COLREGs-Compliant Autonomous Collision Avoidance Using Multi-Objective Optimization with Interval Programming

Naval Ship Design Symposium

Presented by:

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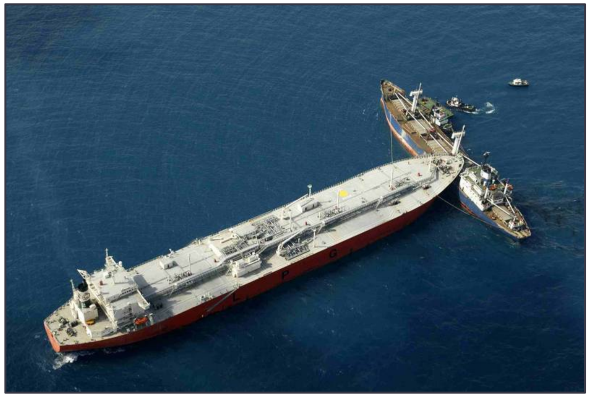
LT USN

Motivation

Importance

- Manned vessel integration
- Society's acceptance of AMVs
- Deployed autonomous assets
- AMV safety and efficiency: can we have both?



Difficulty

- Optimizing efficiency with maximum safety
- Real-time safety and efficiency assessments
- Rules written intentionally vague for humans
- Competing objectives: mission, navigation, contacts
- Real-time closest point of approach (CPA) computations
- Scaling the solution with multiple concurrent vehicles & rules

Literature Review

Basic COLREGs testing
(Benjamin 2006, Teo 2009)

Vehicle following
(Evans 2008, Bibuli 2012)

Emergency Reactive Behaviors
(Evans 2008)

COLREGs heading bias: always turn STBD
(Teo, 2009, Naeem 2010)

COLREGs with fuzzy logic
(Perera 2010, Perera 2012)

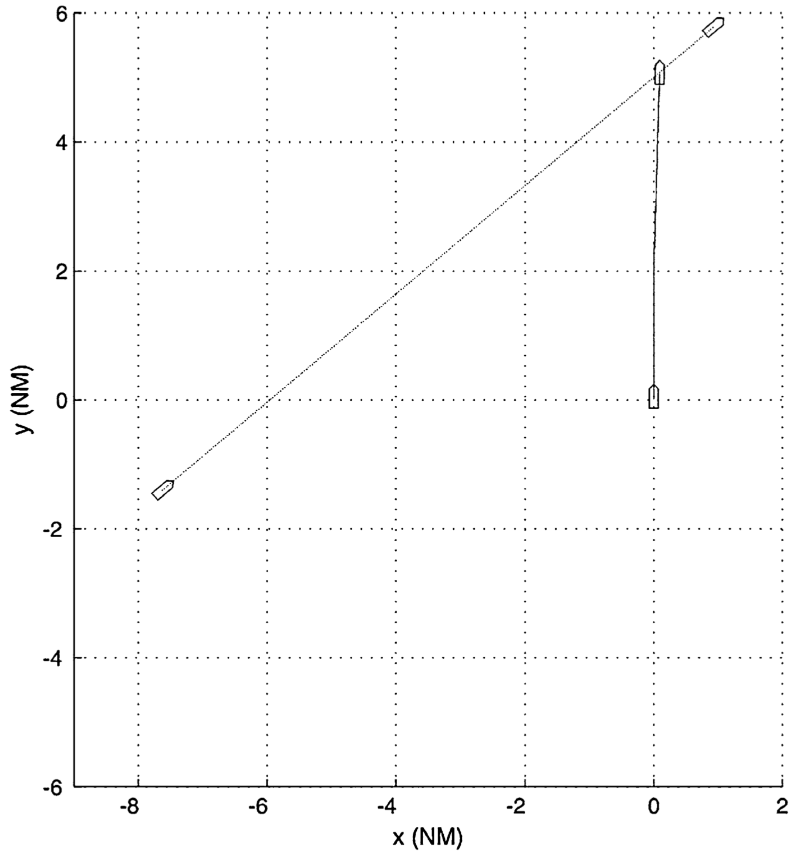


Fig. 24 Crossing situation

LP Perera, JP Carvalho, and CG Soares. Fuzzy logic based decision making system for collision avoidance of ocean navigation under critical collision conditions. *JOURNAL OF MARINE SCIENCE AND TECHNOLOGY*, 16(1):84 – 99, August 2010.

My Contributions to the Field

1. Robust COLREGs-compliant AMV algorithms
   - Multiple concurrent rules with multiple vehicles
   - Dynamic target vehicles with non-canonical geometry
   - Open-source environment: verifiable and reproducible
2. Safety-Efficiency Tradespace Study
   - Design of experiments with regression analysis
3. Extensive simulation and field validation
   - Extensive on-water testing (5 vehicles concurrently; literature max is 2)
   - Long-duration, robust simulation and analysis
   - Robust entry / exit criteria within each COLREGs rule base
4. Certification recommendations for COLREGs-AMVs
   - Testing and certification metrics
   - Compliance requirements and COLREGs changes

Developing COLREGs Algorithms

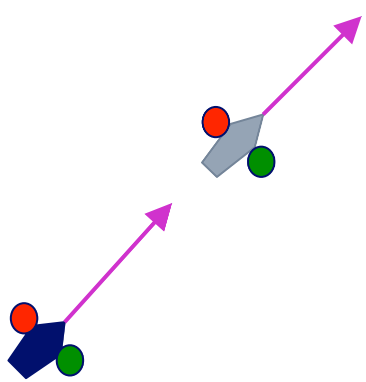
Four primary rules developed

Common approach with rule specifics enforced

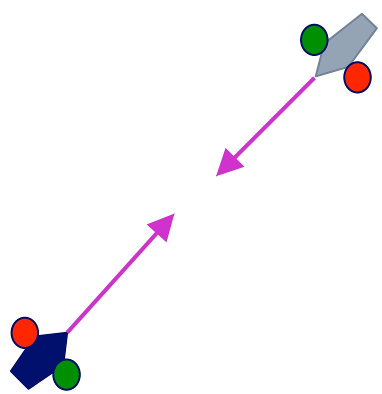
- Entry and exit criteria
- Heavily reward following the rule
- Penalize non-compliant behavior

PORT running light

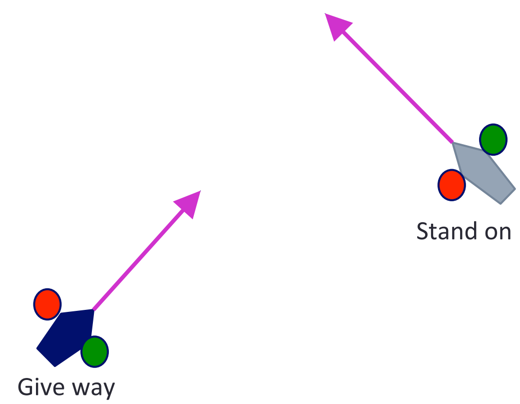
STBD running light



Overtaking



Head On



Crossing

Developing COLREGs Algorithms

$$\vec{x}^* = \operatorname{argmax}_{\vec{x}} \sum_{i=1}^{k} (w_i * f_i(\vec{x}))$$

Solve for the optimal solution of weighted sum of all objectives

- Mission requirements
- Navigational constraints
- Collision avoidance

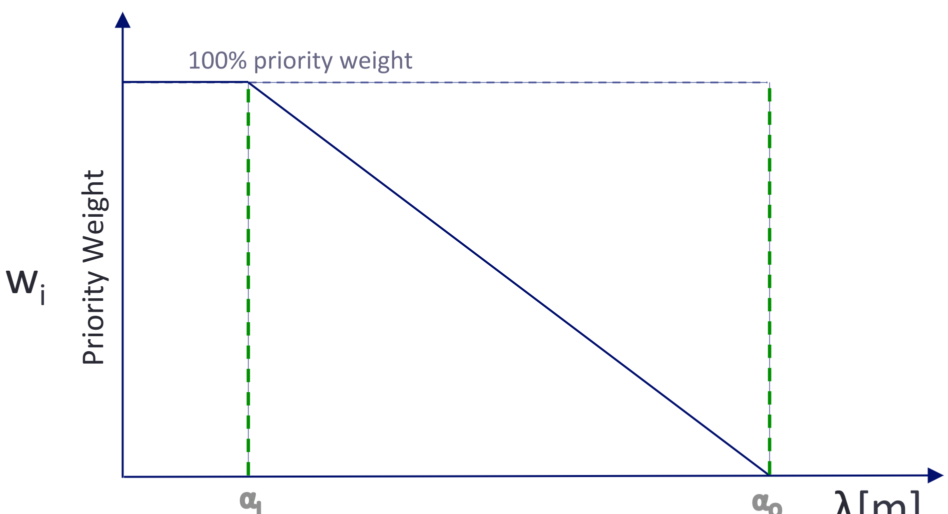
Each objective's weight determined by its relative precedence

- Safety
- Efficiency
- Mission constraints

Each objective f_i is weighted by its precedence w_i

Developing COLREGs Algorithms

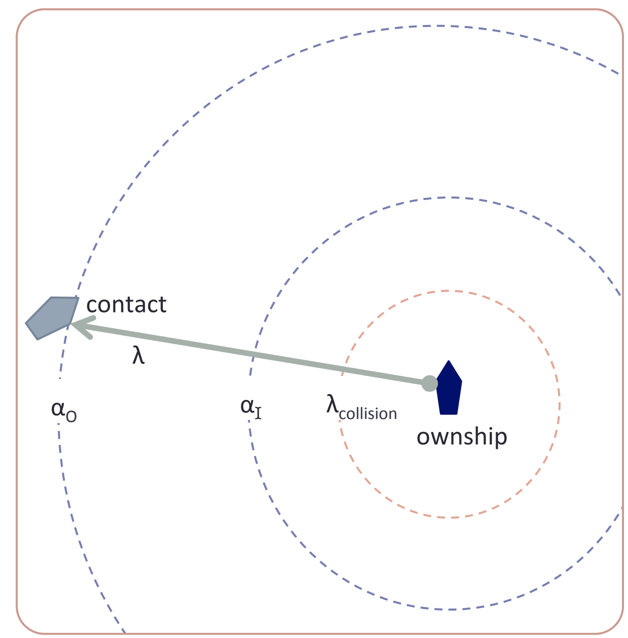
Collision Avoidance Objective Weight



Objective Defined for Each Vehicle Pair:

$$x^i = w_i * f_i(\vec{\xi}_O, \dot{\vec{\xi}}_O, \phi_O, \vec{\xi}_C, \dot{\vec{\xi}}_C, \phi_C)$$

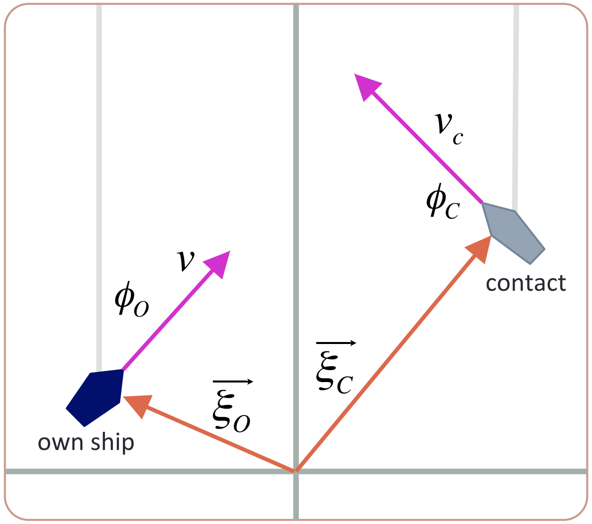
for i = 1,2,…,k



Developing COLREGs Algorithms

Computing λ_{CPA}

Given:	Ownship Position	$\overrightarrow{\xi_O} = (x, y)$
	Contact Position	$\overrightarrow{\xi_C} = (x_C, y_C)$
	Contact Trajectory	$(\phi_C, \lvert\dot{\xi}_C\rvert = v_c)$
Variables:	Course, Speed, Time	(ϕ, v, t)



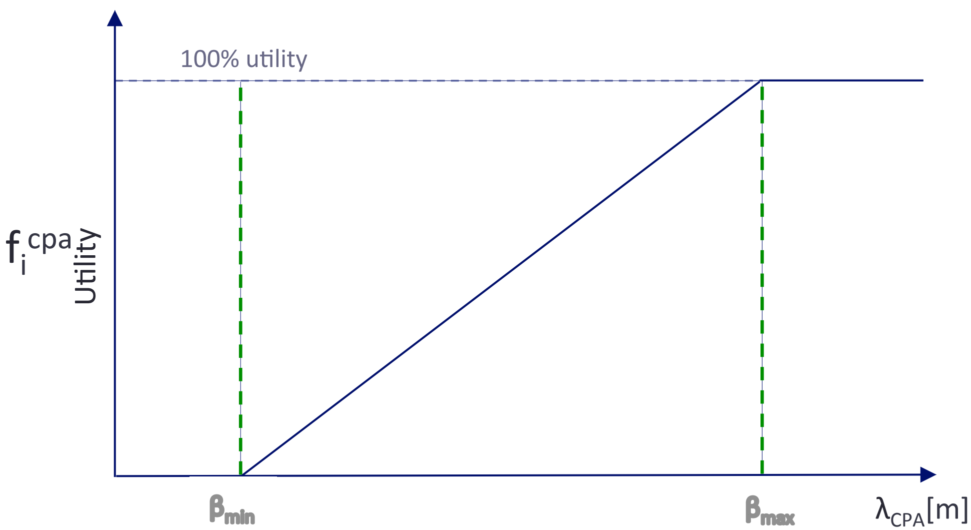
$$\boxed{\lambda^2(\phi, v, t) = k_2 t^2 + k_1 t + k_0}$$

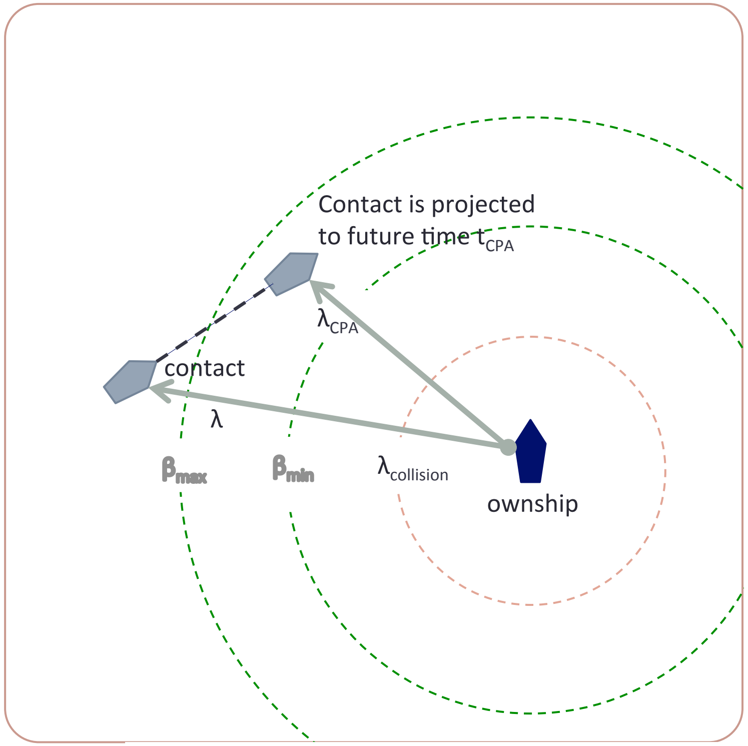
$$k_2 = v^2\cos(\phi) - 2vv_C\cos(\phi)\cos(\phi_C) + v_C^2\cos^2(\phi_C) + v^2\sin^2(\phi) - 2vv_C\sin(\phi)\sin(\phi_C) + v_C^2\sin^2(\phi_C)$$

$$k_1 = 2vy\cos(\phi) - 2vy_C\cos(\phi) - 2yv_C\cos(\phi_C) + 2v_Cy_C\cos(\phi_C) + 2vx\sin(\phi) - 2vx_C\sin(\phi) - 2xv_C\sin(\phi_C) + 2v_Cx_C\sin(\phi_C)$$

$$k_0 = y^2 - 2yy_C + y_C^2 + x^2 - 2xx_C + x_C^2$$

Developing COLREGs Algorithms

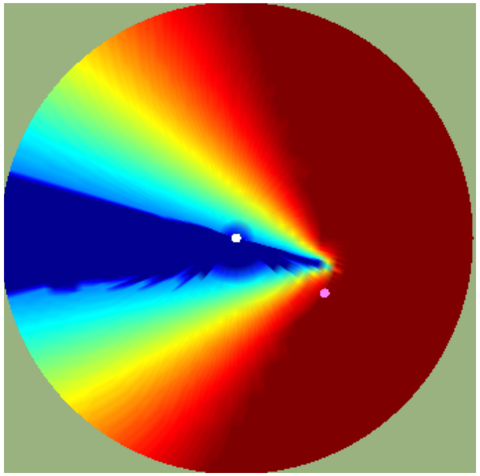




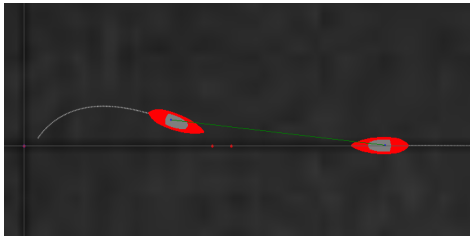
Now Couple CPA with Rule Requirements

Developing COLREGs Algorithms

Rule Coupling



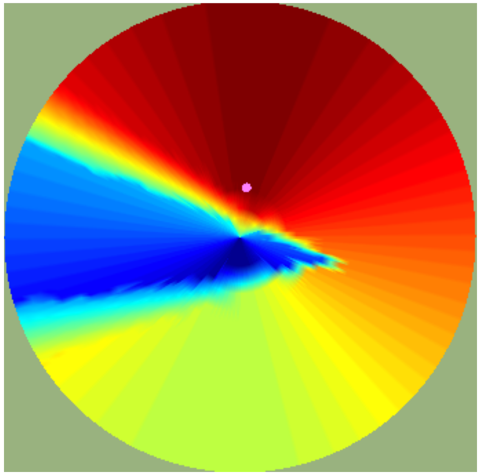
CPA-only allows symmetric maneuvers
← efficiency and safety suffer



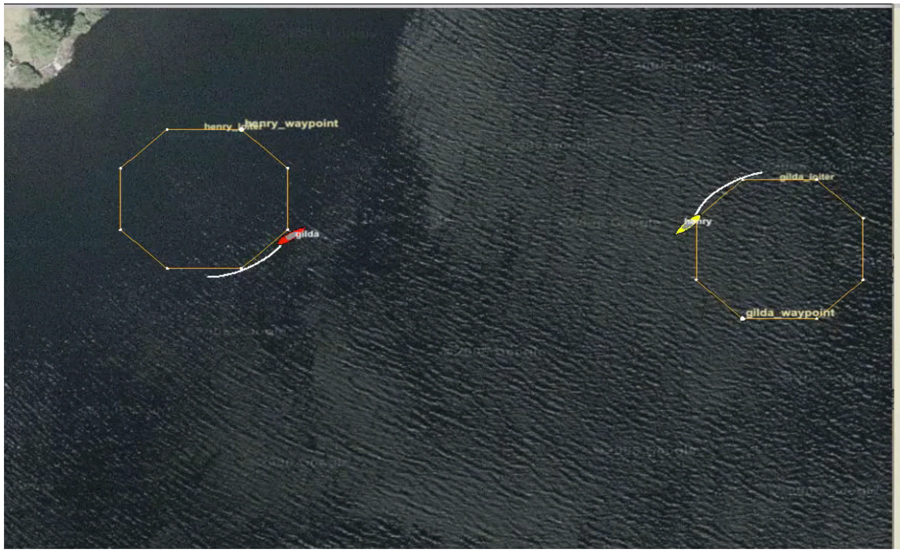
Head On Geometry

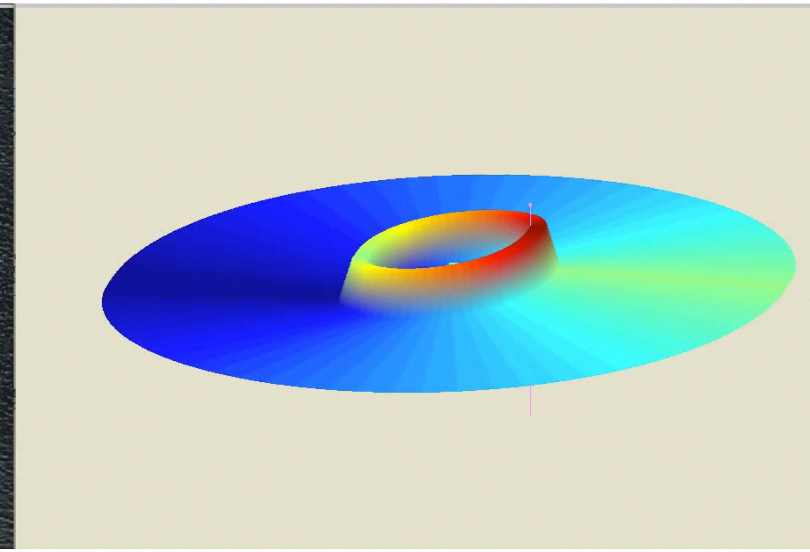
COLREGs based solution
→ Rule-compliant choices attractive
→ Heavy rule weighting couples CPA

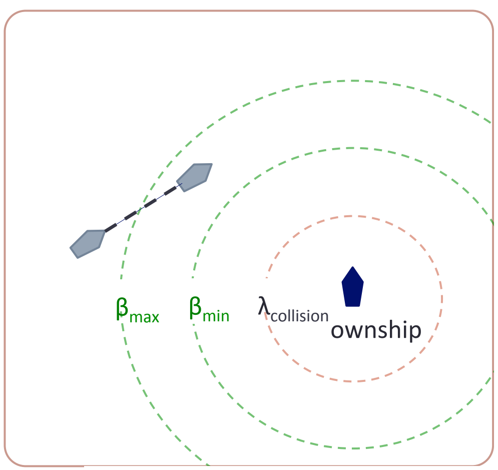
COLREGs example solution: head on
→ Heavy penalty for turning to PORT



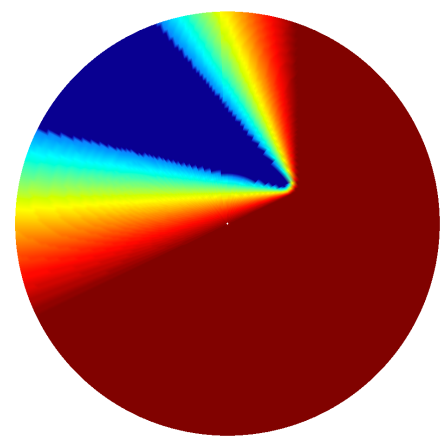
Example Scenario







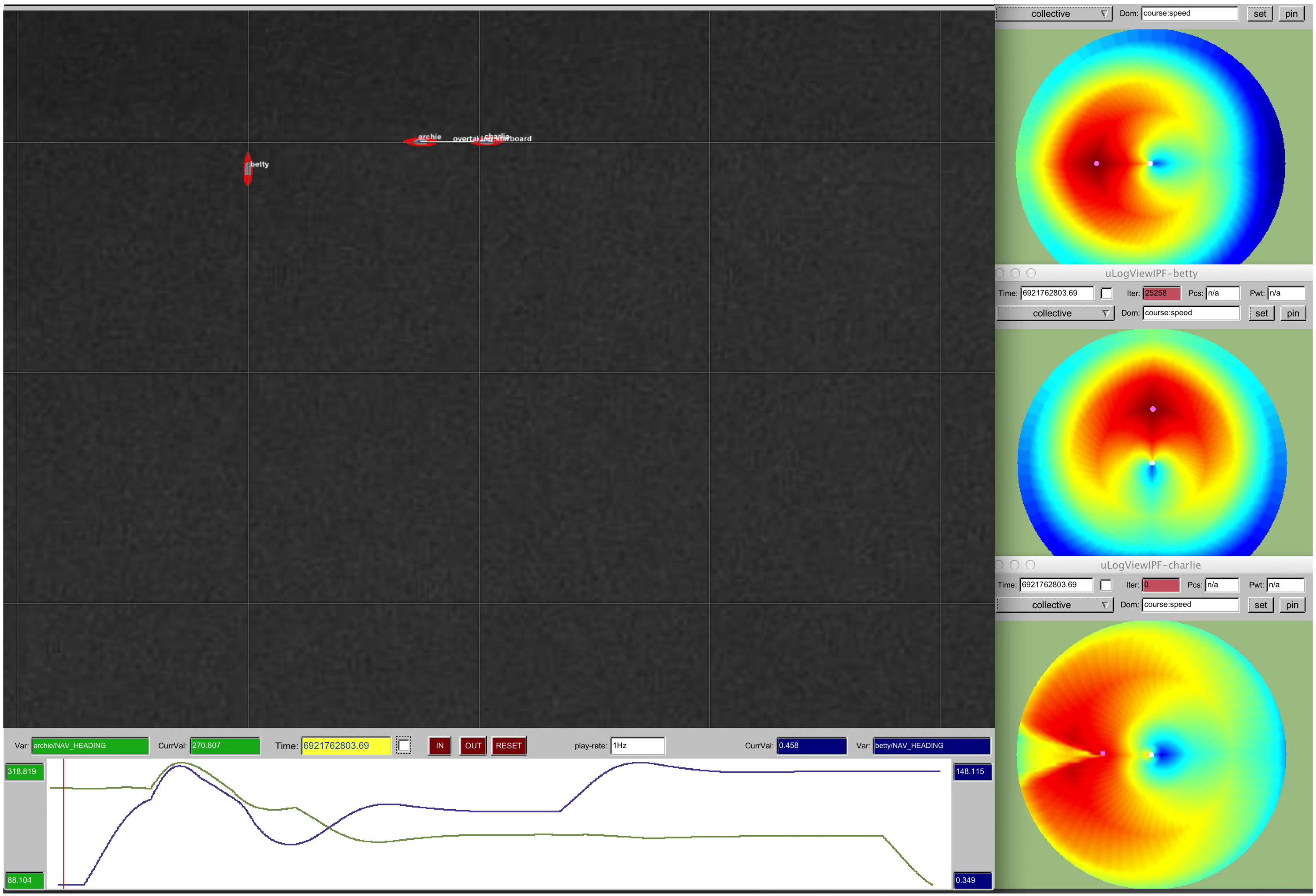
$$\vec{x}^* = argmax_{\vec{x}} \sum_{i=1}^{k} (w_i * f_i(\vec{x}))$$



Multiple Vehicles

Multiple Concurrent Rules

*Vehicle Size Increased For Viewing



CCW Front

CW

CCW Rear

Design of Experiments

Optimizing the Safety-Efficiency Tradespace

What collision avoidance parameters are most important to safety and efficiency?

Can safety be *improved* by adding COLREGs protocols?

How close to contact-free efficiency can be achieved without compromising safety?

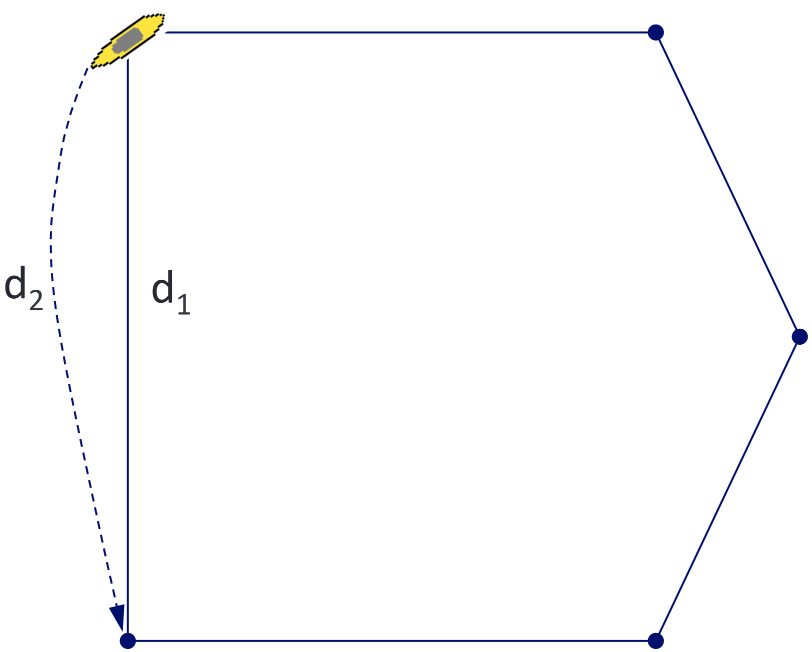
Design of Experiments

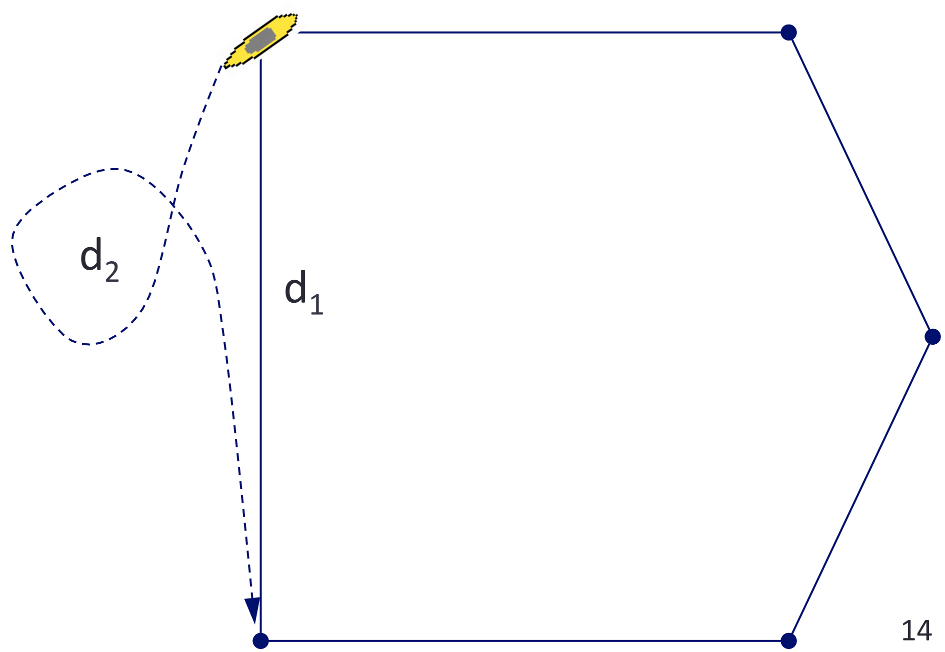
Optimizing the Safety-Efficiency Tradespace

d_1 is the distance directly to the next waypoint once the previous waypoint has been achieved.

d_2 is the observed distance travelled.

$$\eta = \frac{d_1}{d_2}$$





Design of Experiments

Optimizing the Safety-Efficiency Tradespace

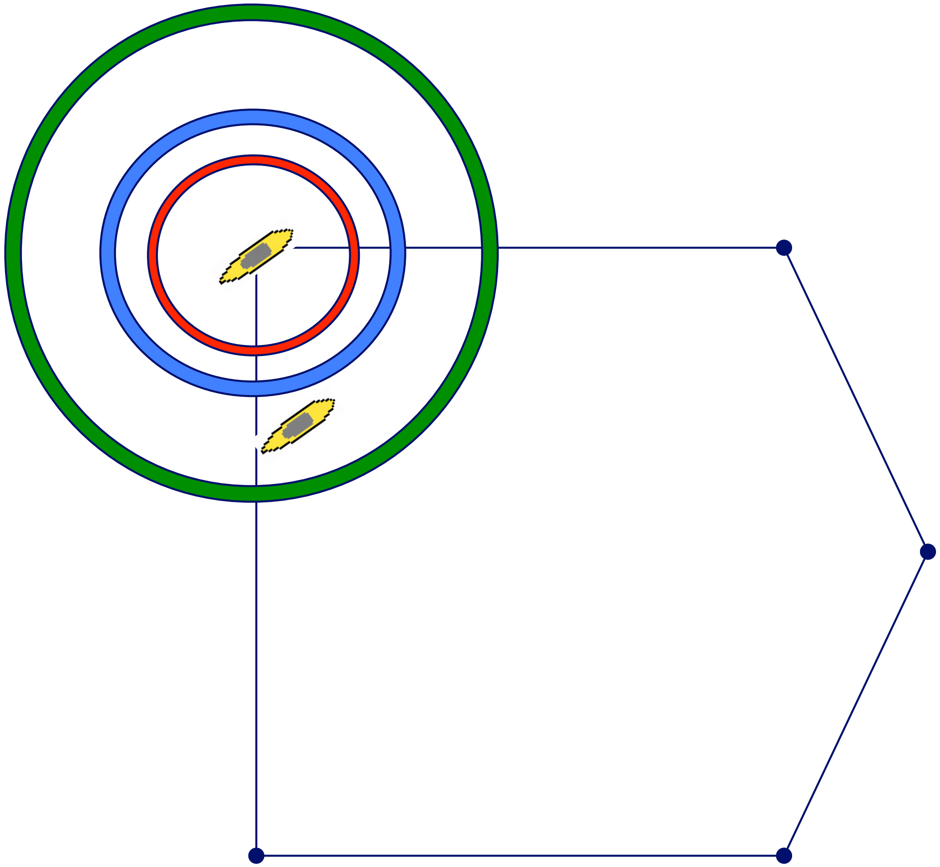
Desires to maintain target between green and blue circles

β_{MAX}

β_{MIN}

Considered a collision if target inside red circle

$\lambda_{collision}$



Collision events determined by uFldCollisionDetect.

Design of Experiments

Optimizing the Safety-Efficiency Tradespace

Each experiment has O(~10^4) vehicle interactions

- long duration statistical averaging
- various interaction geometries

Regression analysis to find optimal explanatory parameter values

- α_I, α_O, β_{MIN}, β_{MAX}, $v_{relative}$ for each algorithm (COLREGs & generic)
- Central Composite Design for Generic Algorithm
- Central Composite Design for COLREGs Algorithm

Study effects on response variables:

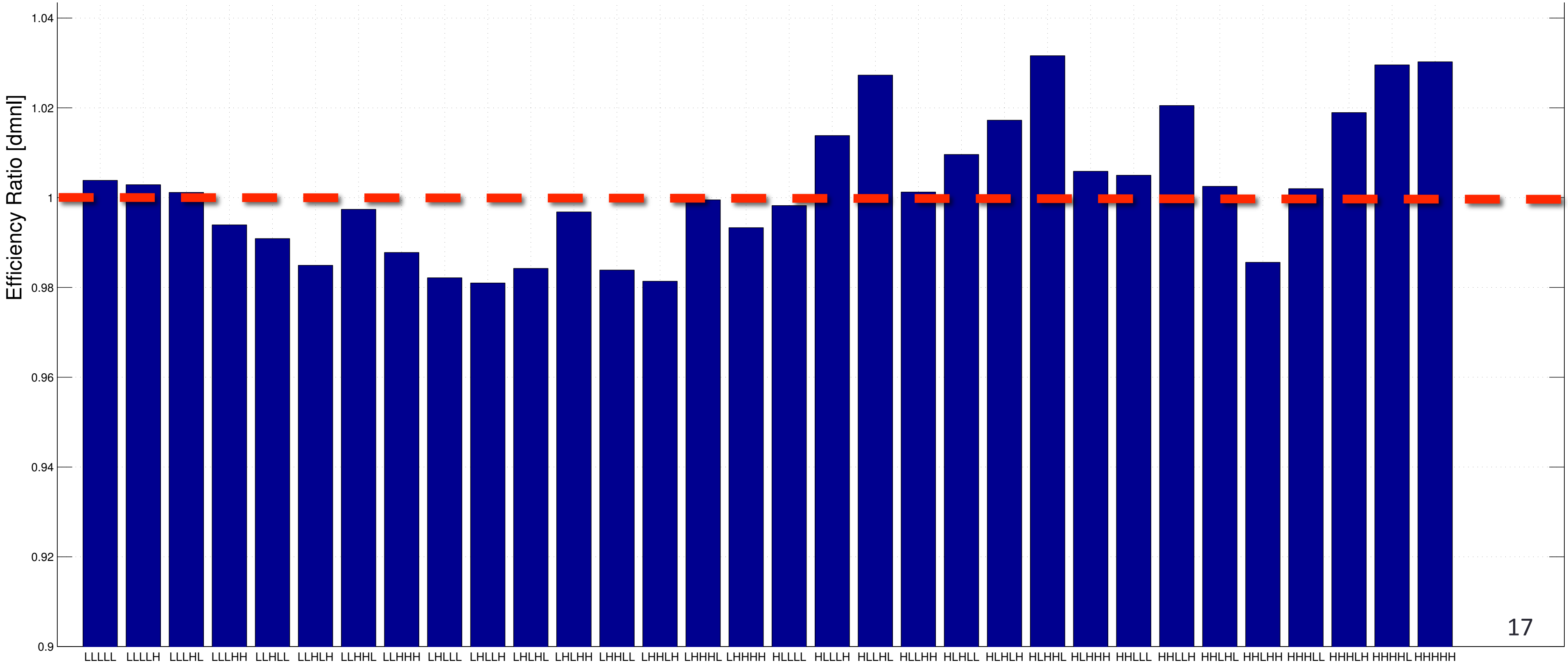
- η_{mean}, η_{std}, η_{min}, η_{max}, percent of "collisions"
- Find optimal parameters for safety then maximize efficiency

Efficiency Factor

Optimizing the Safety-Efficiency Tradespace

Efficiency ratio (COLREGS-to-CPA) of 99.618% over all experiments

Result: Negligible loss in efficiency for cases studied



Safety Improvement Factor

Optimizing the Safety-Efficiency Tradespace

COLREGS safer in 21 of 32 experiments

- average 18.4 times reduction in collisions

CPA safer in 11 of 32 experiments

- Average of 0.91 times safer
- All edge cases where normal operation not expected

Result: COLREGS safety improvement significant

Follow On Applications

- Inclusion of other onboard sensors to incorporate manned vessels (e.g., cameras, radar, laser range finder)
- Inclusion of land-based sensors such as pole mounted cameras for greater contact integration
- Inclusion of broadcast information from non-MOOS protocols (e.g., AIS)
- Real-time negotiation of contact maneuvers similar to that accomplished by bridge-to-bridge radio of manned vessels
- Early detection of non-compliant vessels from a shore side watchdog for both community and non-community vessels
- Early detection of non-compliant vessels from own ship watchdog for early determination of potential safety concerns
- Integration of other vessel rules (e.g., sailing vessels, reduced visibility)

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