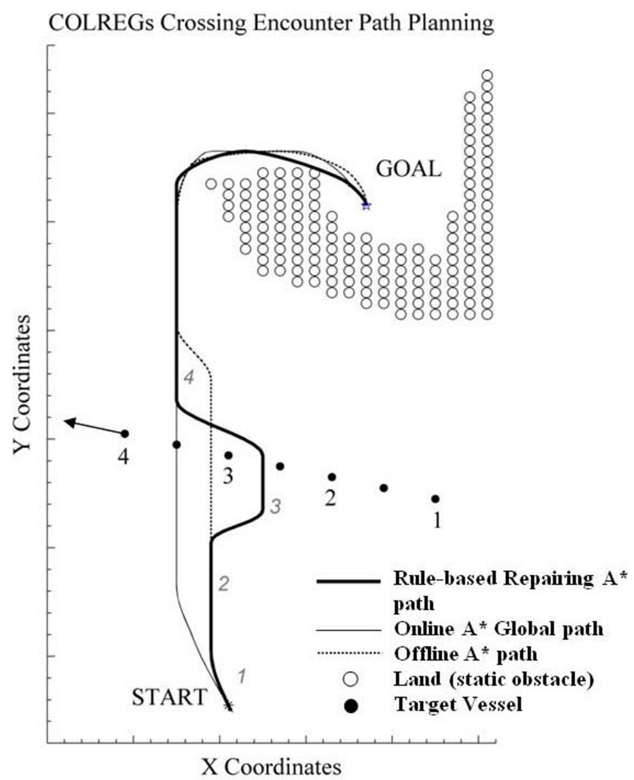


Fig. 6. Comparison of A* and the Rule-based Repairing A* for Rule 15: Crossing situation with a stand-on vessel.

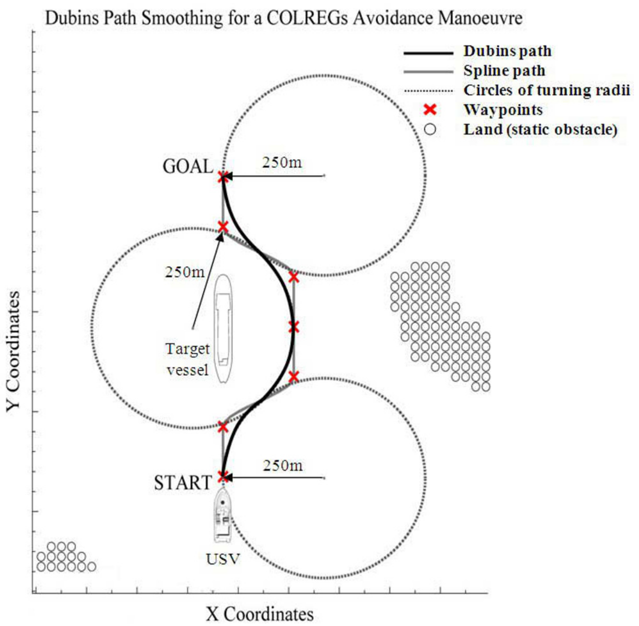


Fig. 7. Dubins path smoothing incorporates the minimum turning radius of the vessel to yield traversable paths where splines are insufficient.

15, the USV becomes the give-way vessel and must pass aft of the stand-on ship. The uninformed A* path fails to take this into account and chooses the most optimal path which disobeys the guidelines. However the modified algorithm chooses a suitable and safe path which is optimal when encompassing COLREGs.

The heuristic search time for R-RA* is shorter because it replans only shorter sub-paths and not the path-to-goal from every position, which is inefficient. By only repairing the current path when necessary, this avoids extraneous computation. For R-RA*, each subsequent replanning phase took less than 0.2 seconds to compute, whereas the maximum time for a single A* iteration was in excess of 2 seconds. Therefore the proposed R-RA* method proves to be more computationally efficient than the standard online A* path planning technique and thus suitable for real-time implementation. In addition, it is capable of yielding safe, COLREGS-compliant paths.

Finally, for completeness, the dynamics of a vessel is incorporated in the proposed strategy. A simulation was performed for a less manoeuvrable USV, with a minimum turning radius of $250m$. Fig. 7 shows that the spline-smoothed path for simple head-on avoidance is non-traversable due to a higher curvature between several of the waypoints. Dubins circles rectify this issue by smoothing the line-of-sight paths where required.

5. CONCLUSION

The R-RA* algorithm in conjunction with a COLREGs decision making framework addressed some of the deficiencies with previously investigated methods. In particular the proposed technique produced safe, optimal and feasible paths, where they existed. It executed intelligent manoeuvres by planning online, using real-time sensor information to establish situation awareness and implement the *Rules of the Road* as required. This theory can be easily extended to include multiple vessel encounters and has the possibility of becoming even more efficient by retaining and reusing cost information for faster searches. An extension using a multi-resolution grid creates possibilities for more intricate manoeuvres and increased optimality. The increased autonomy of USVs paves the way for establishing legal policies for their operation at sea due to enhanced safety measures via COLREGs compliance, hence extending their applications and expanding the market for commercial availability.

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