Safe Maritime Autonomous Navigation With COLREGS, Using Velocity Obstacles

Yoshiaki Kuwata, Michael T. Wolf, Dimitri Zarzhitsky, and Terrance L. Huntsberger, *Senior Member, IEEE*

***Abstract*—This paper presents an autonomous motion planning algorithm for unmanned surface vehicles (USVs) to navigate safely in dynamic, cluttered environments. The 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, for COLlision REGulationS). 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. Three primary COLREGS rules are considered in this paper: crossing, overtaking, and head-on situations. For autonomous USVs to be safely deployed in environments with other traffic boats, it is imperative that the USV's navigation algorithm obeys COLREGS. Furthermore, when other boats disregard their responsibility under COLREGS, the USV must fall back to its HA algorithms to prevent a collision. The proposed approach is based on velocity obstacles (VO) method, which generates a cone-shaped obstacle in the velocity space. Because VOs also specify on which side of the obstacle the vehicle will pass during the avoidance maneuver, COLREGS are encoded in the velocity space in a natural way. Results from several experiments involving up to four vessels are presented, in what we believe is the first on-water demonstration of autonomous COLREGS maneuvers without explicit intervehicle communication. We also show an application of this motion planner to a target trailing task, where a strategic planner commands USV waypoints based on high-level objectives, and the local motion planner ensures hazard avoidance and compliance with COLREGS during a traverse.**

***Index Terms*—COLREGS, unmanned surface vehicle (USV), velocity obstacles (VOs).**

I. Introduction

In recent years, significant technological advancements have increased onboard capabilities of unmanned surface vehicles (USVs), so that their intended mission scenarios now routinely include environments shared with other seagoing traffic [1], [2]. Consequently, as autonomous USVs are operated alongside other manned and unmanned vehicles, they must be able to safely avoid other vessels. In maritime navigation, ships should obey the International Regulations for Preventing Collisions at Sea (known as COLREGS, for COLlision REGulationS), agreed to by the International Maritime Organization (IMO) in 1972 [3].[1] These "rules of the road" specify the types of maneuvers that should be taken in situations where there is a risk of collision. When USVs are operated near other vessels, their navigation algorithms must abide by COLREGS, so that the USVs can safely avoid other vessels and the drivers of other vessels can rely on a range of safe behaviors from the USVs. A variety of approaches to maritime navigation obeying COLREGS have been proposed in the past, such as fuzzy logic [4], [5], evolutionary algorithms [6], neural networks, hybrids of these algorithms [7], interval programming [8], and 2-D grid maps [9]. However, these previous approaches do not scale well to multiple traffic boats and multiple COLREGS rules, especially on robotic platforms with real-time computational requirements. Furthermore, most results cited in the literature are limited to simulation, where uncertainties of USV motion, computational and communication delays, along with noise in the perception system are not present.

The velocity obstacle (VO) approach has been adopted by several researchers for moving hazard avoidance. Since it was first proposed in 1998 for robot motion planning [10], several extensions to VO have been made, including a cooperative form of collision avoidance [11], probabilistic velocity obstacles [12], [13], and crowd simulation [14]. VO approaches generate a cone-shaped obstacle in the velocity space (hence the name velocity obstacles) and ensure that there will be no future collisions as long as the robot's velocity vector is outside the VO. To identify the risk of future collisions, one could predict both the pose of the moving hazard and the pose of the robot for several time steps into the future, 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 becomes very high. On the other hand, VO makes a first-order (i.e., linear) prediction, and the collision check is done in the velocity space. Since a single collision check accounts for collision checks at all future times (due to the linear velocity assumption), VO is very fast to compute and extends well to high-speed

Manuscript received October 27, 2011; revised November 25, 2012; accepted March 18, 2013. Date of publication May 24, 2013; date of current version January 09, 2014. This work was supported by the U.S. Office of Naval Research under Contract N00014-09-IP-2-0008 and by the Defense Advanced Research Projects Agency under Contract NAS7-03001, Task #82-15473. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). This work was supported by the U.S. Office of Naval Research under Code 33 (Dr. R. Brizzolara) and by the Defense Advanced Research Projects Agency (R. McHenry and S. Littlefield). The views expressed are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government. Distribution Statement A. Approved for public release; distribution is unlimited.

Guest Editor: A. Bouchard.

Y. Kuwata was with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA. He is now with Space Exploration Technologies, Hawthorne, CA 90250 USA (e-mail: kuwata@alum.mit.edu).

M. T. Wolf, D. Zarzhitsky, and T. L. Huntsberger are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (e-mail: Michael.T.Wolf@jpl.nasa.gov; dimzar@cs.uwyo.edu; Terrance.L.Huntsberger@jpl.nasa.gov).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JOE.2013.2254214

[1]There are actually separate sets of rules for international waters and, say, inland waters in the United States. For this paper, we consider the international regulations specified by the 1972 COLREGS.

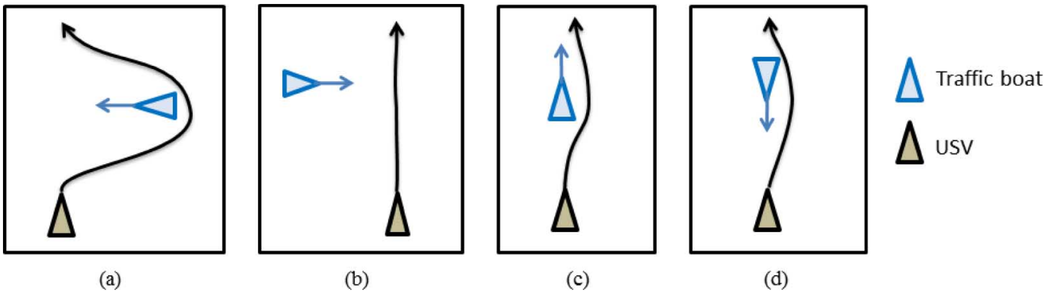


Fig. 1. Maneuvers required for various COLREGS situations (a) Crossing from right. (b) Crossing from left. (c) Overtaking. (d) Head-on.

operations with short reaction time. Furthermore, its simplicity is suited for our behavior-based control architecture.

This paper extends VO in the context of maritime navigation subject to 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 addressed, as well as some of the implementation challenges. Section III briefly reviews VOs and describes the motion planning algorithm for COLREGS navigation. Several results from on-water testing are presented in Section IV.

II. Review of COLREGS

The work presented in this paper addresses the following three primary COLREGS situations: crossing, head-on, and overtaking. Fig. 1 illustrates the rules in these situations. The dark triangle represents the robot (USV), and the blue triangle represents the traffic boat. In Fig. 1(a), 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 [3]. 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 Fig. 1(b), 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.[2] In Fig. 1(c), the USV is overtaking a slow traffic boat. In this situation, the 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 dictates that the overtaking boat should pass on the right-hand side of the traffic boat. In Fig. 1(d), the USV and the traffic boat are moving straight toward 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 in a simple scenario, whether a COLREGS rule applies is not a trivial evaluation to make, especially as the rules are written for human operators and often include subjective measures, nor is the evaluation a simple function of the vehicles' relative position (e.g., bearing angle or distance) and/or vehicle heading. For example, as shown in Fig. 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.

[2]In this paper, we assume that all surface traffic consists of roughly equivalent power-driven vessels. Different COLREGS priorities apply to sailing vessels and other special situations.

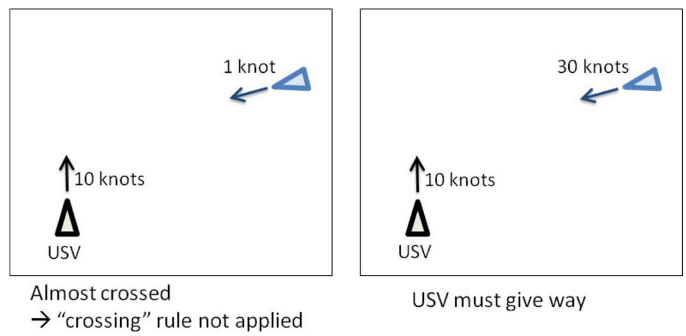


Fig. 2. An example illustrating that COLREGS might or might not apply even with the identical geometric setup.

III. COLREGS Motion Planner

We consider the following problem. Given:
- a near-term waypoint;
- a reference speed; and
- a list of contacts representing moving and static hazards;

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

A. Review of Velocity Obstacles

This section briefly reviews the VO approach to robot motion planning [10] that serves as a foundation for our work. Let us first introduce some mathematical notations. Let $\vec{p} \in \mathbb{R}^2$ denote the robot's position vector and $\vec{v} \in \mathbb{R}^2$ denote the velocity vector in a 2-D space. A ray starting from $\vec{p}$ going into the direction of $\vec{v}$ is defined as

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

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

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

$$\text{reflection:} \quad -\mathcal{A} = \{-\vec{a} \mid \vec{a} \in \mathcal{A}\}. \tag{3}$$

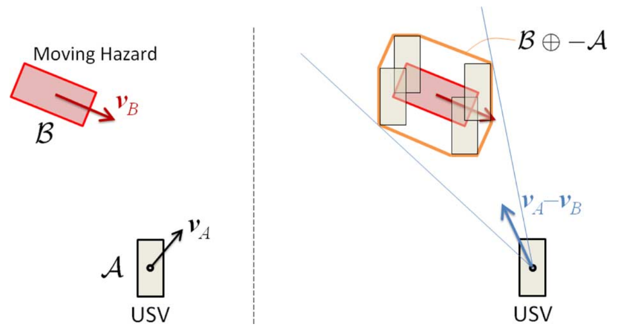


Fig. 3. Graphical interpretation of VOs. When the relative velocity of the robot $\vec{v}_A - \vec{v}_B$ points inside the cone formed by the robot center and the expanded obstacle $\mathcal{A} \oplus \mathcal{B}$, they will collide. The VO imposed on robot's velocity $\vec{v}_A$ is this cone shifted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

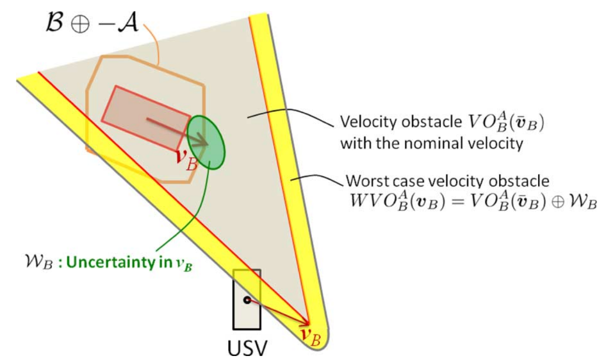


Fig. 4. Worst case VO when there are uncertainties in the velocity of the moving obstacle.

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

$$VO_B^A(\vec{v}_B) = \{\vec{v}_A \mid \lambda(\vec{p}_A, \vec{v}_A - \vec{v}_B) \cap (\mathcal{B} \oplus -\mathcal{A}) \neq \emptyset\} \quad (4)$$

where $\vec{p}_A$ and $\vec{p}_B$ are the position of the robot and the obstacle, and $\vec{v}_A$ and $\vec{v}_B$ are their velocity vectors, respectively. A simple interpretation of (4) is that the ray starting from robot A and going in the direction of the relative velocity $(\vec{v}_A - \vec{v}_B)$ intersects the obstacle $\mathcal{B}$ expanded by the robot size $\mathcal{A}$. The reason for this C-space expansion is the ability to treat the robot as a point. Fig. 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 the VO, it will not collide with the obstacle, assuming that the velocity vectors are constant over time. If the velocity vectors change over time, the VO-based approach reacts by replanning using the latest sensor information. In practice, when the replanning rate is much faster than the change in the vehicles' trajectories, the assumption of linear velocities is reasonable. In our test configuration, the replan rate is 1 Hz on an embedded system,[3] and the angular velocity of the boat is typically less than 30°/s.

When multiple craft are involved, simply overlaying the VO of each ship and taking a superposition generates a set of constraints on the robot's feasible velocity vector. The runtime of the VO-based approach is at worst linear with the number of hazards considered.

B. Time to Collision

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

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

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.

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

C. 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 onboard sensors such as radar [15], cameras [16], and lidar. Performance characteristics of the sensor in turn affect the noise and state estimation errors for the tracked traffic boat.

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

$$\mathrm{WVO}_B^A(\vec{v}_B) = \mathrm{VO}_B^A(\bar{\vec{v}}_B) \oplus \mathcal{W}_B. \quad (6)$$

Fig. 4 shows the same case as was shown in Fig. 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 $\bar{\vec{v}}_B$. The worst case VO, shaded with yellow, is slightly larger than the nominal VO, and the boundary lines are parallel to those of the 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 to provide a safety buffer.

D. VO With COLREGS

VO is a set of constraints in the USV's velocity space needed 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 the USV should pass. Fig. 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 $\mathrm{WVO}_B^A(\vec{v}_B)$ and is perpendicular to the centerline

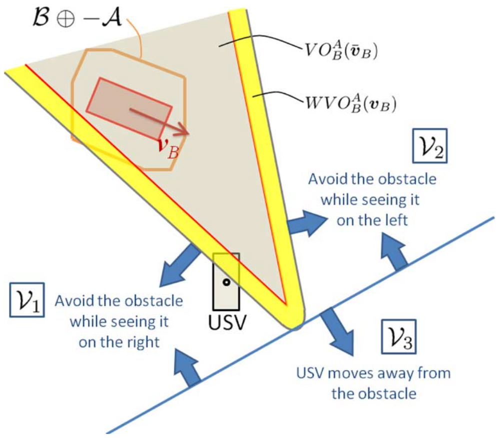


Fig. 5. Constraints in the velocity space imposed by COLREGS. The traffic vessel to apply COLREGS constraints is assumed to be in front of the USV.

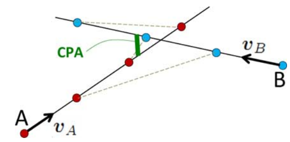


Fig. 6. Closest point of approach. Each dot corresponds to a position at a specific time, and the dashed lines show the distance between two agents A and B. The closest distance is marked with a thick bar.

of the VO cone, which is parallel to $\vec{p}_B - \vec{p}_A$, 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.,

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

so that the vehicles do not approach any closer.

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

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

then the USV will pass the obstacle while seeing it on the right-hand side. Here, the $[\cdot]_z$ operator 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 $\vec{v}_A \in \mathcal{V}_1$, USV will see the vessel B on the starboard side, thus cutting in front of the vessel B.

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

Note that when vessel B is crossing from the left, there is no COLREGS constraint 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 measures. Similarly, while being overtaken, no COLREGS constraints are applied.

E. 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 respect to the USV. As illustrated in Fig. 2, it is not sufficient to analyze only the geometric relation between the USV and moving hazards.

1) Precollision Check: The rule selector first computes the closest point of approach (CPA) with the current position and velocity of the USV and traffic vessels, and evaluates if any COLREGS rules need to be applied at all. This approach ensures that we apply COLREGS only to the relevant vehicles and is more efficient than computing CPA for every potential USV velocity with every moving vessel.

The CPA between two vessels is computed as follows. Given two points $\vec{p}_A$ and $\vec{p}_B$ and their velocity vectors $\vec{v}_A$ and $\vec{v}_B$, the time to CPA t_{CPA} is given by

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

as shown in Fig. 6. The distance at CPA d_{CPA} is then computed by

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

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

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

2) Rule Selection: Once the CPA meets condition (9), the rule selector identifies which COLREGS situation applies by analyzing a set of geometric constraints, as shown in Fig. 7. The following constraints are considered:

- heading: $\theta_{\min} \le \theta_B - \theta_A \le \theta_{\max}$;
- bearing: $b_{\min} \le b_B \le b_{\max}$;
- cross track: $y_{\min} \le y_B \le y_{\max}$;
- along track: $x_{\min} \le x_B \le x_{\max}$;

where subscripts A and B represent the variable of the USV and the traffic vessel, respectively. Because "crossing from the left" and "crossing from the right" require USV to perform distinctly different maneuvers, the rule selector considers the following four rules: overtake, head-on, crossing from the left, and crossing from the right. Different thresholds $(\cdot)_{\min}$ and $(\cdot)_{\max}$ are used for each rule. For example, the heading constraints ensure that the headings of the USV and the traffic vessel are nearly aligned (for overtaking), nearly opposite (for head-on), or nearly orthogonal (for crossing).

3) Hysteresis: If a completely new decision is made at every time step, as in the CPA-based rule selection discussed above, the USV might result in 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 alters the feasible region of the decision space, as shown in $\mathcal{V}_1$ of Fig. 5.

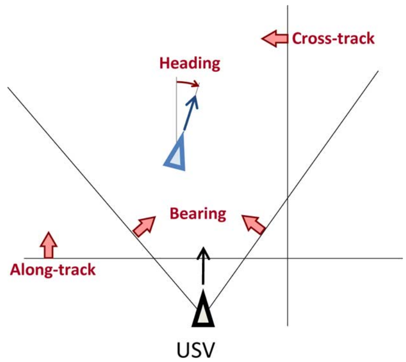


Fig. 7. Illustration of geometric constraints used to check if a specific COLREGS rule applies.

To alleviate churning, we introduce hysteresis to the rule selector and lower the rate at which USV can change what rules to apply. Its benefit is that once a COLREGS maneuver (e.g., overtaking, crossing) is initiated, it continues to direct the boat for at least a minimum duration of time, thereby making the USV's decision more obvious and predictable to human drivers on other vessels. Note that this alteration, of course, that is large enough to be apparent to other vessels is also specified in COLREGS [3]. The minimum duration is selected to be larger than the time constant of the USV dynamics.

The moving obstacles are output by the vehicle tracker, and each moving obstacle is assigned a unique ID [16]. 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 Section III-E2. 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. Informally, 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 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 mitigate sensing noise and to ensure vehicle safety. Constraints for multiple COLREGS rules in the velocity space can be easily generated by simply superposing each COLREGS-based constraint.

4) Cost: To find the best velocity vector, we construct a velocity space grid, a regular discrete grid in the v–θ space, where v denotes the USV speed and θ is the heading, and use this as a decision space. Once the constraint sets of VO and COLREGS are generated, for each v_i and θ_j that is still admissible, the vehicle computes the following cost:

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

where w_τ is a weight on the time to collision, $\vec{v}_{\text{ref}}$ is a desired velocity to reach the next near-term goal, w_v is a weight on the deviation from desired velocity, and $\|\cdot\|_Q$ is a weighted two-norm of a vector. The weighting matrix Q of size 2-by-2 allows us to weigh the deviation of the along-track velocity and the cross-track velocity differently. 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 to soften the constraints on WVO.

Once all the costs are computed, the $(v_i,\ \theta_j)$ pair with the minimum cost is selected and the velocity command is sent to the vehicle controller.

In principle, even though VO "looks ahead" into 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. However, such situation is unlikely to happen in practice, especially for on-water applications, where there are typically only a few vehicles that need to be avoided 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 range.

IV. On-Water Results

A. Setup

The COLREGS algorithm was integrated within the Jet Propulsion Laboratory's (JPL, Pasadena, CA, USA) autonomy suite called Control Architecture for Robotic Agent Command and Sensing (CARACaS) [17] that can receive vehicle state estimates from the onboard inertial navigation system (INS) unit and perception outputs such as hazard maps, moving contact lists from the JPL stereo camera server [16], or the Spatial Integrated Systems, Inc., world map server [15].

CARACaS commands the USV through an integrated controller area network (CAN) bus. Fig. 8(a) shows the USV, called combatant maritime vessel (CMV), used in the test. CMV has been tested on the water, controlled with CARACaS, to demonstrate various capabilities in the past including harbor patrol, boat following, and static hazard avoidance [15], [16], [18]. The traffic ships used in the tests are one 12-m craft [shown in Fig. 8(b)] and two 7-m rigid-hulled inflatable boat (RHIBs) [shown in Fig. 8(c)].

Fig. 9 shows a picture of the stereo cameras. The stereo bar has two pairs of stereo cameras, where one pair is looking left, and the other pair is looking right. The current JPL stereo system provides the position and velocity estimates of contacts (e.g., traffic boats) but not their orientation. The heading estimate of the traffic boat becomes noisier when the speed of the traffic boat is very low, especially with the waves in the ocean. Those contacts that are moving slower than an empirically determined threshold are treated as stationary hazards, and COLREGS constraints are not applied.

B. Legends

Fig. 10 shows a snapshot of a simulation run, involving one USV at the bottom and two moving vessels. The waypoint of the USV is set in front of the vehicle start location. There is a

(a) (b) (c)

Fig. 8. Boats used in the on-water COLREGS testing: (a) CMV, the USV; (b) 12-m traffic boat; and (c) 7-m RHIB, a traffic boat.

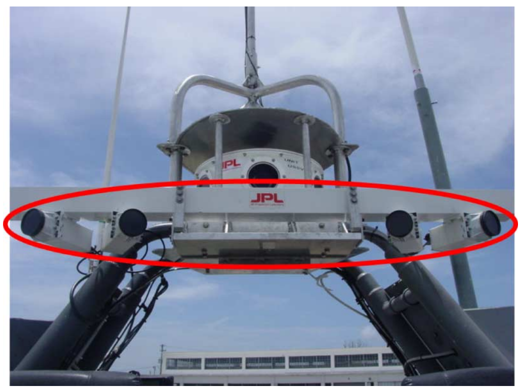


Fig. 9. JPL stereo cameras on the USV.

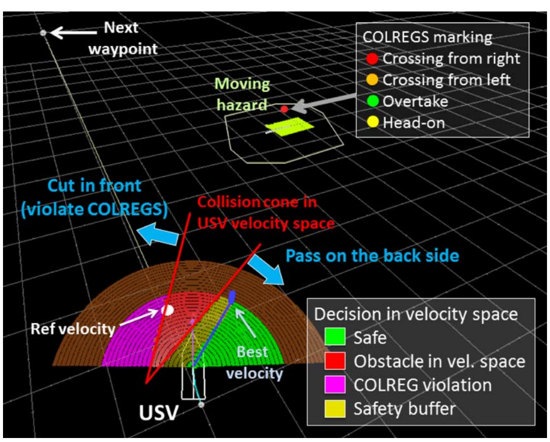


Fig. 10. A snapshot of a simulation run (the USV is in a crossing situation).

traffic boat coming from the right. The USV recognizes that it is in a crossing situation and starts maneuvering toward starboard.

The colored region around the USV represents the velocity decision space. 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, acting as a safety buffer, and the purple region represents a COLREGS violation (the "crossing" rule in this figure). Since the cost is continuous, the color has some shading. The brown region limits the maximum velocity that the motion planner can choose. The blue line from the USV shows the best velocity selected by the algorithm.

As shown in the upper right of the figure, a small dot is plotted above the moving contact if it is in a COLREGS situation with the USV. The color represents the type of the COLREGS, and we consider head-on, overtaking, and crossing from the right and left in this paper. Note that because of the hysteresis in the rule selection, a traffic vessel could be considered to be in more than one COLREGS situation and could be marked with multiple dots with different colors.

C. COLREGS Runs With Four Vessels

This section presents COLREGS on-water tests involving four vessels. The CMV was used as the USV, as shown in Fig. 8(a), and the 12-m craft and two 7-m RHIBs are used as traffic vessels, as shown in Fig. 8(b) and (c). In all scenarios, the USV was given a waypoint that was about 1000 m away in front, and was commanded to reach the waypoint while obeying COLREGS with traffic vessels. The USV's nominal speed was 8 kn (4 m/s) in these tests. The algorithmic parameters such as thresholds to decide which rules to apply were tuned through simulation and initial at-sea testings with feedback from boat drivers.

1) Scenario 1: Head-On and Crossing: In this scenario, the USV first overtakes a traffic vessel. As it maneuvers around it, other two vessels start to approach the USV, creating a head-on situation. Fig. 11 shows the results of the on-water run.

The figures on the left show the body-fixed view of the run: two images at the top are from the left-looking and right-looking stereo cameras, and the image below them shows the USV, detected objects, and the decision space of the COLREGS motion planner, as shown in Fig. 10. The figures on the right are the 2-D plots in the global frame, showing the USV path, the current pose of the USV (marked with a triangle), the stereo camera field of view (denoted with gray lines), and the objects that were detected by the stereo system.

The USV is first given a waypoint and drives toward it. In Fig. 11(a), the USV detects one of the 7-m RHIBs at a far distance. The estimated velocity is low enough that the USV simply treats it as a stationary hazard, and no COLREGS constraint is applied. The direction of the waypoint is represented with a white line. As the 7-m RHIB approaches, the USV recognizes the head-on situation and applies the COLREGS constraint, as shown in Fig. 11(b). The COLREGS constraints encourage the head-on evasive maneuver to turn right by prohibiting velocities to the left. The head-on situation is marked with a yellow dot on top of the detected vessel.

In Fig. 11(c), the USV detects another vessel approaching from the front, recognizes the USV is in a head-on COLREGS situation with both vessels, and moves to the starboard side. At this moment, although the 12-m boat is visible in the image, it is not yet detected by the vehicle tracker in the stereo system.

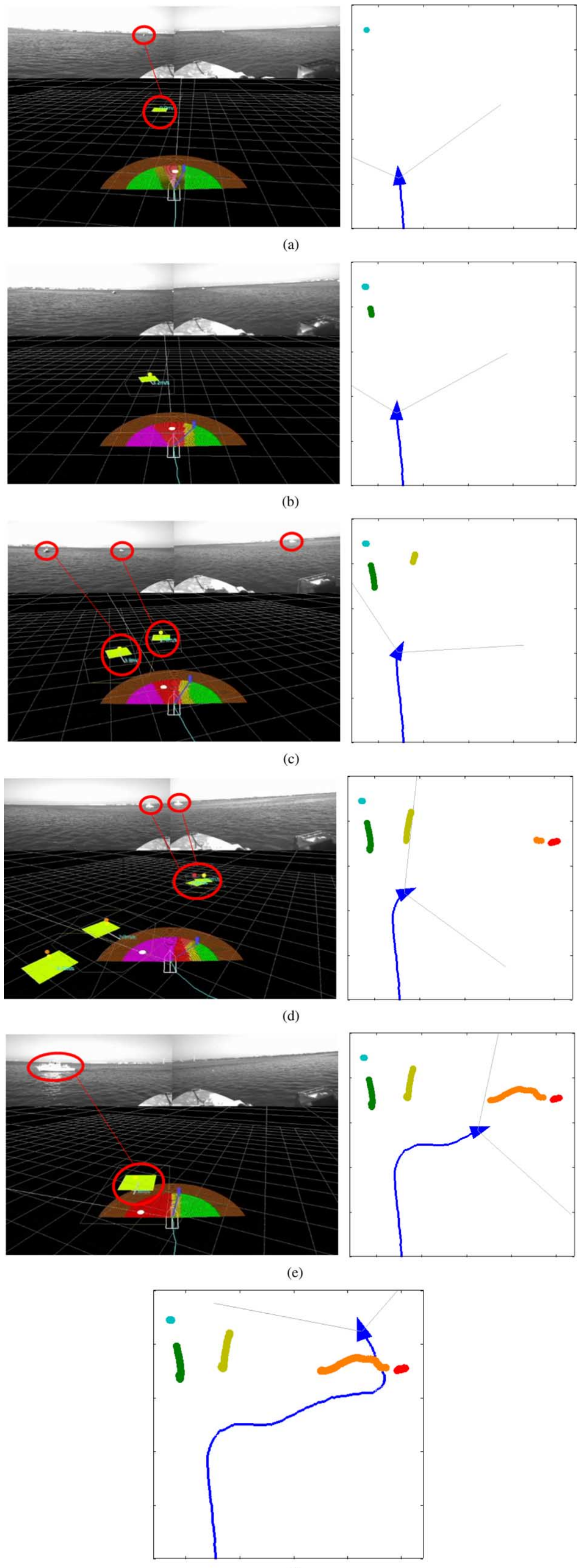


Fig. 11. Scenario 1 of the four-boat COLREGS runs: Overtaking and head-to-head: (a) USV detects a contact; (b) USV recognizes a head-on situation; (c) USV detects another vessel in the head-on situation; (d) USV detects a crossing vessel; (e) USV avoiding the crossing vessel; and (f) USV's overall path after a series of successful COLREGS maneuvers.

As it maneuvers around the two vessels, the 12-m craft comes from USV's starboard side, creating a crossing situation. In Fig. 11(d), the 12-m ship is detected, and the USV avoids all three vessels by further altering its path to its starboard. As the USV turns and changes its orientation, the heading difference between the 12-m boat and the USV changes from almost perpendicular to almost opposite. The USV treats the 12-m vehicle to be in both the crossing situation (marked with a red dot) and the head-on situation. Note that both "crossing from the right" and head-on COLREGS require that the USV alter its path to the starboard, and they correspond to the same COLREGS constraints in the USV's decision space.

Fig. 11(e) shows successful avoidance of the 12-m boat. Note that the rectangular contact shown in the lower left includes the detected contact and the minimum clearance between vessels (imposed by boat drivers). Therefore, the contact in the lower left plot looks closer to USV than the 12-m boat in the stereo image. The USV then continues its drive toward the waypoint that was given initially, as shown in Fig. 11(f).

The plots of the traffic vessels are generated purely based on the stereo system's output and show the information that was available to the motion planner to make decision on USV's maneuver. In fact, there is no intervehicle communication during the run.

2) Scenario 2: Overtake, Head-On, and Crossing: In Fig. 12(a), the USV recognizes the overtaking situation and initiates a turn maneuver toward starboard, even though the straight line to the waypoint passes on the port side of the traffic boat. This behavior emerges from the COLREGS constraints (purple region shown in the decision space), which forces the USV to overtake from the starboard side, obeying COLREGS.

During the overtaking in Fig. 12(b), the USV detects another vessel in the head-on situation. The USV recognizes that it is in the head-on situation as well as overtaking. COLREGS constraints (marked in purple) force the USV to turn away from the waypoint when avoiding the head-on vessel.

In Fig. 12(c), the USV avoids the head-on vessel. Another vessel coming from the right is visible in the stereo image, but is yet to be confirmed by the vehicle tracker of the stereo system.

After a successful avoidance of the head-on vessel, the USV is in both the head-on and crossing situation in Fig. 12(d). It turns to its starboard to let the 12-m boat maintain its course, because that boat is the stand-on vessel in this situation.

Subsequent the successful avoidance of the 12-m boat in Fig. 12(e), the 7-m RHIB being overtaken comes in the view again in Fig. 12(f). Because it is far enough, the USV does not consider this situation to be overtaking. Note that the hazard avoidance constraint is always on, as shown in the red cone in the left plot.

Fig. 12(g) shows the overall paths of the USV and detected vessels. Note the slight meander of the USV's path in the last segment. This is caused by the inaccurate state estimate of the vessel that was being overtaken (the contacts shown in the upper left corner of the figure). When the traffic vessel first enters the field of view of the camera while the USV is turning, the current object tracker tends to treat it as a vessel heading toward the USV. Mitigation of this sensor issue is beyond the scope of this paper, but one solution is to extend the field of view of the stereo camera system by adding another pair of cameras pointing sideways, so that the USV can maintain tracking of the target vessel during the overtake maneuver.

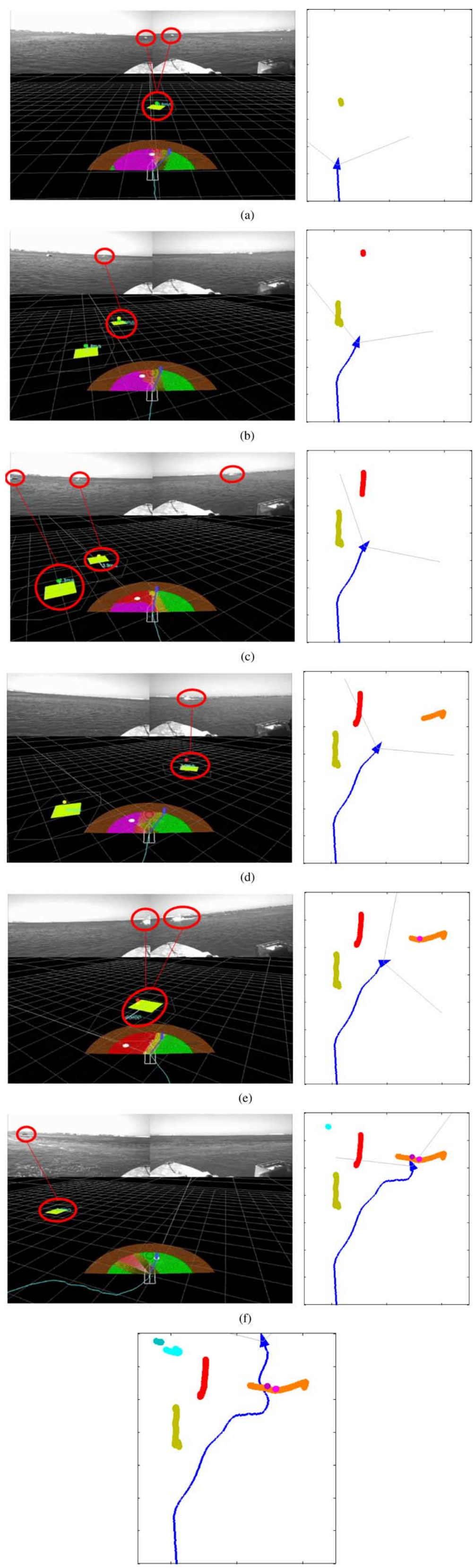


Fig. 12. Scenario 2 of the four-boat COLREGS runs: Overtaking, head-on, and crossing: (a) detected a contact; (b) recognized a head-on situation; (c) detected another vessel in the head-on situation; (d) detected a crossing vessel; (e) avoiding the crossing vessel; (f) avoiding the crossing vessel, USV starts seeing the boat that was being overtaken; and (g) USV's overall path after series of successful COLREGS maneuvers.

We have attempted nine runs of four-boat COLREGS scenarios. Eight runs, which total to 24 COLREGS maneuvers, were successful. In the other run, the USV failed to respond safely to a crossing vessel that approached outside the stereo sensor's FOV. This is a topic of the future work, in which we fuse data from other sensors with a wider FOV.

The runtime of the motion planning algorithm of each cycle was a few milliseconds 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, the algorithm continues to run well in real time.

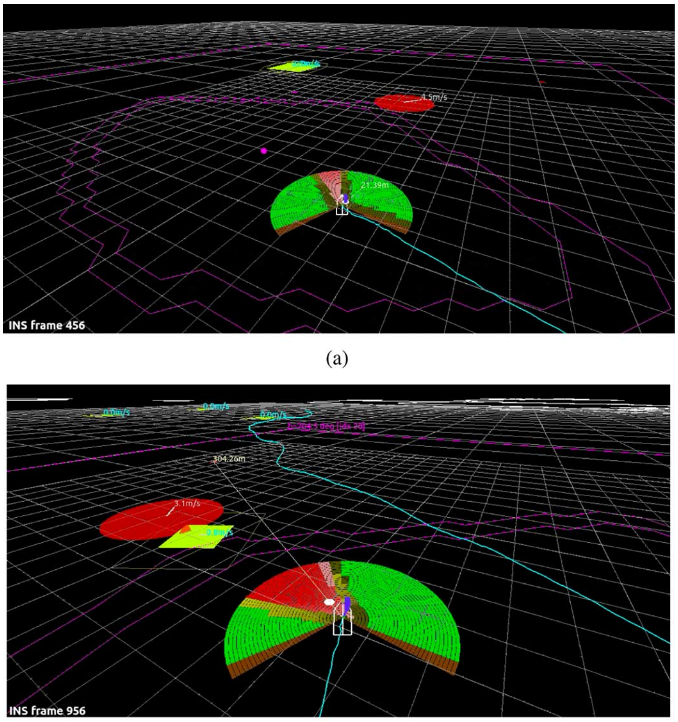
D. Trailing Runs

The results in this section illustrate how the local motion planner presented so far can be integrated with higher level behaviors. The mission considered here is to trail a moving target using a forward-looking sensor, while avoiding hazards and obeying COLREGS with surface traffic vessels. A high-level planner computes a near-term waypoint goal for the local motion planner, by considering the target position and speed and the sensor cone. The results that follow describe live, on-water tests in which the surface traffic and obstacles were detected by the USV's sensors; however, the target position was simulated (manually driven by joystick) and sent to the motion planner if within a simulated sensor cone.

1) Trailing a Maneuvering Target With Hazards: Fig. 13 show snapshots from a scenario in which the driver of the simulated target was attempting to evade the USV with changes of direction and speed in the presence of static obstacles. The USV trails the target (shown with a large red circle) as the simulated target passes "through" a buoy, turns around, and passes through the buoy again. The waypoints provided by the high-level planner to the local motion planner are frequently updated to keep track of the simulated target.

In Fig. 13(a), the buoy is fairly distant, and thus has a modest time to collision, not significantly impacting the velocity chosen by the local planner. In Fig. 13(b), the nearby buoy's representation in the velocity space is significant and must be avoided. The waypoint-based reference velocity is in a "red" region (short time to collision with the buoy), so a velocity to the side (in the green region) is chosen instead, as indicated by the blue "post." Once the USV is clear of the buoy, the velocity space changes to green and the USV followed the reference velocity directly. During these runs, the driver of the simulated target was unable to cause the USV to lose trail via maneuvers and use of static surface hazards.

2) Trailing With Stationary Hazards and COLREGS: Figs. 14 and 15 show COLREGS situations that were encountered while trailing the target. In Fig. 14, the USV applies COLREGS crossing while simultaneously avoiding a stationary hazard. The purple COLREGS velocity space constraint is visible for the crossing situation, with the entire port side colored red because of the buoy on that side. In Fig. 15, the USV is in a head-on situation, and the COLREGS rule excludes turning to port. At the same time, the velocity obstacle to the buoy excludes continuing straight, so the USV turns to starboard, as expected.



(a)

(b)

Fig. 13. On-water test results for trailing. (a) The simulated target is maneuvering to the right as the USV trails, and a fairly distant buoy places modest constraint on the USV's velocity. (b) The USV navigates around a nearby buoy while trailing the target.

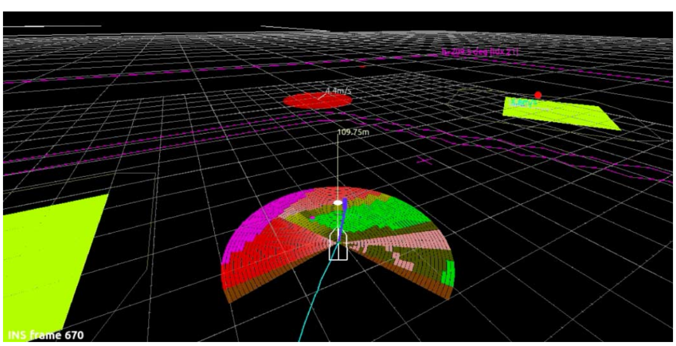


Fig. 14. A COLREGS crossing situation during trailing; note the red dot above the contact on the right and the purple region in the velocity decision space. Also, buoys to the port of the USV are being avoided simultaneously.

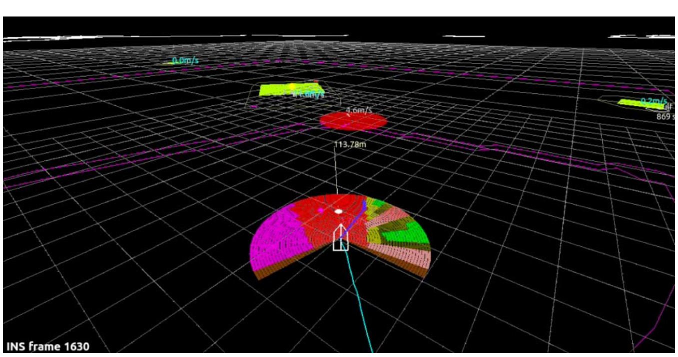


Fig. 15. A COLREGS head-on situation during trailing; note the yellow dot above the contact and the purple region in the velocity decision space.

V. Conclusion

This paper presented a maritime navigation algorithm for avoiding hazards and obeying COLREGS using VOs. 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 precollision check using CPA, the safety buffer to account for uncertain movement of moving hazards, and rule hysteresis to ensure that the each COLREGS maneuver 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.

Acknowledgment

The authors would like to thank Spatial Integrated Systems, Inc. for their support of at-sea testing.

References

[1] Program Executive Officer for Littoral and Mine Warfare [PEO (LMW)], "The Navy Unmanned Surface Vehicle (USV) Master Plan," Tech. Rep., 2007.

[2] J. Larson, M. Bruch, and J. Ebken, "Autonomous navigation and obstacle avoidance for unmanned surface vehicles," *SPIE Proc.—Int. Soc. Opt. Eng., Unmanned Syst. Technol. VIII*, vol. 6230, pp. 17–20, 2006.

[3] U.S. Dept. Homeland Security/U.S. Coast Guard, "Navigation rules," Paradise Cay Publications, 2010.

[4] S.-M. Lee, K.-Y. Kwon, and J. Joh, "A fuzzy logic for autonomous navigation of marine vehicles satisfying COLREG guidelines," *Int. J. Control Autom. Syst.*, vol. 2, no. 2, pp. 171–181, 2004.

[5] 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 *Proc. Int. Workshop Advanced Ship Design for Pollution Prevention*, 2009, pp. 205–216.

[6] J. Colito, "Autonomous mission planning and execution for unmanned surface vehicles in compliance with the marine rules of the road," M.S. thesis, Dept. Aeronaut. Astronaut., Univ. Washington, Seattle, WA, USA, 2007.

[7] T. Statheros, G. Howells, and K. M. Maier, "Autonomous ship collision avoidance navigation concepts, technologies and techniques," *J. Navig.*, vol. 61, no. 1, pp. 129–142, 2008.

[8] M. Benjamin, J. Curcio, and P. Newman, "Navigation of unmanned marine vehicles in accordance with the rules of the road," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2006, pp. 3581–3587.

[9] K. Teo, K. W. Ong, and H. C. Lai, "Obstacle detection, avoidance and anti collision for MEREDITH AUV," in *Proc. MTS/IEEE OCEANS Conf., Marine Technol. Our Future: Global and Local Challenges*, Biloxi, MS, 2009.

[10] P. Fiorini and Z. Shiller, "Motion planning in dynamic environments using velocity obstacles," *Int. J. Robot. Res.*, vol. 17, no. 7, pp. 760–772, 1998.

[11] J. van den Berg, M. Lin, and D. Manocha, "Reciprocal velocity obstacles for real-time multi-agent navigation," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2008, pp. 1928–1935.

[12] B. Kluge and E. Prassler, "Reflective navigation: Individual behaviors and group behaviors," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, vol. 4, pp. 4172–4177.

[13] C. Fulgenzi, A. Spalanzani, and C. Laugier, "Dynamic obstacle avoidance in uncertain environment combining PVOs and occupancy grid," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2007, pp. 1610–1616.

[14] J. van den Berg, S. Patil, J. Sewall, D. Manocha, and M. C. Lin, "Interactive navigation of multiple agents in crowded environments," in *Proc. Symp. Interactive 3D Graphics Games*, 2008, pp. 139–147.

[15] 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," *J. Field Robot.*, vol. 27, no. 6, pp. 790–818, 2010.

[16] T. Huntsberger, H. Aghazarian, A. Howard, and D. C. Trotz, "Stereo vision-based navigation for autonomous surface vessels," *J. Field Robot.*, vol. 28, no. 1, pp. 3–18, 2011.

[17] 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 *Proc. AUVSI Unmanned Syst. North Amer.*, , pp. 111–123.

[18] M. T. Wolf, C. Assad, Y. Kuwata, A. Howard, H. Aghazarian, D. Zhu, T. Lu, A. Trebi-Ollennu, and T. Huntsberger, "360-degree visual detection and target tracking on an autonomous surface vehicle," *J. Field Robot.*, vol. 27, no. 6, pp. 819–833, 2010.

Yoshiaki Kuwata received the B.Eng. degree from the University of Tokyo, Tokyo, Japan, in 2001 and the S.M. and Ph.D. degrees from Massachusetts Institute of Technology, Cambridge, MA, USA, in 2003 and 2007, respectively, all in aeronautics and astronautics.

He has more than eight years of experience in developing planning and control systems for various types of autonomous vehicles, including sea surface vehicles, sport utility vehicles (SUVs), small rovers, fixed-wing aircraft, quadrotors, and Montgolfier balloons. Before joining Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, CA, USA, in 2008, he was a Postdoctoral Associate at the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, leading the development of the planning and control system of the MIT vehicle in DARPA Urban Challenge. Since 2010, he has been JPL's Technical Task Manager for Office of Naval Research (ONR) Littoral Combat Ships, which has demonstrated autonomous COLREGS maneuvers using stereo vision sensors, health monitoring, and replanning on faults, and intercept and inspect using multiple vision sensors. Since October 2012, he has been a Guidance, Control, and Navigation Engineer at Space Exploration Technologies, Hawthorne, CA, USA.

Michael T. Wolf received the B.S. degree in mechanical engineering from Stanford University, Stanford, CA, USA, in 1997 and the M.S. and Ph.D. degrees from the Mechanical Engineering Robotics Laboratory, California Institute of Technology (Caltech), Pasadena, CA, USA, in 2003 and 2008, respectively.

He is a Research Scientist with the Advanced Robotics Controls group at the Jet Propulsion Laboratory (JPL), Caltech. At JPL, he leads projects in maritime robotics, with emphasis on autonomous perception and navigation systems for unmanned surface vehicles. His other research interests include natural human–robot control interfaces and probabilistic estimation, classification, and tracking.

Dimitri Zarzhitsky received the B.S. degree in computer science from Colorado State University, Fort Collins, CO, USA and the Ph.D. degree in computer science from University of Wyoming, Laramie, WY, USA, in 2008.

He contributed to this research as a member of the Robotic Software Systems group at the Jet Propulsion Laboratory, California Institute of Technology (Caltech), Pasadena, CA, USA. His research focuses on distributed autonomy, perception, and event-driven programming. He also contributed machine vision software to a proposed lunar sample return mission. He has developed methods for improving onboard sensor and control capabilities of unmanned aerial and surface robotic vehicles tasked with remote site exploration and monitoring.

Terrance L. Huntsberger (SM'08) received the Ph.D. degree in physics from the University of South Carolina, Columbia, SC, USA, in 1978.

He has been developing and testing perception and autonomy technology for unmanned systems for over 30 years, the last nine of which have been for the U.S. Navy and commercial partners. He is the primary architect of the CARACaS autonomy system, which is running on a number of unmanned surface and underwater vehicles. He was the Technology Lead at the Jet Propulsion Laboratory, California Institute of Technology (Caltech), Pasadena, CA, USA, for the FIDO rover that was used for development and testing of autonomy technology in support of the Mars Exploration Rovers (MER), and was a MER Rover Driver for Spirit and Opportunity from 2005 to 2007. He also served as a member of the pre-Phase-A Design Team for the MSL rover and was the Project Lead for the MSL Autonomy Technology Testing Project at JPL. Before joining JPL in 1999, he was an Associate Professor (currently an Adjunct Full Professor) and Founder/Director of the Intelligent Systems Laboratory in the Department of Computer Science, University of South Carolina.