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A Reactive COLREGs-Compliant Navigation Strategy for Autonomous Maritime Navigation

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Abstract: This paper reports the development of an automatic collision avoidance technique for unmanned marine vessel incorporating standard collision regulations or COLREGs, defined by the International Maritime Organisation. Like any ship, all unmanned vessels must adhere to COLREGs at all times in order to minimise or eliminate the risk of collisions. The proposed approach is essentially a reactive path planning algorithm based on a modified well known Artificial Potential Fields (APF) framework. It is shown through simulations that the proposed strategy is able to generate COLREGs-compliant trajectories in the presence of both stationary and dynamic obstacles. Rules 13, 14 and 15 of the COLREGs, which apply to the overtaking, head-on and crossing scenarios respectively, are simulated for multiple dynamic vessels in an environment inclusive of land features.

Keywords: Artificial Potential Fields, COLREGs, Unmanned Surface Vehicles, Autonomous, Navigation, Path Planning.

1. INTRODUCTION

There has been a growing interest in the use and application of unmanned marine vehicles (UMVs). UMVs are generally classified into underwater and surface vehicles with underwater vehicles currently taking the lion's share of the market because of their range of applications including subsea pipeline/infrastructure surveying and inspection, search and rescue to name a few. Unmanned surface vehicles (USVs) have also gained a widespread interest for applications ranging from oceanography, remote sensing, weapons delivery, force multipliers, environmental monitoring, surveying and mapping, and providing navigation and communication support to underwater vehicles. In particular, the USV industry has seen a widespread surge when in 2012, DARPA released the USV Master Plan which entailed $3 billion funding for projects involving surface vehicle development for submarine tracking (Doyle, 2011). Currently, DARPA (Defense Advanced Research Project Agency) is carrying out at-sea trials of its brand-new 132-foot-long Autonomous Submarine Hunter vessel[1]. Some of the other worldwide USV programs both in the defence and civil sectors include the *Delfim* USV for mapping applications (Pascoal et. al., 2000) *Autosea* Project for unmanned USV (Loe, 2008) and *Protector* USV (Protector, 2010) for maritime assets protection.

Most of these systems 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 (Corfield and Young, 2006). 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 (Caccia, 2006; Corfield and Young, 2006). Besides developing a system that generates evasive manoeuvres to avoid an object, it is important that the USV behaves in a manner that is discernible by other ships in the vicinity. This attribute would aid in integrating the USVs with the surrounding marine traffic. The coastguard regulations on prevention of collision at sea (COLREGs), defined by the International Maritime Organisation (IMO) (Cockcroft and Lameijer, 2003; Commandant, 1999), can usefully be incorporated for this purpose. It should be noted that all manned vessels are required to adhere to these regulations at all times in order to avoid a collision. The DARPA's Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV[2]) has shown to be capable of operating the ship in compliance with maritime laws and conventions for safe navigation.

Here, an Artificial Potential Field (APF) method has been adapted to generate a collision free COLREGs-compliant path for an USV. Whilst the principle of using potential energy fields remains consistent with the original works of Khatib (1986), significant adaptation is required for automatic implementation in any arbitrary encounter scenario, rather than those predetermined.

APFs have been investigated, under limited circumstances previously for COLREGs avoidance for USVs (Lee et. al. 2004; Xue et. al, 2009) due to their potential suitability and characteristic merits. However, no additional significant

[1] http://www.engadget.com/2016/04/08/darpa-christens-actuv-sea-hunter/

[2] http://www.darpa.mil/news-events/2016-04-07

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related research has been identified, thus there are still opportunities to shape and develop this method. The well-known limitations of APFs mainly pertaining to a need for more robust exceptions handling, addressing the local minima issues and a need for more complex encounter scenarios will also be considered.

The structure of the paper is as follows. Section 2 outlines the background and motivation of the research including a summary of the IMO collision regulations. In Section 3, the APF algorithm fundamentals are presented along with the proposed adaptation to this well-known reactive path planning technique. The method of defining COLREGs zones within the APF framework and gain tuning is also provided in Section 3. Simulation results are presented in Section 4 followed by concluding remarks in Section 5.

2. MOTIVATION AND BACKGROUND

Statistics have shown that 60% of casualties at sea are caused by collisions (Jingsong and Wilson, 2008). Furthermore, it is reported in Statheros et al. (2008) that 56% of collisions at sea include violation of COLREGs with the majority occurring due to human error. The infamous Titanic tragedy was in fact as a result of the unwillingness of the crew to change the speed of the vessel (Lord, 1955) as required by the rules of obstacle encounter at that time. Although these studies are compiled for manned ships, unmanned vessels without any form of onboard intelligence could even be more vulnerable. For this very reason, there is an ongoing legal debate about providing cover for these types of vessels. A review of related research has revealed that very few USVs are equipped with an onboard collision avoidance system. In addition, only a handful of research programmes have considered developing COLREGs-based navigation systems. In one instance, Benjamin and others at MIT (Benjamin and Curcio, 2004; Benjamin *et. al.* 2006) 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 (Larson *et. al.* 2006; Larson *et. al.* 2007). Another collision avoidance method using fuzzy logic with reference to COLREGs is devised for vessel traffic service (VTS) (Kao, 2007), 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 (Xue et. al., 2009) 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, Kuwata *et.al.* (2014) from the Jet Propulsion Lab proposed a velocity obstacle method to generate COLREGs-compliant trajectories. A series of on-water experiments involving up to four vessels has been conducted implementing three fundamental COLREGs rules (crossing, overtaking and head-on). These are further described in the following.

2.1 The International Regulations for Avoiding Collisions at Sea

COLREGs were set out in 1972 by the IMO as a set of guidelines for vessel encounters at sea. It is expected that all vessel operators comply with these regulations, which outline procedures for determining right of way and correct avoidance manoeuvres. Thus, if intelligent autonomous marine vessels can operate in accordance with these guidelines, many traffic-related accidents at sea caused by human error could be avoided.

Without a human operator or crew physically present onboard the vessel, the rules must still be obeyed if an unmanned ship is to be lawfully operational at sea. Otherwise unpredictable or incorrect actions may lead to confusion and potentially catastrophic collisions amongst other marine traffic. In the case of remotely operated vessels, the operator shall implement all manoeuvring decisions. Conversely, an autonomous vessel should have the ability to make these same decisions based largely on sensor information. The regulations are comprised of three main sections:

- General (Part A): Outlining the applicability and responsibilities of the regulations.
- Steering and Sailing Rules (Part B): Part B consists of two sections, where Section I refers to the conduct of vessels in any visibility conditions and Section II regards the conduct of vessels in sight of one another.
- Lights and Shapes (Part C): Covers protocols for issuing indicating, warning or distress signals etc. and safe guidelines for the use of lighting.

Although rules from all sections are applicable, the Steering and Sailing Rules in particular, of vessels in sight of one another present perhaps the greatest challenge in achieving full autonomy. The fundamental rules/practices for ships in sight of one another are defined as follows.

Rule 13 - Overtaking: Any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

Rule 14 - Head-on Situation: When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other.

Rule 15 - Crossing Situation: When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

3. APF FUNDAMENTAL THEORY AND ADAPTATION

In this section, the foundations and basic concept of APFs will be provided first to provide a basis of understanding, which enables the reader to follow the development of the APF COLREGs path planner. Unlike grid-based heuristics such as A*, APFs are designed to operate in a continuous environment. APFs consist of a potential energy gradient, determined by the sum of individual potential functions. In this case, the USV is considered to be a positively charged particle moving towards a negatively charged goal location. The USV will follow the gradient of steepest descent in the virtual field, being repelled by positively charged obstacles along the way. The aspects which make this methodology particularly attractive as an online, real-time path planner are the rapid computation times, reactive avoidance capability, no requirement for C-space discrete grid decomposition, smooth path generation, ability to handle multiple objects and also the ability to incorporate COLREGs constraints by adapting the potential function. Limitations however, include cluttered and evolving environment handling, with tendency to get trapped in local minima, the standard of modelling objects as points and the USV considered to be a point source, and failure to execute where no solution can be found. The success of APFs largely depends on the initial set of assumptions made and the level of control desired.

Potential functions used in APFs represent any obstacle, hazard, constraint (repulsive, positively charged), as well as a global or local waypoint (attractive, negatively charged). The sum of forces at any location is equal to the vectorial addition of the sum of attractive and repulsive forces.

3.1 APF Adaptation

The attractive potential monotonically increases with the distance from the goal and may be modelled as a quadratic or linear function depending on the desired field shape. Both will result in a convex environment, analogous to a marble inside a bowl with a sink where the goal is situated. A quadratic function given by (1) yields a parabolic shaped field, which avoids the discontinuity problem at the singularity and shall thus be selected for implementation.

$$U(q)_{att} = \frac{1}{2} K_G d_G^2(q, q_{goal}) \qquad (1)$$

where d_G is the Euclidean distance between the each set of coordinates in the field, q and the global goal coordinates, $U(q)_{att}$ is the magnitude of the attractive potential field at co-ordinate, q and K_G is the attractive gain constant for the goal. The nonlinearities do not affect the system's performance as the computation time is only fractionally slower than the linear function, which is not critical in this application.

As the USV shall essentially be a point under influence, whilst the attractive pull towards the goal should be constant and influential at any given location, repulsion from obstacles should only be in effect within a given radius of the object. There is no need to repel objects which are far away, therefore there should be a discrete and defined region of influence, with the strength of this field diminishing radially outwards to encourage flow around the obstacle. This is achieved by setting the repulsive potential function as follows (Khatib, 1986).

$$U(q)_{rep} = \begin{cases} \frac{1}{2} K_{ob}\left(\frac{1}{d(q, q_{obs})} - \frac{1}{D_o}\right) & if \quad d \le D_o \\ 0 & if \quad d \ge D_o \end{cases} \qquad (2)$$

where d is the Euclidean distance between the each set of coordinates in the field, q and obstacle coordinates q_{obs}, D_o is a prespecified distance to an obstacle, $U(q)_{rep}$ is the magnitude of the repulsive potential field at co-ordinate, q and K_{ob} is the repulsive gain constant for the obstacle. Although all obstacles in general robotic path planning may be assigned common adjustable parameters, for a more flexible and optimised design, individual parameters (gains) shall be assigned to each type of obstacle, differentiating between static obstacles, moving vessels and coastlines. The APF programme and set-up are designed, based on this foundation theory.

3.2 Gain Tuning and Obstacle Placement

The proposed APF program was developed and tested to deal with offline, static obstacle avoidance, to online, iterative path processing, dealing with multiple approaching static and dynamic objects, incorporating the COLREGs rules where the Risk Assessment unit identifies a significant threat.

The proposed APF strategy takes the inputs and computes the outputs as illustrated in Fig. 1. The only gain constants required are those associated with the repulsion of static map features (K_{bound}) and for any *a priori* known vessels, which are assumed to be instantaneously static (K_{obs}), as well as the attractive gain constant towards the goal, (K_{att}). These gains tend to be found empirically, rather than according to a set protocol. For the shortest path computation, the other variables required are simply the global start and goal coordinates.

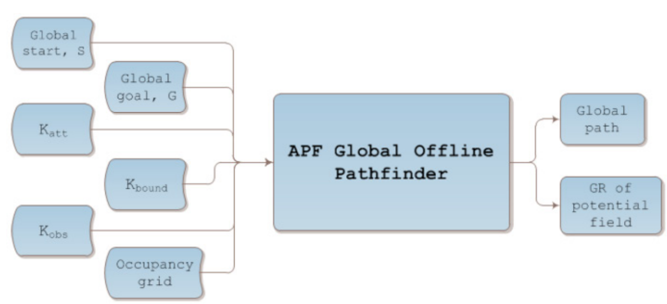


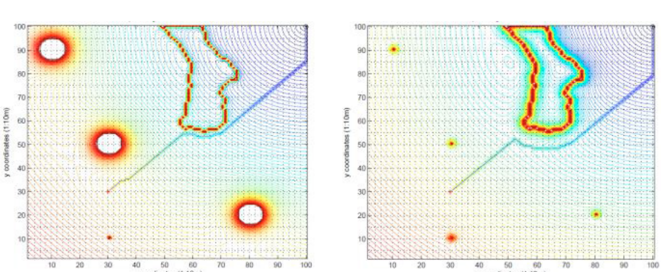
Fig. 1. Inputs and outputs of the APF global pathfinder program.

The gains for each attractive or repulsive source will ultimately determine the shape of the field and contours. Gains must be assigned to (a) the global goal - to determine the "pull" towards the sink; (b) the boundaries of the coastline and any coastal features - modelled as mini discrete obstacles tracing the land borders; (c) Static obstacles - e.g. stationary ships should be given sufficient clearance due to the repulsive charge; (d) Moving obstacles - represented as static obstacles, with updated positions at each sample interval and any relevant COLREGs zones and (e) COLREGs zones – which are not physical objects, but virtual ones, which repel the USV from forbidden regions proximal to the target vessel.

As the potential field equation takes into account the overall force distribution throughout the field, attributable to each positively charged and negatively charged feature, gains influence the field relatively. Rather than representing land and coastal features as large, block objects, it was deemed more suitable to represent the coastline only, as a dense repulsive source otherwise it would significantly interfere with the potential field force distribution thus causing a large disruption. Likewise, having too strong a sink would a large force concentration at this location and hence, any repulsive features would be simply ignored. Static and moving vessels shall be modelled as point sources with an adequate repulsive field, rather than modelling specific shapes, such as rectangles, polygons, etc. It is not necessary to consider shapes of relatively small obstacles, as it makes no difference to avoidance protocols when dealing with an open sea scale map, unlike coastlines, which occupy a large proportion of C-space. It is highly important to show a detailed coastline, in order to avoid grounding in shallow depths. The magnitude of each gain shall be tuned empirically to achieve the desired field properties. In Fig. 2, a sample of varying parameters are shown, and the optimum case, where gains are of a 50:50:3 ratio for $K_{bound} : K_{obs} : K_{att}$.

3.3. COLREGs Zones

When a risk is detected, the Decision Maker attempts to implement COLREGs by determining which region proximal to the approaching vessel is forbidden and assign virtual obstacles, which generate their own repulsive field individually and collectively. Rather than merely adding a string of discrete objects which could cause discontinuities in the path or trapping in local minima, these virtual objects are connected (see Fig. 3) to exhibit continuity in the field generated. The placement of these obstacles on the map with suitably tuned gains achieves a *tapered* avoidance region. This would encourage natural flow during avoidance and prevent the USV approaching too close to the target vessel ship.



(a) Gain ratio of 5:5000:3. (b) Gain ratio of 50:50:3.

Fig. 2. Effect of varying gain ratios.

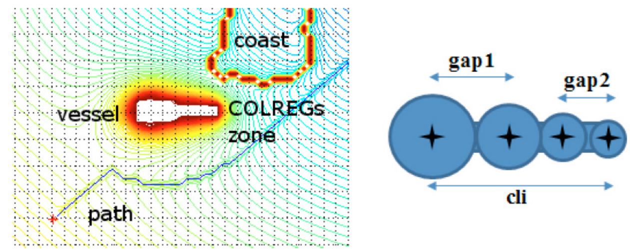


Fig. 3. Illustration of the COLREGs zone of virtual obstacles.

3.4. Risk Assessment

When a path planner is in the iterative online replanning phase, it recalculates the waypoints towards each path subgoal to take the shortest route whilst avoiding any static and dynamic obstacles. However, it could be the case that although a target vessel is detected on the map, it may not pose a direct threat at its current distance, speed and heading and thus, any computation in replanning the path is a waste of processing effort and memory resource. In order to avoid this, a threshold can be set for the minimum acceptable proximity between vessels, commonly known as a "circle of acceptance". The actual minimum distance between the USV and target vessel, based on the assumption that both vessels continue at their current speeds and headings, is referred to as the Closest Point of Approach (CPA) which is the measure used here to determine a risk of collision.

4. SIMULATION RESULTS

4.1. APF Pseudocode

The pseudocode for the APF pathfinder is provided in Algorithm 1. Simulations were carried out, recreating the overtaking, head-on and crossing scenarios. The results are provided visually as maps, with the path progression clearly shown. It is important to remember that the ultimate measure of suitability is safety, not necessarily efficiency, although it is highly desirable.

In APF, rather than computation, effort is not reduced when determining the entire remaining path to goal. This is because the whole field force distribution must be calculated in any instance, and so finding the path of steepest descent is very straight forward. Thus, the typical concept of subgoals was not used for APFs and the global path towards the goal shall be generated at every iteration.

Here, simulations have been carried out for single and multiple moving vessels, covering the three main COLREGs rules (Rules 13, 14, 15). The CPA limits are varied for each simulation to achieve desirable behaviour, rather than having an excessively *high safety:path efficiency* ratio.

4.2. Crossing Encounter

As can be seen in Fig. 4, the target vessel is not initially considered a threat, as the CPA distance is not lower than the CPA limit. This is evident in Fig. 4(a), as there are no virtual vessels proximal to the target, representing a COLREGs zone. The USV safely gives-way to the crossing vessel by avoiding the COLREGs zone in front of the target, and instead passing behind. After the encounter, there is no longer any risks identified and the USV proceeds towards the goal.

The resulting path taken exhibits some jaggedness (although not excessive, taking into account the map scale). This would imply that there may be a need to introduce smoothing in some instances when using APFs. Safe COLREGs execution is observed for crossing in this scenario with a large clearance of 51m.

```
read start and goal coordinates
read K_att and K_bound  ▶Attractive and repulsive gains
try
read L and K_obs  ▶ Array of any known obstacles and their corresponding gain constant
catch error
display 'No stationary obstacles exist'
set identifier for set case no obstacles
end
initialise occupancy grid of all geographical map features
determine boundary nodes ▶ e.g. coastline
set occupancy = 1 for boundary nodes
procedure Create Artificial Potential Field
        ▶ Decision Maker determines COLREGs rule and inserts virtual objects
        call Encounter
    for all nodes do
        Calculate distance from node to goal
        Calculate distances to each geographical boundary node
    end for
    for all nodes do
        if case no obstacles then
            Calculate potential field value
        else
            Calculate distance to any stationary obstacle
            Calculate potential field value
        end if
    end for
    for all nodes do
        set limit on potential field magnitude
    end for
    initialise starting node and set to current
    SEEK
    get global path from start to goal by steepest descent of gradient
end procedure
procedure SEEK
        while current node ≠ goal node do
            if elapsed time > set limit then
                exit
                display 'No solution found to goal'
            else
                get neighbouring node with least potential value
                add node coordinates to path
            end if
        end while
end procedure
```

Algorithm 1: Pseudo code of the modified APF algorithm

4.3. Multiple Vessel Encounter

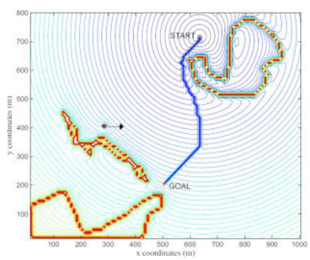
The complex multiple COLREGs encounter shall now be considered using APFs. This will demonstrate how APFs deal with more complex navigational problems. The simulation requires the USV to perform multiple COLREGs avoidance protocols: overtaking and then crossing and head-on simultaneously. Fig. 5 depicts the various stages of path planning in this complex environment. Vessel A is successfully negotiated, avoiding overtake on the coastal side to minimise the risk of grounding. Next, the USV is about to cross just ahead Vessel B whilst Vessel C approaching head-on is also flagged as a collision risk. The Decision Maker immediately assigns virtual objects (see small added circles by a target vessel) to generate COLREGs zones. As a result, the USV turns towards starboard to avoid both vessels, eventually passing aft of Vessel B and abiding by a safe clearance distance (a minimum of 34 m for Vessel B and 39 m for Vessel C). Once again, in segments of the path, further smoothing would be desirable to avoid damaging actuators e.g. when avoiding Vessel A initially. The APF method has demonstrated successful capability to deal with the COLREGs scenarios posed.

4.4 Exception Handling

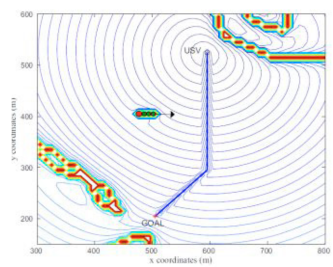
On several occasions during the validation and verification process of APFs with COLREGs, the path failed to execute. In order to determine the cause of this failure, the data was analysed which showed that even during global path planning in large map environments, the 'moving particle' still had the potential to get trapped in local minima. The standard path planning system was simply not equipped with a method of dealing with this. Solutions from literature in the past include the use of harmonic functions and "wall-hugging", where the particle will essentially follow the boundary until it emerges out of the local minimum. Harmonic functions could have been explored, however, a novel and *fast* solution to this problem was proposed. When a failure occurs, the solution involves backstepping iteratively along the path in reverse until a solution can be found. A virtual obstacle is then placed at the point of failure on the path to deter trapping and the algorithm is re-run. This will generally result in a desirable path to goal, however, it does reduce the accuracy of the field and may conflict with other repulsive obstacles which may present themselves.

5. CONCLUSIONS

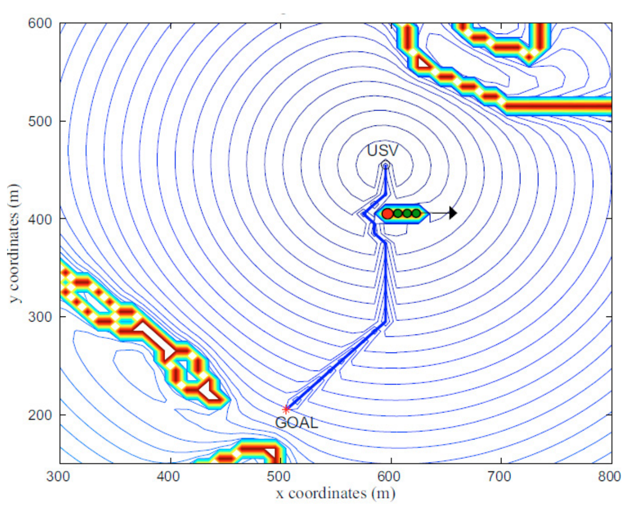
It can be summarised on the basis of the results presented in this work that the proposed APF method offer an effective solution to the online COLREGs path planning problem. The proposed technique is shown to handle static, dynamic and multiple obstacles simultaneously. A method to avoid local minima was also presented. This is done by regenerating the entire path in every sampling interval. However, it is difficult to tune gains to achieve specific clearances, as the magnitude is not directly proportional to the clearance distance of objects. A repulsive region does not guarantee no access to that zone and depends on the relative strength of other attractive and repulsive sources. Also, adjusting one parameter independently has a relative effect on the entire field.



(a) Crossing scenario – initial path



(b) Crossing scenario – mid manoeuvre



(c) Path replanning for the stand-on vessel

Fig. 4. Crossing scenario – successful COLREGs-compliant navigation showing (a) initial path; (b) when the risk is identified; (c) path replanning stage

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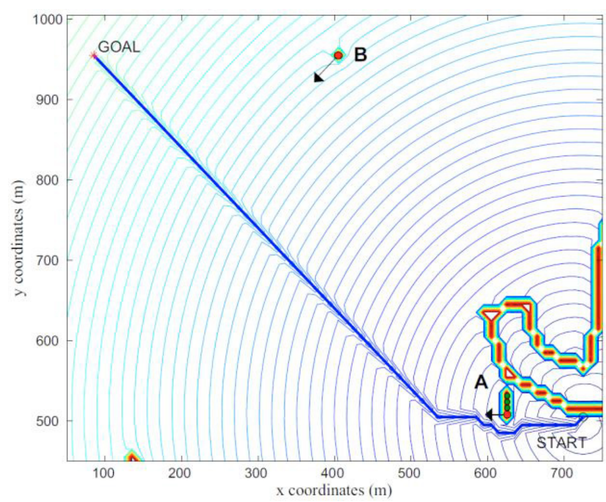
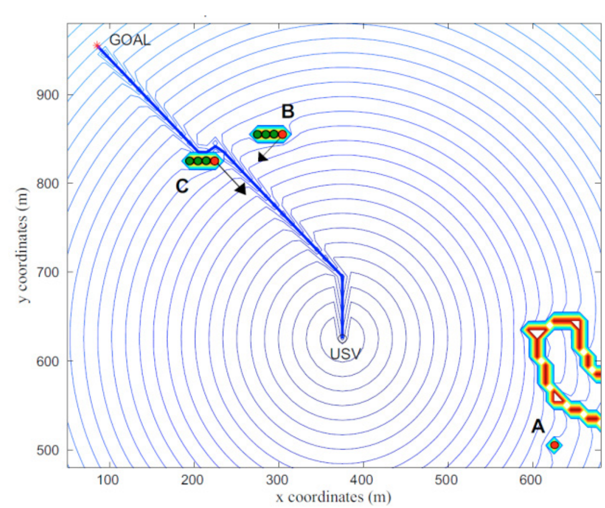
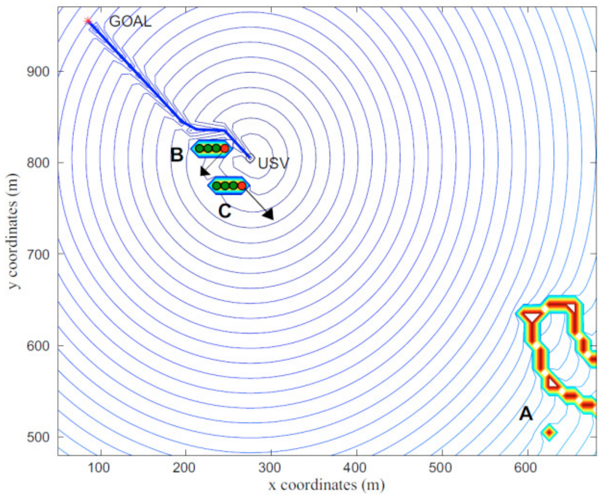


(a) Multivessel encounter - Overtaking first target ship.



(b) Multivessel encounter – Simultaneous head-on and crossing scenarios.



(c) Successful COLREGs-complaint navigation.

Fig. 5. Multivessel encounter showing single vessel overtake followed by simultaneous crossing and headon scenarious.

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