

# **Safe Maritime Navigation with COLREGS Using Velocity Obstacles**

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# COLREGS

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- USVs becoming to be used in more cluttered environment
    - Need to detect & avoid stationary hazards
    - Need to detect & avoid moving hazards
    - Need to follow “rules of the road” in various situations
- } Focus of this paper
- COLREGS (International Regulations for Preventing Collisions at Sea)
    - Specify the types of maneuver, ~40 rules
    - Focus on the major three situations
      - Overtaking
      - Crossing
      - Head-on



# COLREGS Situation

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- RULE 13: Overtaking
  - Any vessel overtaking any other shall keep out of the way of the vessel being overtaken.
  - A vessel shall be deemed to be overtaking when **coming up with another vessel from a direction more than 22.5 degrees abaft her beam**, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.
  - When a vessel is **in any doubt** as to whether she is overtaking another, **she shall assume that this is the case** and act accordingly.
  - Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of **keeping clear of the overtaken vessel until she is finally past and clear**.
- 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.
  - Such a situation shall be deemed to exist when **a vessel sees the other ahead or nearly ahead** and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.
  - When a vessel is **in any doubt** as to whether such a situation exists **she shall assume that it does exist** and act accordingly.
- 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.



# COLREGS Maneuvers

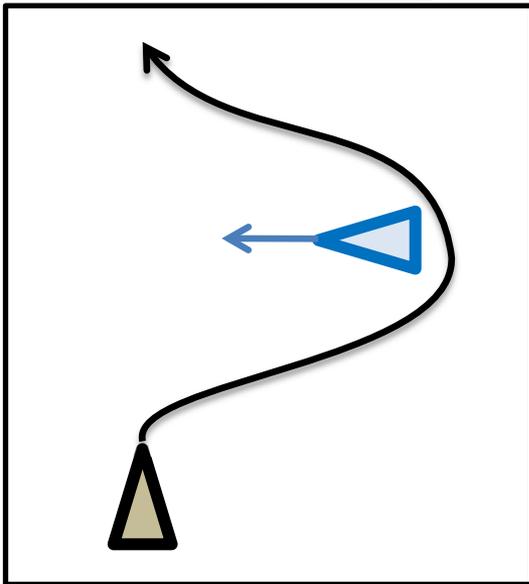
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- RULE 16: Action by Give-way Vessel
  - Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, **take early and substantial action** to keep well clear.
- RULE 17: Action by Stand-on Vessel
  - (i) Where one of two vessels is to keep out of the way **the other shall keep her course and speed**.
  - (ii) The latter vessel **may however take action to avoid collision by her maneuver alone**, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.
  - When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she **shall take such action as will best aid to avoid collision**.
  - A power-driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel **shall**, if the circumstances of the case admit, **not alter course to port for a vessel on her own port side**.
  - This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

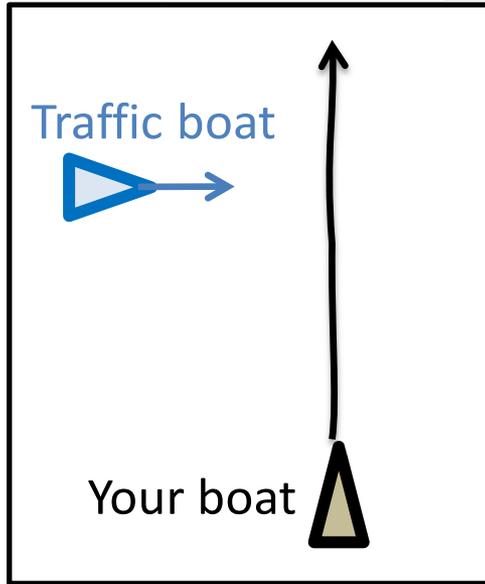
These Rules are written for human drivers with enough ambiguity  
➔ need to encode them in USV's motion planner



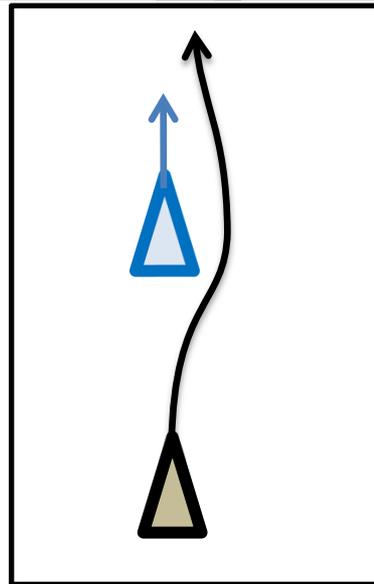
# COLREGS illustration



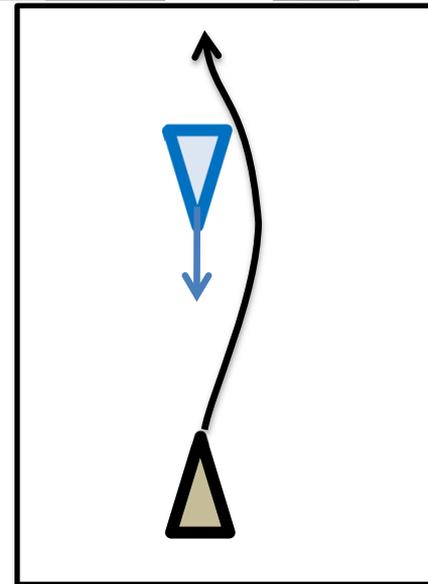
Crossing from right



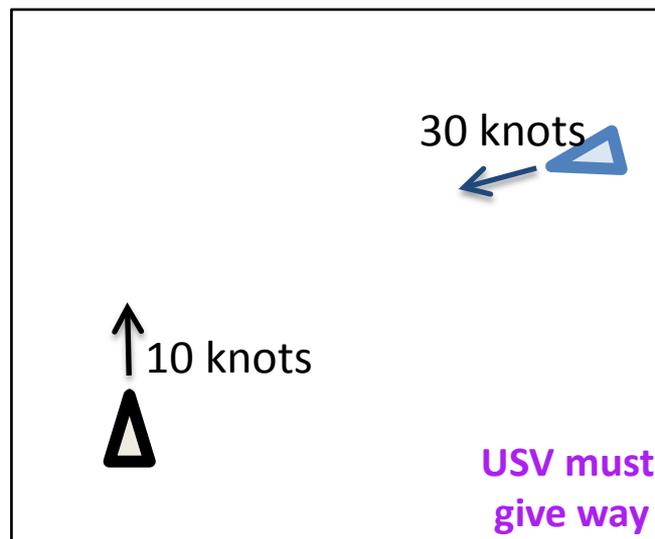
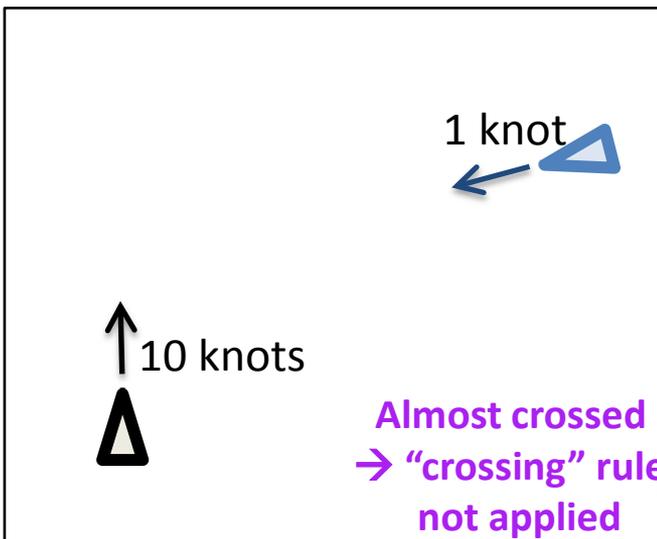
Crossing from left



Overtaking



Head-on



Need more than  
the geometry to  
determine COLREGS  
situations



# Approach

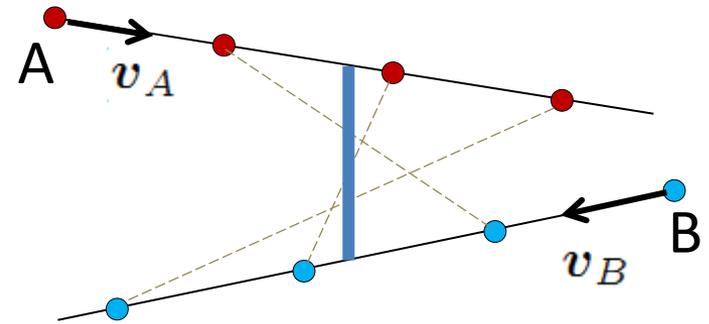
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- Rule selector
  - Detect the COLREGS situation based on
    - Relative geometry
    - Relative heading
    - CPA
  - Hysteresis to maintain the maneuver it started
- Motion planner using Velocity Obstacles
  - Generate a velocity command that
    - Avoids stationary & moving hazards
    - Accounts for sensing uncertainties
    - Observes COLREGS



# CPA

- Closest Point of Approach
  - Assume a straight line motion
  - Distance & time at when two objects are the closest



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

$$d_{CPA} = \|(\mathbf{p}_A + \mathbf{v}_A t_{CPA}) - (\mathbf{p}_B + \mathbf{v}_B t_{CPA})\|$$

- ➔ Tells us if two vehicles are **nearly on a collision course**
- Consider COLREGS only when

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



# Rule Selection

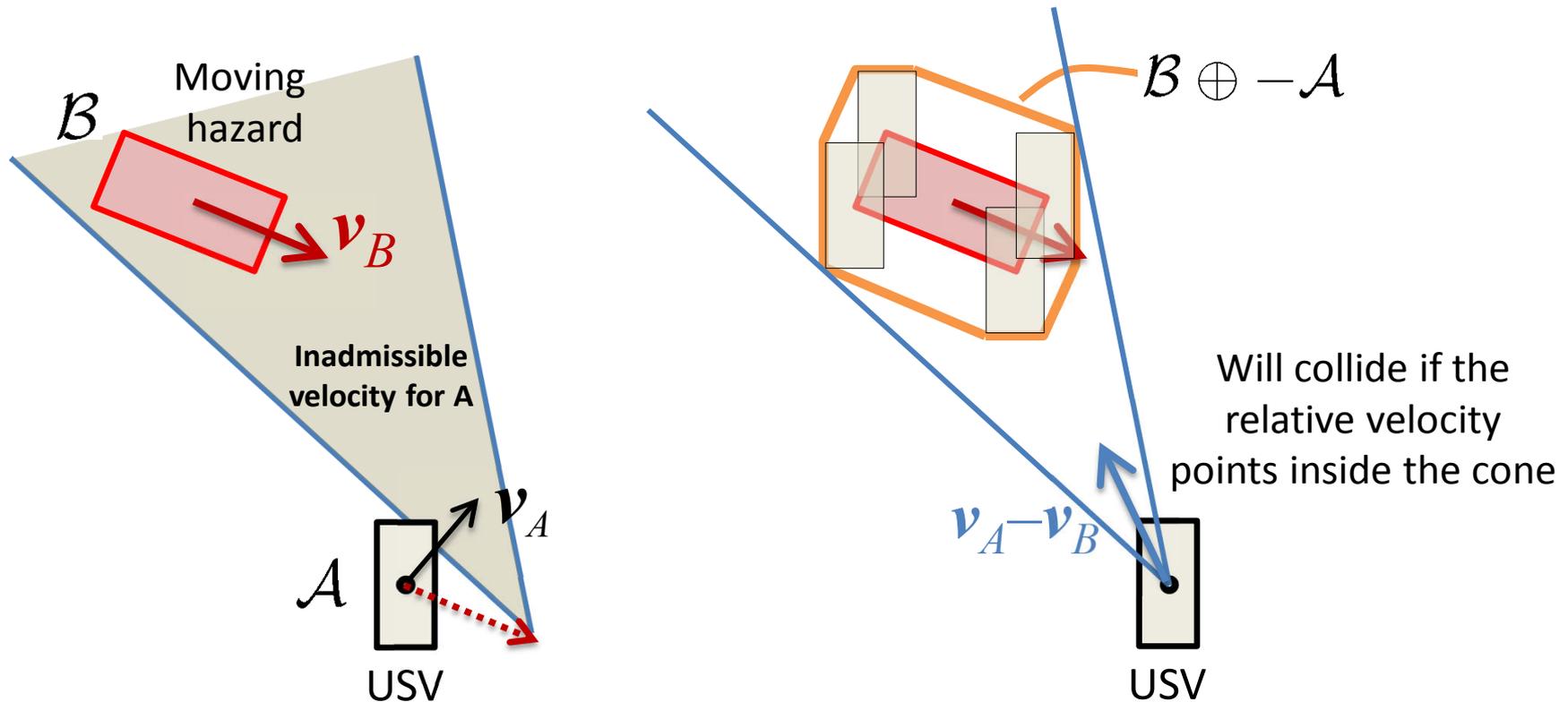
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- Overtaking
  - Two vehicles close enough (Euclidean, cross-track)
  - Heading nearly aligned
- Head-on
  - Two vehicles close enough (Euclidean, cross-track)
  - Heading nearly opposite
- Crossing-from-right
  - Heading nearly perpendicular
  - Bearing
  - Heading-bearing
  - Cross-track



# Velocity Obstacles [Fiorini & Shiller, 1998]

- Assumes first-order (linear) prediction

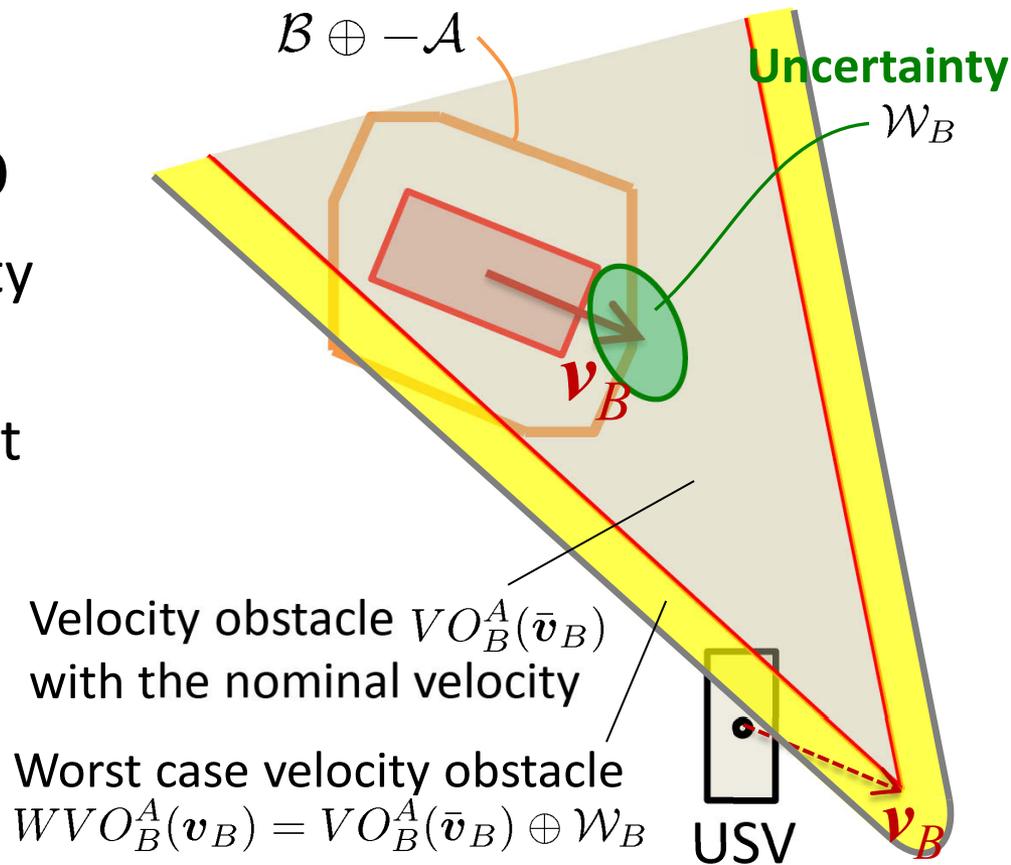


- “Cone-shaped” obstacle in the velocity space
  - Superpose them for multiple hazards
  - Then, USV chooses a velocity outside of the velocity obstacles



# Uncertainty Handling in VO

- Velocity estimates of moving obstacles are noisy
  - Appearance (shape) changes as ships maneuver
  - Stereo has limited FOV
- Generate worst-case VO
  - If USV chooses its velocity in here, it *could* collide
  - One additional constraint & easy to compute





Moving hazards

739.48m

1.6m/s

1.6m/s

1.6m/s

1.6m/s

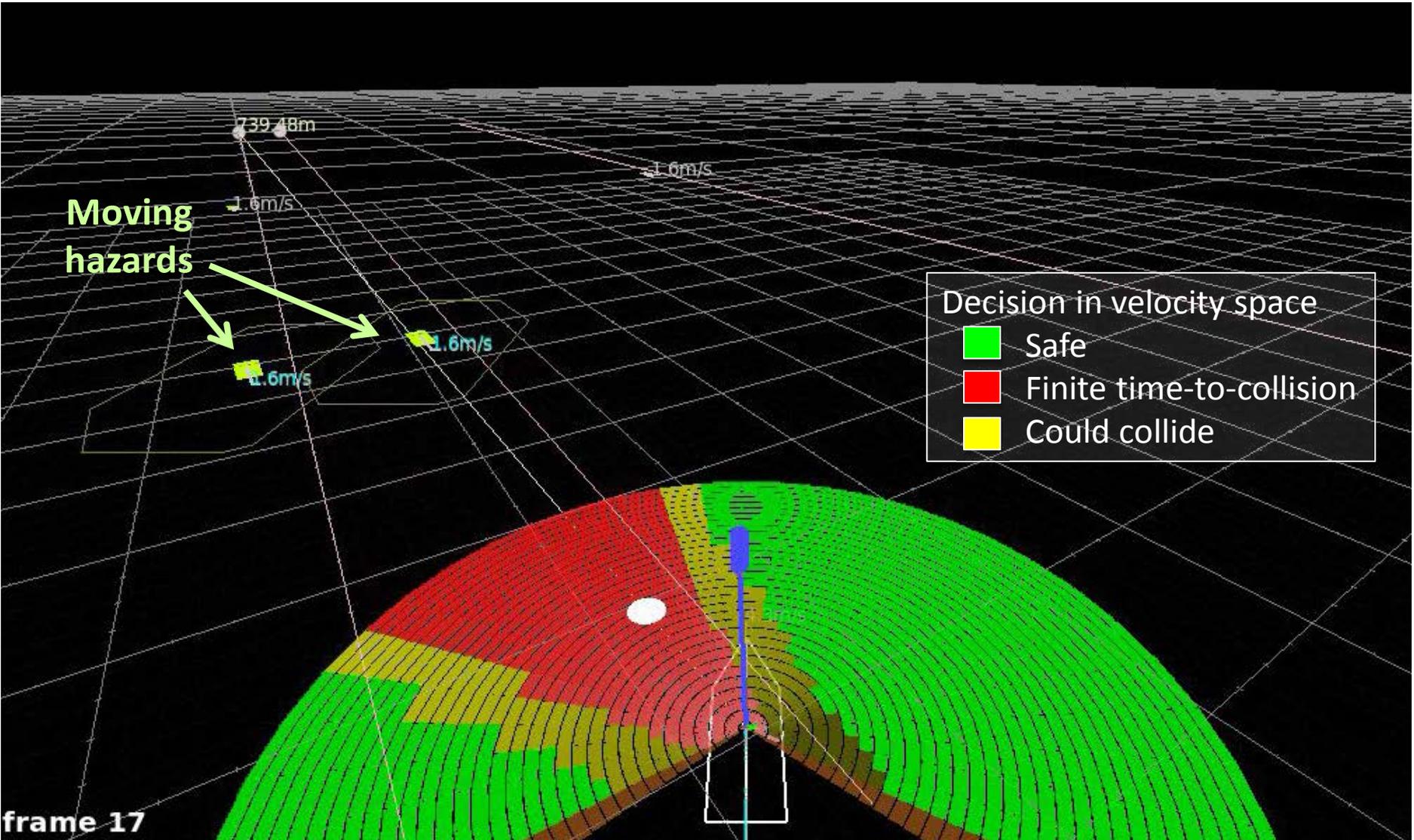
Decision in velocity space

Safe

Finite time-to-collision

Could collide

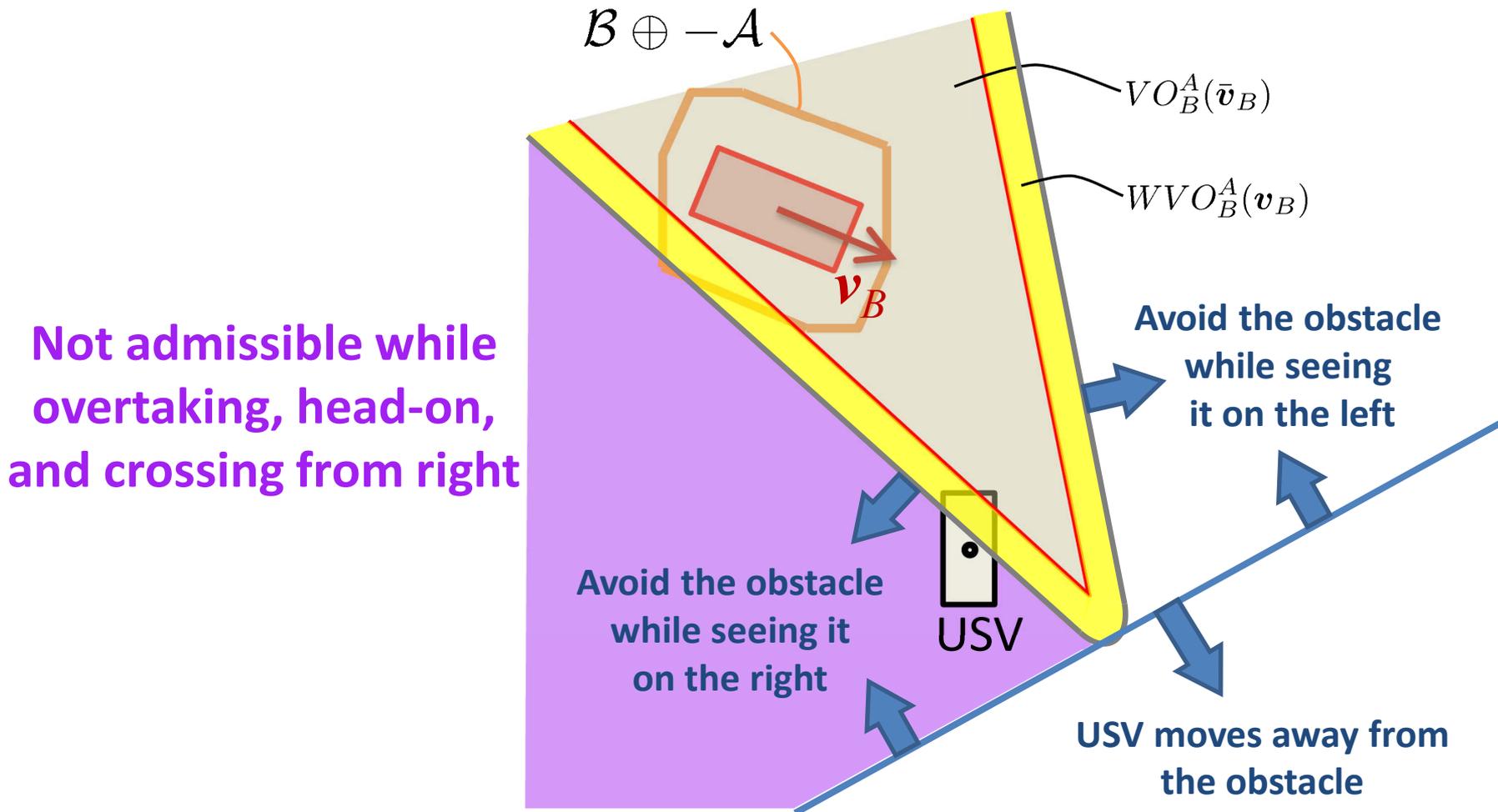
frame 17

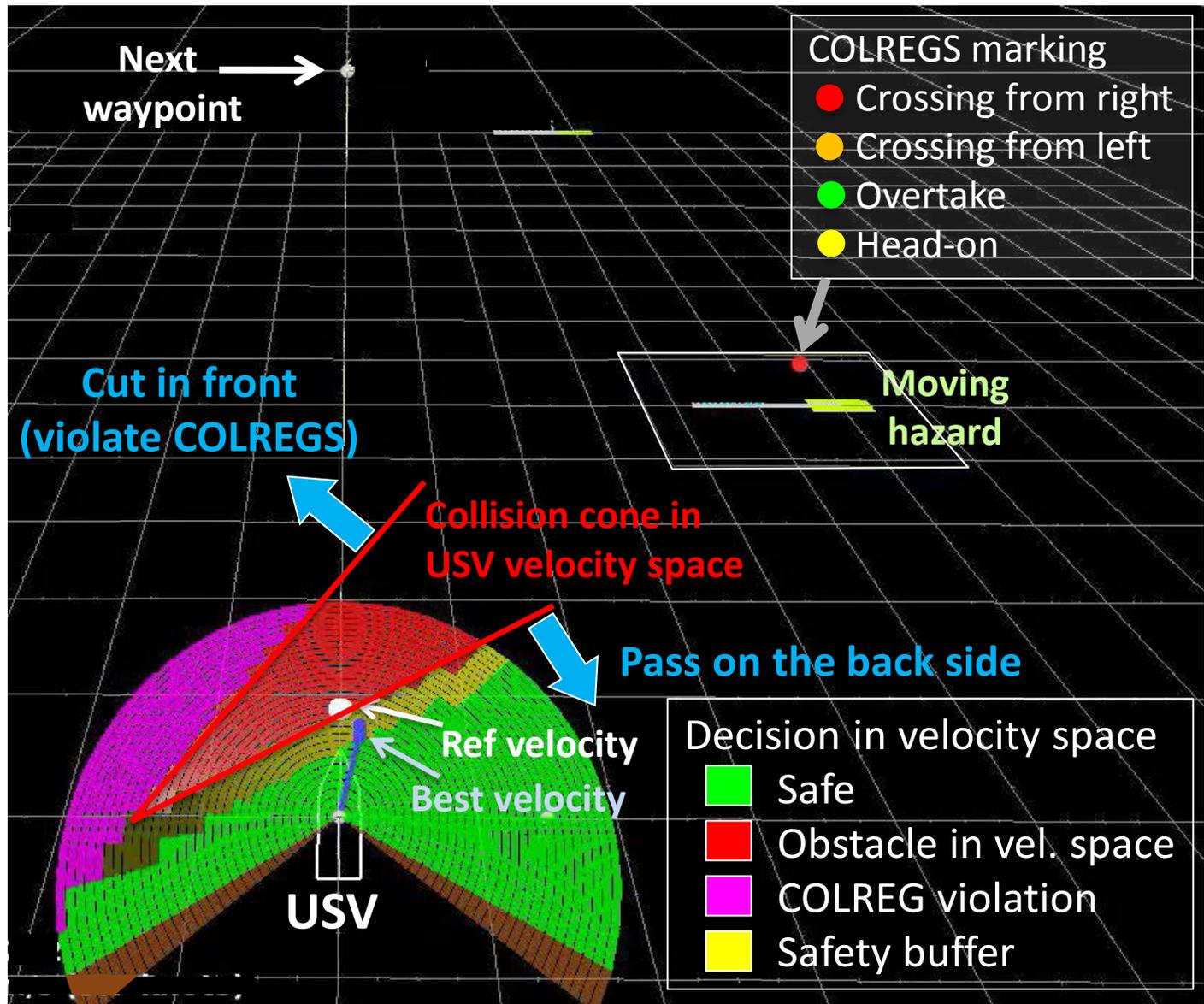




# COLREGS in Velocity Space

- Velocity Obstacles tells “which side” of the obstacle the avoidance maneuver will pass







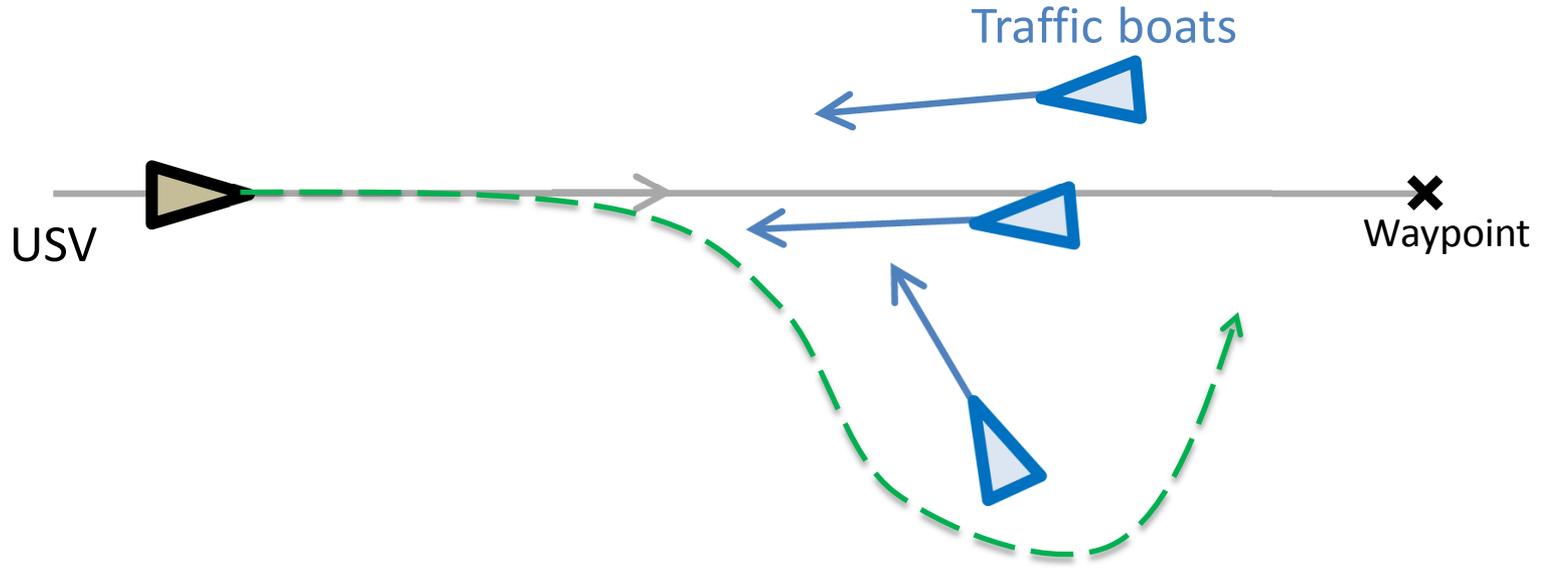
# Field Testing

- Boats
  - Autonomous boat: CMV
  - Two 7m RHIBs (Rigid Hull Inflatable Boat)
  - One 41-footer
  
- 4 scenarios
- Parameters tuned based on several field trials, and feedback from boat drivers





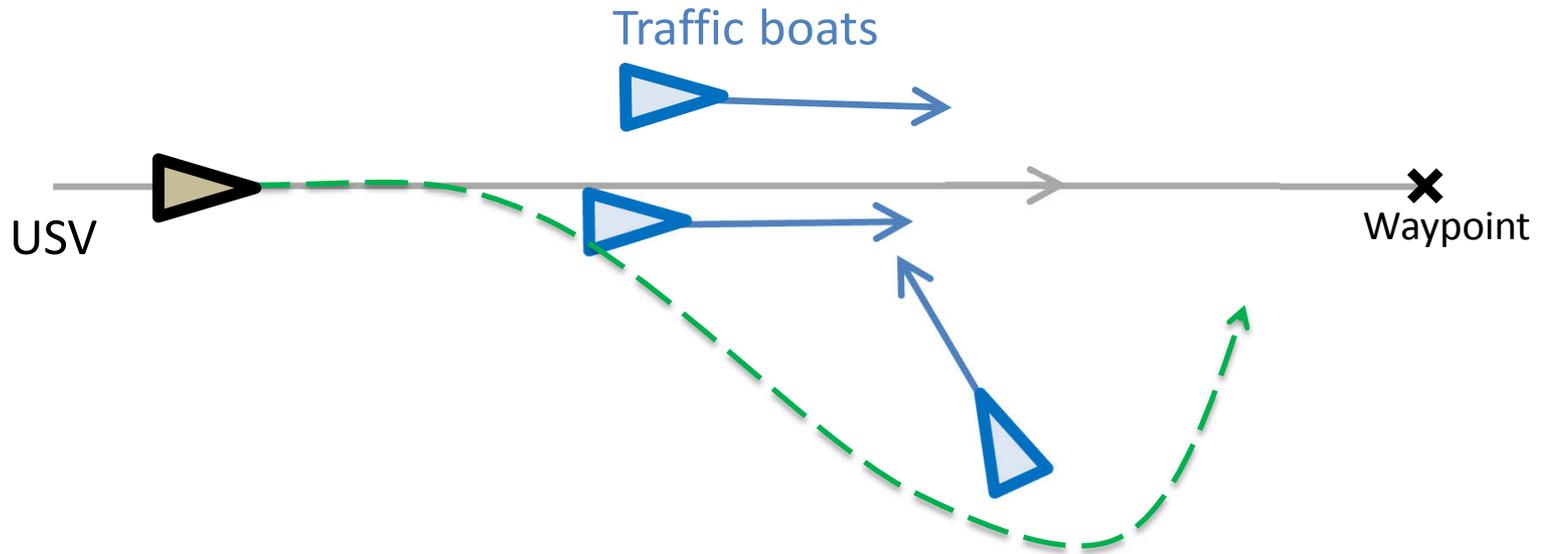
# Head-on + Crossing



- Two “head-on” vehicles, and one “crossing from right” vehicle
- As USV maneuvers around the head-on vehicles, the “crossing-from-right” vehicle could become another head-on vehicle



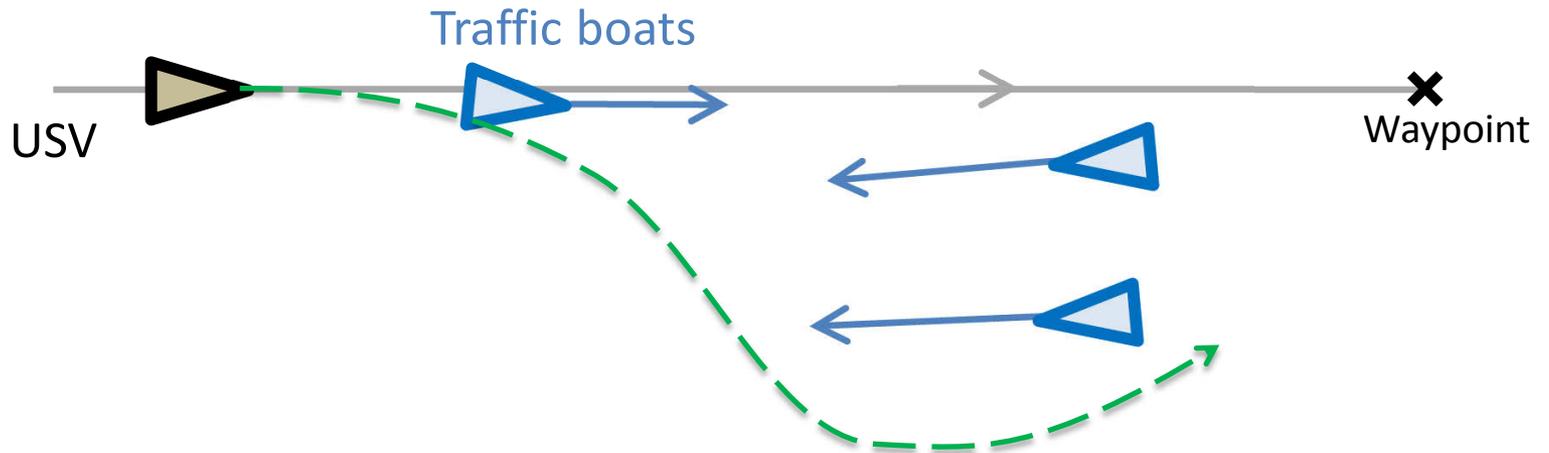
# Overtake + Crossing



- Two vehicles to overtake, and one crossing from right
- As USV overtakes two vehicles, the “crossing-from-right” vehicle could become a head-on vehicle



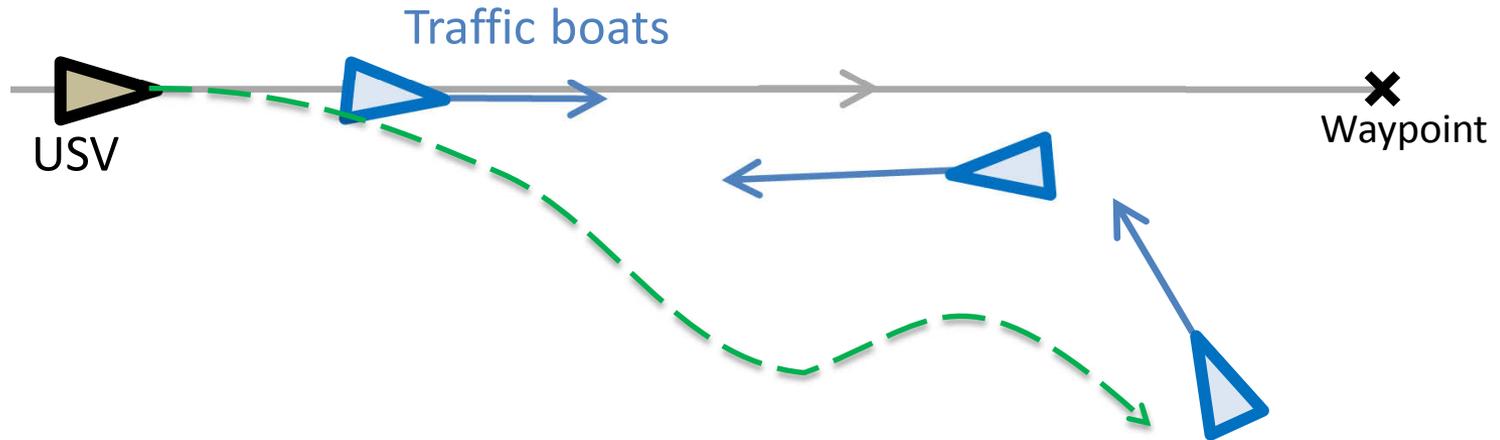
# Overtake + Head-on



- During the overtaking of one vehicle, another two head-on vehicle come in
- USV would need to maneuver around all of them



# Overtake + Head-on + Crossing



- During the overtaking of one vehicle, a new head-on vehicle comes in
- During the head-on maneuver, a new vehicle crosses from the right
- USV would need to maneuver around all of them



# Conclusions

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- Extended Velocity Obstacles for COLREGS navigation
  - COLREGS as an **additional set of constraints** in the velocity space
  - VO tells which side the maneuver will avoid the hazard
    - natural way to add COLREGS
  - Computationally efficient (~20ms on PC104)
  - Handles uncertainties
- Demonstrated three COLREGS situations
  - Overtaking, Head-to-head, and Crossing
  - Arbitrary combination of them
  - Successfully demonstrated on the water using 4 boats
- Future work
  - Higher speed operations
  - Unfriendly traffic boats



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- Cons:
    - Assumes constant speed (correct assumption for stand-on vessels) → Continuously replan
    - Local planner → subject to local minimum, but not an issue when dealing with a few vehicles; Can be combined with a global planner