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Safe Maritime Navigation with COLREGS Using Velocity Obstacles

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Abstract— **This paper presents a motion planning algorithm for Unmanned Surface Vehicles (USVs) to navigate safely in dynamic, cluttered environments. The proposed algorithm not only addresses Hazard Avoidance (HA) for stationary and moving hazards but also applies the International Regulations for Preventing Collisions at Sea (known as COLREGS). The COLREGS rules specify, for example, which vessel is responsible for giving way to the other and to which side of the "stand-on" vessel to maneuver. The three primary COLREGS rules were considered in this paper: crossing, overtaking, and head-on situations. For USVs to be safely deployed in environments with other traffic boats, it is imperative that the USV's navigation algorithm obey COLREGS. Note also that if other boats disregard their responsibility under COLREGS, the USV will still apply its HA algorithms to avoid a collision. The proposed approach is based on Velocity Obstacles, which generates a cone-shaped obstacle in the velocity space. Because Velocity Obstacles also specify which side of the obstacle the vehicle will pass during the avoidance maneuver, COLREGS are encoded in the velocity space very naturally. The algorithm is demonstrated via both simulation and on-water tests.**

Index Terms— **COLREGS, Velocity Obstacles, Maritime Navigation, USV**

I. INTRODUCTION

In recent years, significant advancements have been made in the capabilities of Unmanned Surface Vehicles (USVs), and their intended operating regions increasingly include environments shared with other boats. As USVs are operated in situations with other manned or unmanned vessels, they must be able to safely avoid other vessels. In maritime navigation, vessels should obey the International Regulations for Preventing Collisions at Sea (known as COLREGS), agreed to by the International Maritime Organization (IMO) in 1972 [1]. These "rules of the road" specify the type of maneuvers that should be taken in certain situations where there is risk of collision. When USVs are operated with other vessels, its navigation algorithm must abide by COLREGS, so that the USVs can safely avoid other vessels and the drivers of other vessels can expect a certain safe behaviors from USVs. There have been variety of approaches to maritime navigation obeying COLREGS proposed in the past, such as fuzzy logic [2], [3], evolutionary algorithm [4], neural network, hybrid of these algorithms [5], interval programming [6], and 2D grid map [7]. However, they do not scale well with multiple traffic boats with multiple COLREGS rules, especially on robotic platforms with real-time computational requirements. Furthermore, most results are limited in simulation where uncertainties of USV motion, computational and communication delays, and noises in the perception system are not present.

When the goal is to simply avoid moving obstacles, the Velocity Obstacle (VO) approach has been adopted by several researchers. Since it was first proposed in 1998 [8], several extensions to VO have been made, including a cooperative form of collision avoidance [9], probabilistic velocity obstacles [10], [11], and crowd simulation [12]. VO approaches generate a cone-shaped obstacle in the velocity space (hence the name Velocity Obstacles) and ensures that there will be no future collisions as long as robot's velocity vector is outside of the VO. In order to identify the risk of future collisions, one could predict both the pose of the moving hazard and the pose of the robot at several future time steps, and perform collision checks using their configurations at each time slice. This approach has the advantage that it can check collisions of vehicles following arbitrary trajectories. However, because it needs to perform collision checks at many time slices, the computational load can become very high. On the other hand, VO makes a first-order (linear) prediction, and the collision check is done in the velocity space. Because one collision check accounts for collision checks at all future times (under the linear velocity assumption), VO is very fast to compute and is well-suited for robotic applications, where the algorithm is implemented on embedded systems that have limited computational resources and hard real-time requirements.

This paper extends the VO in the context of maritime navigation obeying COLREGS. In particular, we use VO to avoid moving and static hazards, but also generate an additional set of constraints in the velocity space when the USV is in certain COLREGS situations. Because both VO and COLREGS are defined in vehicle's body-fixed frame, COLREGS constraints are expressed together with VO in a very natural way.

The rest of the paper is organized as follows. Section II describes the subset of COLREGS situations we address and discusses some challenges. Section III briefly reviews Velocity Obstacles and describes the motion planning algorithm

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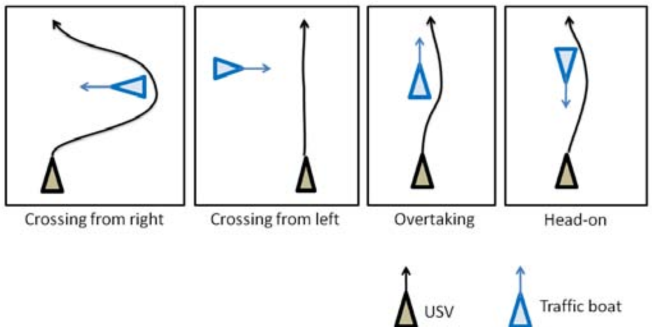


Fig. 1. Maneuvers required for various COLREGS situations

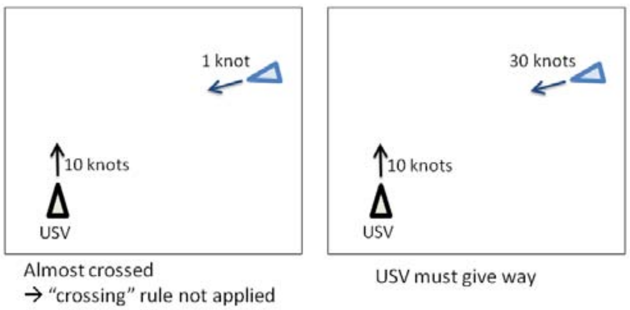


Fig. 2. An example illustrating that COLREGS might or might not apply even with the identical geometric setup.

for COLREGS navigation. Section IV shows the simulation results as well as several runs from on-water tests.

II. Review of COLREGS

The work presented in this paper addresses the following three primary COLREGS situations: crossing, head-on, and overtaking. Figure 1 illustrates the rules in these situations. The dark triangle represents the robot (USV), and the blue triangle represents the traffic boat. In the left-most figure, the traffic boat is crossing from the right. The COLREGS rule states that in this situation, the vessel that has the other on its starboard (right) side must give way [1]. Therefore, the USV (the "give-way" vessel) must avoid the traffic boat (the "stand-on" vessel), and the traffic boat does not need to alter its path. In the second left figure, the traffic boat is crossing from the left. In this case, the traffic boat is the give-way vessel, and USV should be allowed to maintain its course. In the third subfigure, the USV is overtaking a slow traffic boat. In this situation, USV must ensure enough clearance, so that it keeps out of the way of the traffic boat being overtaken. Although COLREGS do not specify which side of the boat it must overtake, common practice on the water is that the overtaking boat should pass on the right side of the traffic boat. In the right-most figure, the USV and the traffic boat are moving straight towards each other, head-on. Here, both vessels must alter their course toward the starboard, so that they pass with the other vessel to its port (left) side.

Even for a simple scenario, whether or not a COLREGS rule applies is not a trivial evaluation, especially as the rules are written for human operators and often include subjective measures. Nor is the evaluation a simple function of vehicle geometry (e.g., bearing angle or distance) and/or vehicle heading. For example, as shown in Figure 2, even when the traffic vessel and USV are in the same geometric configuration, the crossing rule might or might not apply, depending on their speed.

III. COLREGS Motion Planner

A. Problem Statement

The problem considered in this paper is stated as follows. *Given*

- *a near-term waypoint,*
- *a reference speed, and*
- *a list of objects representing moving and static hazards,*

find the best velocity command that avoids the hazards and obeys COLREGS.

B. Review of Velocity Obstacles

This subsection briefly reviews the basic idea of Velocity Obstacles [8], which provides a foundation for our approach. Let us first introduce some mathematical notations. Let $\boldsymbol{p} \in \mathbb{R}^2$ denote the robot's position vector and $\boldsymbol{v} \in \mathbb{R}^2$ denote the velocity vector in two dimensional space. A ray starting from $\boldsymbol{p}$ going into the direction of $\boldsymbol{v}$ is defined as

$$\lambda(\boldsymbol{p}, \boldsymbol{v}) = \{\boldsymbol{p} + t\boldsymbol{v} \mid t \geq 0\}. \tag{1}$$

Furthermore, the following set operations are used to express the VO.

$$\text{Minkowski sum:} \quad \mathcal{A} \oplus \mathcal{B} = \{\boldsymbol{a} + \boldsymbol{b} \mid \boldsymbol{a} \in \mathcal{A}, \boldsymbol{b} \in \mathcal{B}\} \tag{2}$$

$$\text{Reflection:} \quad -\mathcal{A} = \{-\boldsymbol{a} \mid \boldsymbol{a} \in \mathcal{A}\} \tag{3}$$

Given a robot of shape $\mathcal{A}$ and a obstacle of shape $\mathcal{B}$ moving at velocity $\boldsymbol{v}_B$, the VO in the velocity space of robot A is given as

$$VO^A_B(\boldsymbol{v}_B) = \{\boldsymbol{v}_A \mid \lambda(\boldsymbol{p}_A, \boldsymbol{v}_A - \boldsymbol{v}_B) \cap (\mathcal{B} \oplus -\mathcal{A}) \neq \emptyset\} \tag{4}$$

where $\boldsymbol{p}_A$ and $\boldsymbol{p}_B$ are the position of the robot and the obstacle, and $\boldsymbol{v}_A$ and $\boldsymbol{v}_B$ are their velocity vectors, respectively. A simple interpretation of (4) is that the ray starting from robot A and going in the direction the relative velocity $(\boldsymbol{v}_A - \boldsymbol{v}_B)$ intersects the obstacle $\mathcal{B}$ expanded by the robot size $\mathcal{A}$. The reason of this C-space expansion is to treat the vehicle as a point. Figure 3 graphically shows the VO using a rectangular robot and a rectangular moving hazard. As shown in this example, a VO is a cone in the velocity space.

As long as the robot's velocity lies outside of VO, it will not collide the obstacle, assuming that the velocity vectors are constant over time. If the velocity vectors change over time, the VO-based approach simply reacts and replans using the latest information of the world. When the replanning rate is much faster than the change in configuration, this assumption of linear velocities is reasonable. In our maritime applications, the replan rate was 1Hz on an embedded system[1], and the angular velocity of the boat is typically less than 30 degrees per second.

[1]This replan rate could be increased, as the motion planning computation itself is very fast (on order of several msec).

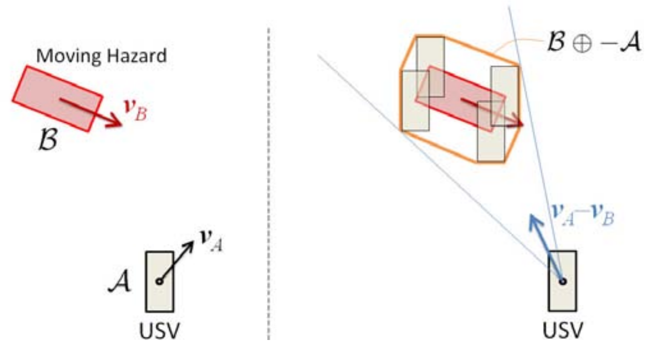


Fig. 3. Graphical interpretation of Velocity Obstacles. When the relative velocity of the robot $\boldsymbol{v}_A - \boldsymbol{v}_B$ points inside the cone formed by the robot center and the expanded obstacle $\mathcal{A} \oplus \mathcal{B}$, they will collide. The VO imposed on robot's velocity $\boldsymbol{v}_A$ is this cone shifted by a vector $\boldsymbol{v}_B$.

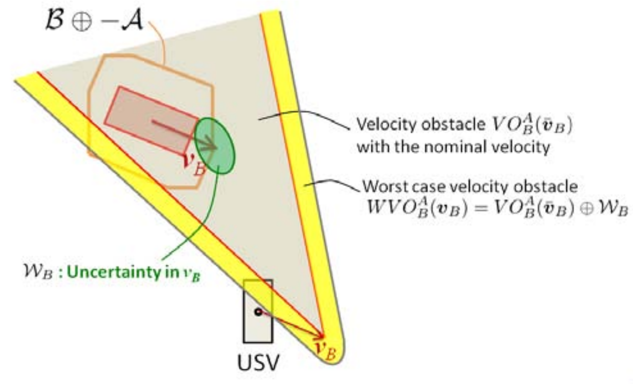


Fig. 4. Worst case Velocity Obstacle when there is uncertainties in the velocity of the moving obstacle

When there are multiple agents, simply overlaying the VO of each vehicle and taking a superposition generate a set of constraints on robot's feasible velocity vector. The run time of the VO-based approach is at worst linear with the number of hazards considered.

C. Time-to-collision

When the velocity $\boldsymbol{v}_A$ is inside the velocity obstacle, the time-to-collision τ can be obtained by computing the time it takes for the relative velocity vector $\boldsymbol{v}_A - \boldsymbol{v}_B$ to hit the boundary of $\mathcal{A} \oplus \mathcal{B}$, i.e.,

$$\boldsymbol{p}_A + \tau(\boldsymbol{v}_A - \boldsymbol{v}_B) \in \partial(\mathcal{B} \oplus -\mathcal{A}) \tag{5}$$

where $\partial(\cdot)$ denotes the boundary of the set. If there are multiple τ's that satisfy (5), the one with the minimum value is selected.

D. Uncertainty Handling

The motion planner that is deployed in the real world must account for various types of uncertainties. Moving hazards are detected and tracked using on-board sensors such as radar [13], cameras [14], and lidar. The tracked traffic boat then has inherent sensing noise and state estimation errors.

Another source of uncertainty comes from the uncertain motion of the moving hazards. VO assumes constant velocities of the moving agents, but in reality their motion does not necessarily retain a constant velocity. In order to account for such uncertainties in the traffic vehicle, its velocity $\boldsymbol{v}_B$ is modeled as $\boldsymbol{v}_B = \bar{\boldsymbol{v}}_B + \boldsymbol{\delta}_B$, where $\bar{\boldsymbol{v}}_B$ is the nominal velocity (i.e., the expected velocity that is estimated by the vehicle tracker), and $\boldsymbol{\delta}_B$ contains the uncertainties of the vehicle velocity. We assume that the uncertain component of the velocity lies in a set $\boldsymbol{\delta}_B \in \mathcal{W}_B$, where $\mathcal{W}_B$ is a bounded set and treated as constant. Then, the velocity obstacle with the worst-case uncertainty (denoted by "WVO") is written as

$$WVO_B^A(\boldsymbol{v}_B) = VO_B^A(\bar{\boldsymbol{v}}_B) \oplus \mathcal{W}_B. \tag{6}$$

Figure 4 shows the same case that was shown in Figure 3 but with uncertainties. The gray cone shows the VO with the nominal velocity. In this example, the moving hazard B has a velocity uncertainty $\mathcal{W}_B$, which is drawn with a green ellipse centered at the nominal velocity $\bar{\boldsymbol{v}}_B$. The worst case VO, shaded with yellow, is slightly larger than the nominal VO, and the boundary lines are parallel to those of VO. As shown later, the VO is treated as a hard constraint, but the region $\mathcal{W}_B$ of WVO is treated as a soft constraint that serves as a safety buffer.

E. VO with COLREGS

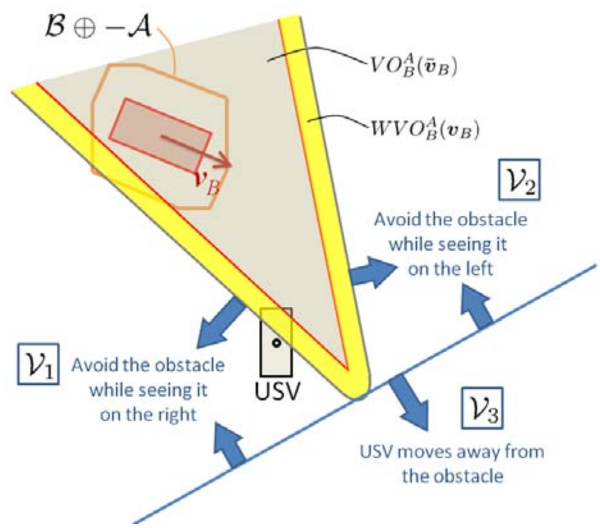


Fig. 5. Constraints in the velocity space imposed by COLREGS

VO is a set of constraints in the USV's velocity space in order to avoid moving obstacles. Our approach treats COLREGS as an additional set of constraints in the velocity space. One advantage of using VO to encode COLREGS is that the VO already has the information on which side of the hazard that the USV will pass. Figure 5 shows a single VO and a feasible velocity space divided into three regions. The line dividing $\mathcal{V}_3$ from $\mathcal{V}_1$ and $\mathcal{V}_2$ is tangent to $WVO_B^A(\boldsymbol{v}_B)$ and is perpendicular to the centerline of the VO cone, which is parallel to $\boldsymbol{p}_B - \boldsymbol{p}_A$, the line connecting the center of the USV and the center of the moving obstacle.

When USV follows a velocity in $\mathcal{V}_3$, the relative velocity of USV points away from the obstacle, i.e.,

$$(\boldsymbol{p}_B - \boldsymbol{p}_A) \cdot (\boldsymbol{v}_A - \boldsymbol{v}_B) < 0, \quad \forall \delta_B \in \mathcal{W}_B.$$

so that the vehicles do not approach any closer.

When USV follows a velocity in $\mathcal{V}_1$,

$$\begin{aligned}\mathcal{V}_1 = \{\boldsymbol{v} \mid \ & \boldsymbol{v} \notin WVO_B^A(\boldsymbol{v}_B), \quad \boldsymbol{v} \notin \mathcal{V}_3, \\ & \exists \delta_B \in \mathcal{W}_B \text{ s.t. } [(\boldsymbol{p}_B - \boldsymbol{p}_A) \times (\boldsymbol{v}_A - \boldsymbol{v}_B)]_z < 0\}\end{aligned}$$

then, the USV will pass the obstacle while seeing it on the right side of USV. The operator $[\cdot]_z$ denotes that it extracts the z component of the vector. We use the conventional body-fixed frame, with $+x$ pointing forward, $+y$ pointing right, and $+z$ pointing downward. This region $\mathcal{V}_1$ is treated as inadmissible when the USV is overtaking the traffic vessel B, when they are in a head-on situation, and when the traffic vessel B is crossing from the right. Note that when $\boldsymbol{v}_A \in \mathcal{V}_1$, USV will see the vessel B on the starboard side, cutting in front of the vessel B.

This rule-based constraint $\boldsymbol{v}_A \notin \mathcal{V}_1$ ensures that the USV will only pass from the right (when $\boldsymbol{v}_A \in \mathcal{V}_2$) or do not pass (when $\boldsymbol{v}_A \in \mathcal{V}_3$).

Note that when the vessel B is crossing from left, there is no COLREGS constraints on USV because vessel B is responsible for avoiding the USV. Even without the COLREGS constraint, however, VO always exists and hence USV will avoid any moving hazard—this is necessary for ensuring safety in case vessel B violates COLREGS and does not take any avoidance maneuver. Similarly, while being overtaken, no COLREGS constraints are applied.

F. Algorithm Flow

The first step in the algorithm flow is done by a rule selector, whose role is to detect if a moving vessel is in a specific COLREGS situation with the USV. As illustrated in Figure 2, it is not enough to analyze the geometric relation between the USV and moving hazards.

1) Pre-collision Check: The rule selector first computes CPA (Closest Point of Approach) with the current poses (i.e., position, orientation, and velocity) of USV and traffic vessels, and evaluate if any COLREGS rules needs to be applied at all. This approach is more efficient than computing CPA for every potential USV velocity with every moving vessel.

Given two points $\boldsymbol{p}_A$, $\boldsymbol{p}_B$ and their velocity vectors $\boldsymbol{v}_A$, $\boldsymbol{v}_B$, the time to CPA t_{CPA} is given by

$$t_{\text{CPA}} = \begin{cases} 0 & \text{if } \|\boldsymbol{v}_A - \boldsymbol{v}_B\| \leq \epsilon \\ \dfrac{(\boldsymbol{p}_A - \boldsymbol{p}_B) \cdot (\boldsymbol{v}_A - \boldsymbol{v}_B)}{\|\boldsymbol{v}_A - \boldsymbol{v}_B\|^2} & \text{otherwise.} \end{cases} \tag{7}$$

The distance at CPA d_{CPA} is then computed by

$$d_{\text{CPA}} = \|(\boldsymbol{p}_A + \boldsymbol{v}_A t_{\text{CPA}}) - (\boldsymbol{p}_B + \boldsymbol{v}_B t_{\text{CPA}})\|. \tag{8}$$

For each moving vessel, the motion planner will examine whether COLREGS rules apply only if the situation is likely to lead to a collision or a near-collision in the near future—that is, by checking if

$$0 \leq t_{CPA} \leq t_{max}, \quad \text{and} \quad d_{CPA} \leq d_{min}. \tag{9}$$

2) Rule Selection: Once the CPA meets the condition (9), the rule selector identifies which COLREGS situation applies. Because the "crossing from left" and "crossing from right" require USV to perform distinctly different maneuvers, the rule selector considers the following four rules: overtake, head-on, crossing from left, and crossing from right.

The rule selector decides that it is in a overtake situation when the following conditions are all satisfied.

- Distance: $\|\boldsymbol{p}_A - \boldsymbol{p}_B\| \leq D_{\max}$
- Heading: $|h_A - h_B| \leq h_{\max}$
- Cross-track: $y_B \leq y_{\max}$
- Along-track: $x_B \geq x_{\min}$

where h_A and h_B are the heading direction of the current velocity vector, (x_B, y_B) are the vehicle B's position measured in A's body-fixed frame.

Similarly, it is considered to be in head-on situation when the following conditions are all satisfied.

- Distance: $\|\boldsymbol{p}_A - \boldsymbol{p}_B\| \leq D_{\max}$
- Heading: $|h_A - h_B + \pi| \leq h_{\max}$
- Cross-track: $y_B \leq y_{\max}$
- Along-track: $x_B \geq x_{\min}$

It is considered to be in "crossing from right" when the following conditions are all satisfied.

- Heading: $h_{\min} \leq h_B - h_A \leq h_{\max}$
- Bearing: $b_{\min} \leq b_B \leq b_{\max}$
- Heading–Bearing relation: $h_B > b_B - \pi$
- Cross-track: $y_B \geq y_{\min}$

where b_B denotes the relative bearing of B from the USV. The third bullet is to ensure that the moving hazard is not coming behind the USV.

It is considered to be in "crossing from left" when the following conditions are all satisfied.

- Heading: $h_{\min} \leq h_B - h_A + \pi \leq h_{\max}$
- Cross-track: $y_B \leq -y_{\min}$

3) Hysteresis: If a completely new decision is made at every time step, as in the CPA-based rule selection discussed above, the USV could lead to a chattering behavior. This is because the uncertainty in the situational awareness could make the COLREGS constraints turn on and turn off very frequently, which drastically changes the feasible region of the decision space, as shown in $\mathcal{V}_1$ of Figure 5.

In order to alleviate churning, we introduce the hysteresis to the rule selector and lower the bandwidth of the system. It also has a benefit that once a COLREGS maneuver (e.g., overtaking, crossing) is initiated, it continues to execute the maneuver for a duration of time, thereby making the USV's decision more obvious and predictable to human drivers on other vessels.

Because the moving obstacles are output of a vehicle tracker, each moving obstacle has a unique tracking ID associated [14]. Using this vehicle ID, we maintain a short history of vehicle–rule pairs, i.e., which vehicle meets the criteria of which rule discussed in Subsection III-F.2. If a vehicle meets the criteria of a certain COLREGS rule, it is considered to be in a COLREGS situation. However, even if a vehicle does not meet the criteria at the current time step, as long as the vehicle met the criteria in any of the last n_h time steps, we still apply the corresponding COLREGS rule. The parameter n_h is a length of the hysteresis and controls how often the USV can "change its mind" in the COLREGS situations. If the vehicle does not meet the criteria n_h times in a row, then the corresponding vehicle–rule pair is removed from the memory.

Note that multiple COLREGS rules could be active at the same time with the same traffic vehicle. For example, if the boat is coming from a diagonal direction around the boundary of crossing and head-on direction, one might want to apply both rules to in order to account for the sensing noise and ensure vehicle safety. Constraints in VO can be easily generated by simply superposing each COLREGS-based constraint.

4) Costing: We use a regular discrete grid in the v–θ space to find the best velocity vector. Once the constraint sets of VO and COLREGS are generated, for each v_i and θ_j that is still admissible, compute the following cost

$$J_{ij} = \frac{w_\tau}{\tau_{ij}} + w_v \left\| \boldsymbol{v}_{\text{ref}} - \begin{bmatrix} v_i \cos\theta_j \\ v_i \sin\theta_j \end{bmatrix} \right\|_Q \tag{10}$$

where w_τ is a weight on the time-to-collision, $\boldsymbol{v}_{\text{ref}}$ is a desired velocity to reach the next far-term goal, w_v is a weight on the deviation from desired velocity, and $\| \cdot \|_Q$ is a weighted two-norm of a vector. If $(v_i, \theta_j) \in WVO$ and $(v_i, \theta_j) \notin VO$, then the weight w_τ on time-to-collision is reduced in order to soften the constraints on WVO.

Once all the cost is computed, the (v_i, θ_j) pair with the minimum cost is selected and the velocity command is sent to the vehicle controller.

Even though VO "looks ahead" the future of the robot and moving agents, it is possible to construct a case where the robot is trapped because VO is a local planner. Such situation is unlikely to happen, especially for on-water applications, where there are typically a few vehicle to avoid simultaneously. If one needs to generate a path in a maze-like environment, while avoiding moving hazards, it can be combined with a global path planner that takes into account the obstacles at a longer rage.

IV. Results

A. Simulation Results

Figure 6 shows a snapshot of a simulation run, involving one USV at the bottom and two moving vessels. The way-point of the USV is set in front of the vehicle start location. There is a traffic boat coming from the right. The USV recognizes it is in a crossing situation and starts maneuvering towards starboard.

The colored region around the USV represents the velocity decision space. The blue line from the USV is the best velocity found by the algorithm. As shown in the lower right of the figure, the green region has a safe velocity, the red region represents VO, the yellow region is the region expanded by WVO, and the purple region represents a COLREGS violation ("crossing" rule in this figure). Because the cost is continuous the color has some shading.

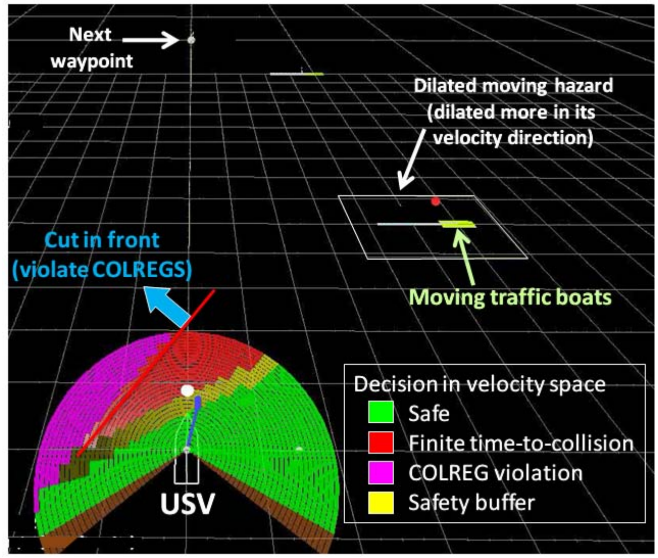


Fig. 6. Snapshot of a simulation run. USV is in a crossing situation.

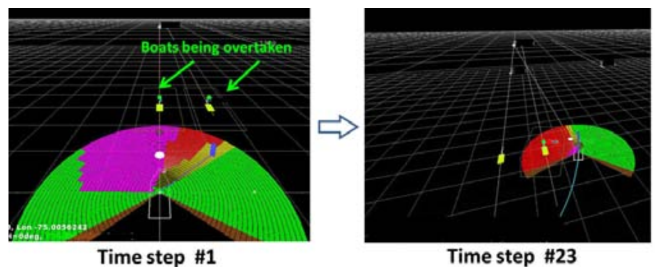


Fig. 7. Snapshot of a simulation run. Left: USV is initially in a overtaking situation. Right: USV overtakes both moving obstacles.

Figure 7 shows another snapshot of a simulation run, involving one USV and two moving vessel. All three are moving in the same direction initially (left figure). Because the spacing between the two traffic vessels is small, USV decides to overtake both of them at the same time. Note the purple region shown in the decision space forces the USV to overtake from the starboard side. The right figure shows a snapshot where the overtake is almost complete.

The setup in Figure 8 is similar to the one shown in Figure 7, but the traffic boats are coming towards the USV. The COLREGS constraints encourages the head-on evasive maneuver to turn right by prohibiting velocities to the left.

The run time of the motion planning algorithm of each cycle was about $1ms$ on a 32-by-128 velocity space grid on a PC104 running Qnx. As mentioned before, the run time is approximately linear with respect to the number of obstacles. Even with 20 or more moving hazards, it is still well-suited to run in real-time.

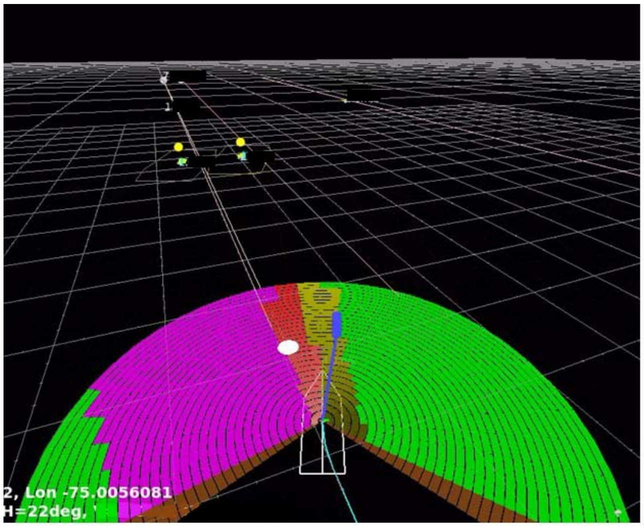
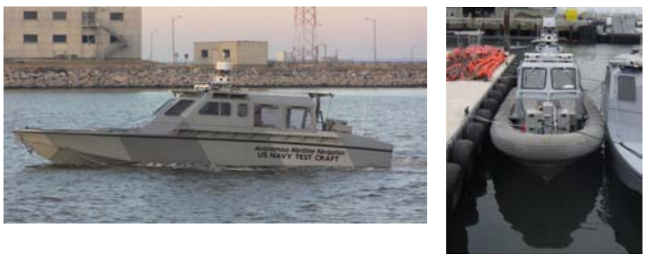
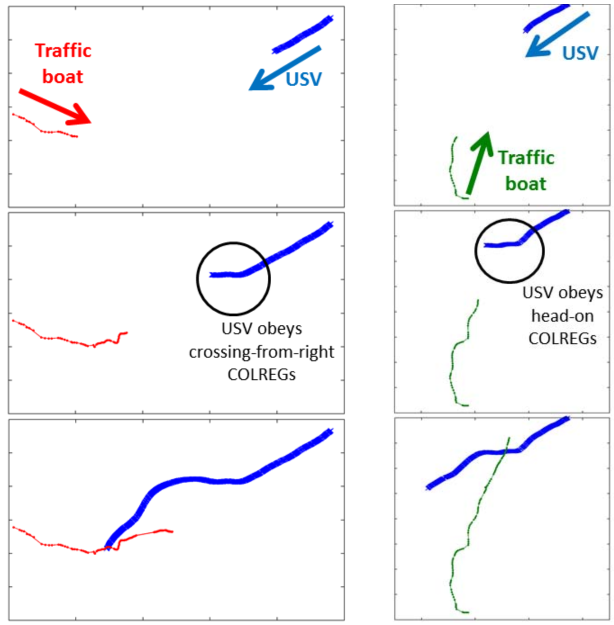


Fig. 8. Snapshot of a simulation run during a head-on situation.



(a) PowerVent – the USV (b) 11m RHIB – the traffic boat

Fig. 9. Boats used in the on-water testing



(a) Crossing from right (b) Head-on

Fig. 10. On-water test results

B. On-water Test Results

The COLREGS algorithm was integrated within JPL's autonomy suite called CARACaS (Control Architecture for Robotic Agent Command and Sensing) [15] that can receive vehicle state estimates from an INS unit and perception outputs such as hazard lists from the JPL stereo server [14] or SIS world map server [13]. CARACaS commands the USV through its CAN bus.

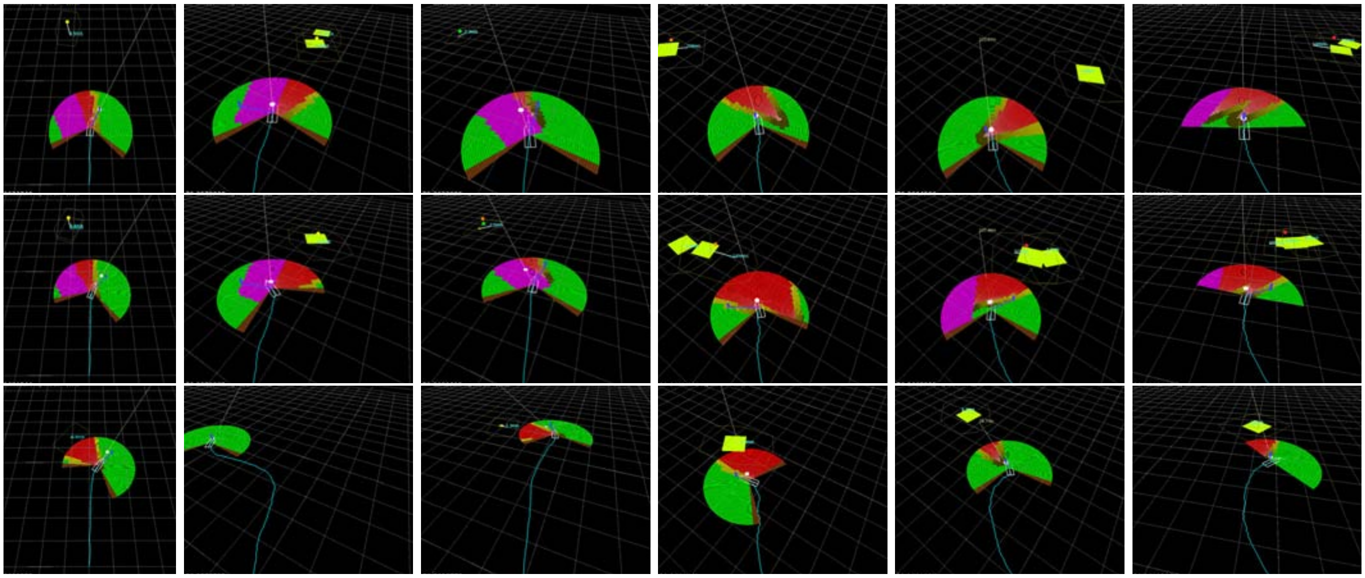
The current perception module can estimate the position and the velocity of the traffic boat, but not its orientation. The heading estimate of the traffic boat becomes more noisy when the speed of the traffic boat is very low. For those moving slower than a threshold, COLREGS constraints are not applied.

Figure 9(a) shows the USV, called Powervent, used in the test. The vehicle speed of 5 to 12 knots were used in the tests. Powervent has been tested on the water within CARACaS to demonstrate various capabilities in the past including harbor patrol, boat following, and static hazard avoidance [13]. Figure 9(b) shows the 11-m RHIB, a traffic boat to generate COLREGS situations.

Figure 10(a) shows the paths of the USV (marked in blue) and the traffic boat (marked in red) during the "crossing from right" situation encountered in the field tests. As shown in the top figure, the USV is initially in the upper right of the plot and is moving towards the lower left part of the figure. The traffic boat is initially in the left of the figure and is moving towards the lower middle of the figure. The traffic boat slowed down in front of USV, so that the rule selector realizes that it is now in the crossing situation, and the USV alters its path to its starboard, as shown in the middle figure. The bottom figure shows that after avoiding the traffic boat, the USV heads towards the original direction of travel. Note that the path of the perceived traffic boat is much more noisy compared to that of the USV.

Figure 10(b) shows a head-on scenario. The USV path is plotted in blue, and the path of the traffic boat is plotted in green. As shown in the top figure, they were initially heading towards each other. The driver of the traffic boat let it go straight, and the USV avoided it by changing its course towards its starboard side, as shown in the middle figure. Note that if the USV knew that traffic boat would maintain its heading (as assumed by VO), it would have been less costly for USV to avoid it by steering left. However, because of COLREGS, the traffic boat was expected to turn toward its right in this head-on situation, and hence the USV also turned towards its right. The bottom figure shows the successful handling of the head-on situation.

Figure 11 shows further set of on-water testing results. In (a), the USV steers to its right when seeing a head-on vehicle. In (b), a head-on vehicle is detected, but because USV's waypoint goal is to the left and there still is enough distance to the head-on vehicle, it decides to avoid to its left. In (c), the USV overtakes a vehicle on the left. The traffic boat veers to the right, and USV further changes its course to the right. In (d), the vehicle crossing from the left did not follow COLREGS, and USV made an emergency avoidance maneuver once they come close. In (e) and (f), the USV obeys the crossing-from-right rule.



(a) Head-on (b) Head-on (c) Overtake (d) Crossing from left (e) Crossing from right (f) Crossing from right

Fig. 11. More on-water test runs with traffic boats detected by stereo cameras. The figures on the top row show when the COLREGS start being applied. The figures on the middle row show when COLREGS force the USV to steer away from the waypoint goal direction. The figures on the bottom row show the results of successful avoidance maneuvers, at which time the COLREGS become inactive.

V. CONCLUSION

This paper presented a COLREGS navigation algorithm using Velocity Obstacles. By identifying which side of the obstacle the VO-based maneuver would pass, COLREGS constraints are naturally expressed in the velocity space together with traditional VOs. Several extensions are also presented, including the pre-collision check using CPA, the safety buffer to account for uncertain movement of moving hazards, and hysteresis to the rule to ensure that the COLREGS maneuver lasts for some duration and is obvious to other drivers. The algorithm was integrated with CARACaS and has been successfully demonstrated on water with radar and stereo as the perception sensors.

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REFERENCES

[1] U.S. Department Of Homeland Security, U.S. Coast Guard, *Navigation Rules*. Paradise Cay Publications, 2010.

[2] S.-M. Lee, K.-Y. Kwon, and J. Joh, "A Fuzzy Logic for Autonomous Navigation of Marine Vehicles Satisfying COLREG Guidelines," *International Journal of Control, Automation, and Systems*, vol. 2, no. 2, pp. 171–181, 2004.

[3] L. P. Perera, J. P. Carvalho, and C. G. Soares, "Autonomous guidance and navigation based on the COLREGs rules and regulations of collision avoidance," in *In Proceedings of the International Workshop "Advanced Ship Design for Pollution Prevention"*, 2009, pp. 205–216.

[4] J. Colito, "Autonomous Mission Planning and Execution for Unmanned Surface Vehicles in Compliance with the Marine Rules of the Road," Master's thesis, University of Washington, 2007.

[5] T. Statheros, G. Howells, and K. M. Maier, "Autonomous Ship Collision Avoidance Navigation Concepts, Technologies and Techniques," *Journal of Navigation*, vol. 61, no. 1, pp. 129–142, 2008.

[6] M. Benjamin, J. Curcio, and P. Newman, "Navigation of Unmanned Marine Vehicles in Accordance with the Rules of the Road," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2006.

[7] K. Teo, K. W. Ong, and H. C. Lai, "Obstacle Detection, Avoidance and Anti Collision for MEREDITH AUV," in *OCEANS, MTS/IEEE Biloxi - Marine Technology for Our Future: Global and Local Challenges*, 2009.

[8] P. Fiorini and Z. Shiller, "Motion Planning in Dynamic Environments Using Velocity Obstacles," *International Journal of Robotics Research*, vol. 17, no. 7, pp. 760–772, 1998.

[9] J. van den Berg, M. Lin, and D. Manocha, "Reciprocal Velocity Obstacles for Real-Time Multi-Agent Navigation," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2008, pp. 1928–1935.

[10] B. Kluge and E. Prassler, "Reflective Navigation: Individual Behaviors and Group Behaviors," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2004.

[11] C. Fulgenzi, A. Spalanzani, and C. Laugier, "Dynamic Obstacle Avoidance in uncertain environment combining PVOs and Occupancy Grid," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2007.

[12] J. van den Berg, S. Patil, J. Sewall, D. Manocha, and M. C. Lin, "Interactive Navigation of Multiple Agents in Crowded Environments," in *Symposium on Interactive 3D Graphics and Games*, 2008.

[13] L. Elkins, D. Sellers, and W. R. Monach, "The autonomous maritime navigation (AMN) project: Field tests, autonomous and cooperative behaviors, data fusion, sensors, and vehicles," *Journal of Field Robotics*, vol. 27, no. 6, pp. 790–818, 2010.

[14] T. Huntsberger, H. Aghazarian, A. Howard, and D. C. Trotz, "Stereo visionbased navigation for autonomous surface vessels," *Journal of Field Robotics*, vol. 28, no. 1, pp. 3–18, 2011.

[15] T. Huntsberger, H. Aghazarian, A. Castano, G. Woodward, C. Padgett, D. Gaines, and C. Buzzell, "Intelligent autonomy for unmanned sea surface and underwater vehicles," in *In AUVSI Unmanned Systems North America*, 2008.