Implementing the COLREG in Collision Avoidance Algorithms

WP4 Online Seminar

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WP2 - Digital infrastructure

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Kunnskap for en bedre verden

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PhD Candidate at Department of Engineering Cybernetics

PhD Title:
Collaborative Collision Avoidance for Autonomous Ships

Affiliated Projects:
SFI Autoship, WP 2, Use Case 2
AMOS

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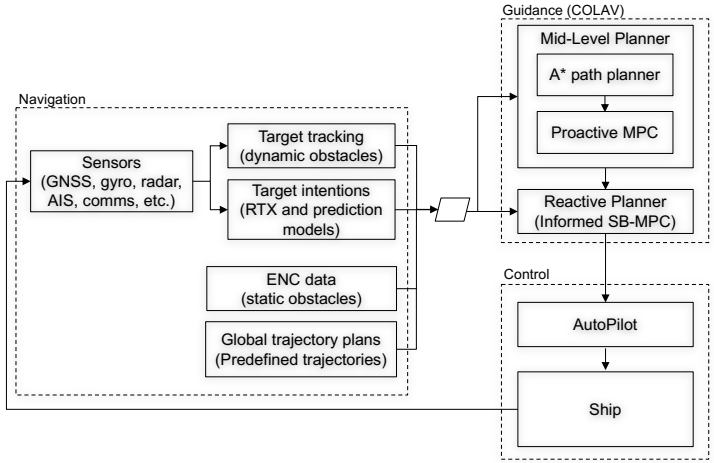
Collision avoidance algorithm

Reactive Algorithms
- No communication
- Independent plans

Collision avoidance algorithm

Hierarchical Algorithms
- Communication
- Exchanging plans



The COLREG

Part A		Rule 1	Application
		Rule 2	Responsibility
		Rule 3	General definitions
Part B	In any vis.	Rule 4	Application
		Rule 5	Look-out
		Rule 6	Safe speed
		Rule 7	Risk of collision
		Rule 8	Action to avoid collision
		Rule 9	Narrow channels
		Rule 10	Traffic separation schemes
	In sight	Rule 11	Application
		Rule 12	Sailing vessels
		Rule 13	Overtaking
		Rule 14	Head-on situation
		Rule 15	Crossing situation
		Rule 16	Action by give-way vessel
		Rule 17	Action by stand-on vessel
		Rule 18	Responsibilities between vessels
	Rest. vis.	Rule 19	Conduct of vessels in rest. vis.
Part C	Lights and shapes	Rule 20	Application
		Rule 21	Definitions
		Rule 22	Visibility of lights
		Rule 23	Power-driven vessels underway
		Rule 24	Towing and pushing
		Rule 25	Sailing vessels underway
		Rule 26	Fishing vessels
		Rule 27	Vessels not under command or rest. in ability to maneuver
		Rule 28	Constrained by draught
		Rule 29	Pilot vessels
		Rule 30	Anchored and aground vessels
		Rule 31	Seaplanes
Part D	Sound and light signals	Rule 32	Definitions
		Rule 33	Eq. for sound signals
		Rule 34	Maneuvering and warning signals
		Rule 35	Sound signals in rest. vis.
		Rule 36	Signals to attract attention
		Rule 37	Distress signals
Part E		Rule 38	Exemptions
			Annexes

[1]

The COLREG

Part A		Rule 1	Application
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[2] [3]

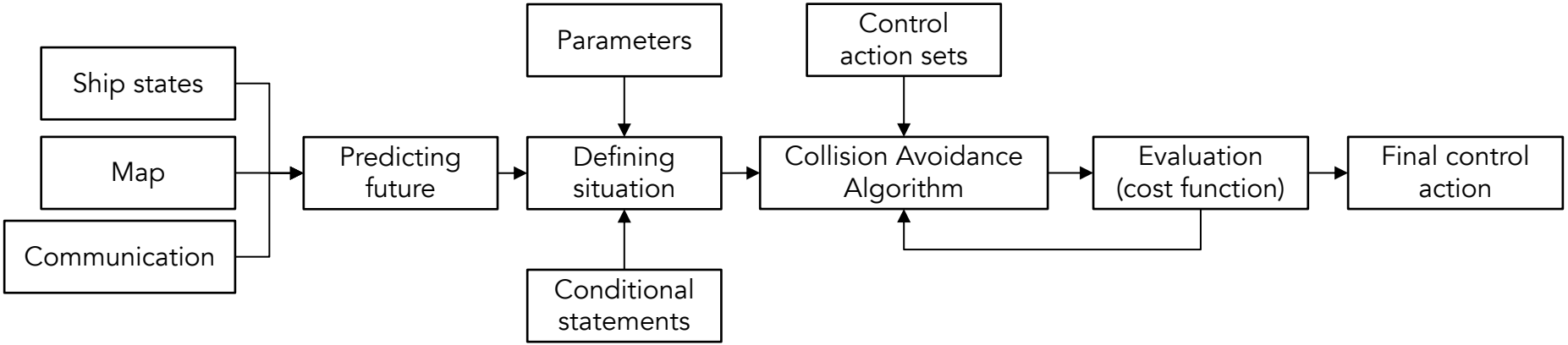
The COLREG

Part A		Rule 1	Application	
		Rule 2	Responsibility	Follow the rules. Deviate from rules if that's the only way to a avoid collision
		Rule 3	General definitions	
Part B	In any vis.	Rule 4	Application	
		Rule 5	Look-out	
		Rule 6	Safe speed	Regulate your speed to a avoid collision
		Rule 7	Risk of collision	Evaluate the scenarios for risk of collision
		Rule 8	Action to avoid collision	Precise, apparent, early actions. Maintain safe distance. Consider course and/or speed change.
		Rule 9	Narrow channels	
		Rule 10	Traffic separation schemes	
	In sight	Rule 11	Application	
		Rule 12	Sailing vessels	
		Rule 13	Overtaking	Keep clear from overtaken ship.
		Rule 14	Head-on situation	Starboard course change.
		Rule 15	Crossing situation	Give way to the vessel on your starboard side.
		Rule 16	Action by give-way vessel	Early and clear action to keep clear.
		Rule 17	Action by stand-on vessel	Keep course and speed. Starboard turn if GW is not acting
		Rule 18	Responsibilities between vessels	
	Rest. vis.	Rule 19	Conduct of vessels in rest. vis.	Keep out of the way of ships with reduced maneuverability

[5]

Implementation of the COLREG

How to implement the COLREG to a collision avoidance algorithm?

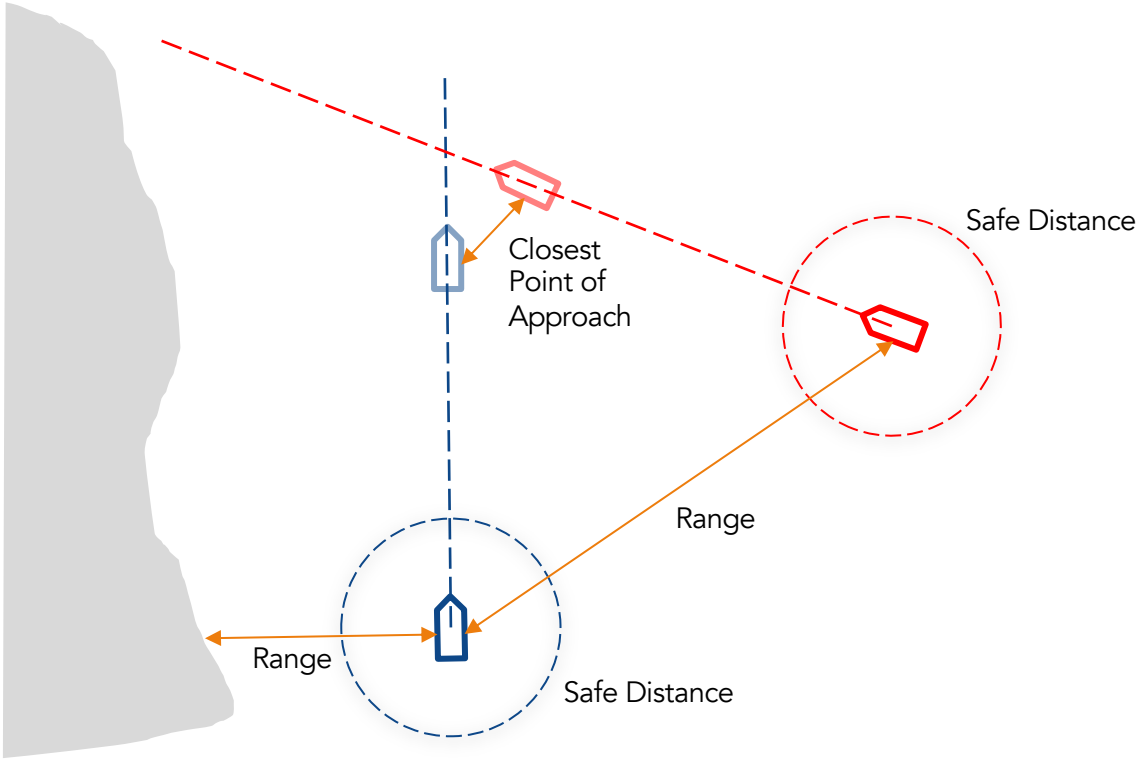


Implementation of the COLREG

Rule 7 – Risk of collision

Collision risk evaluation:

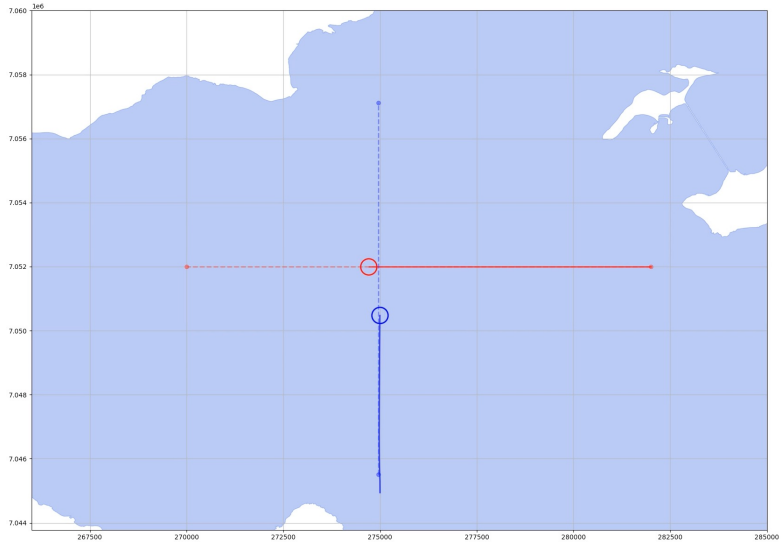
- Distance at CPA
- Time to CPA
- Safe distance
- Range
- Ship speeds



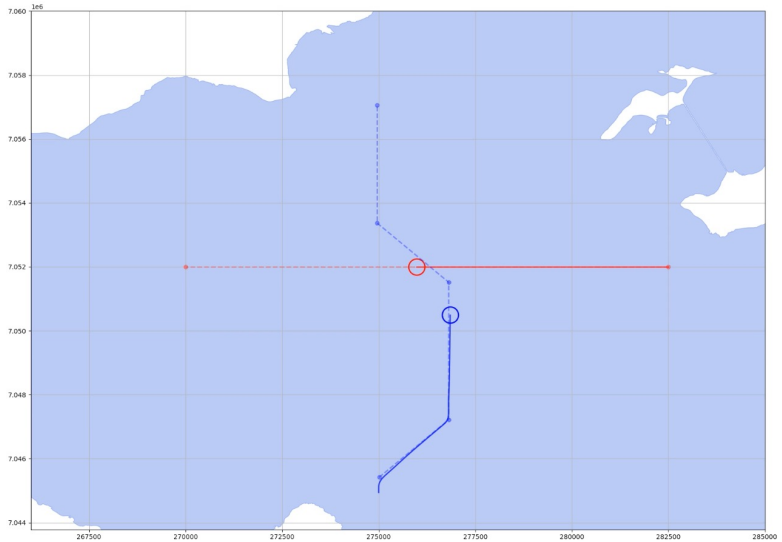
Implementation of the COLREG

Rule 6 – Safe speed

- Multiple trajectory planning with different speeds (Between nominal speed and half speed)
- Comparing trajectories with cost functions (speed change, length, collision risk, etc.)



Changing speed

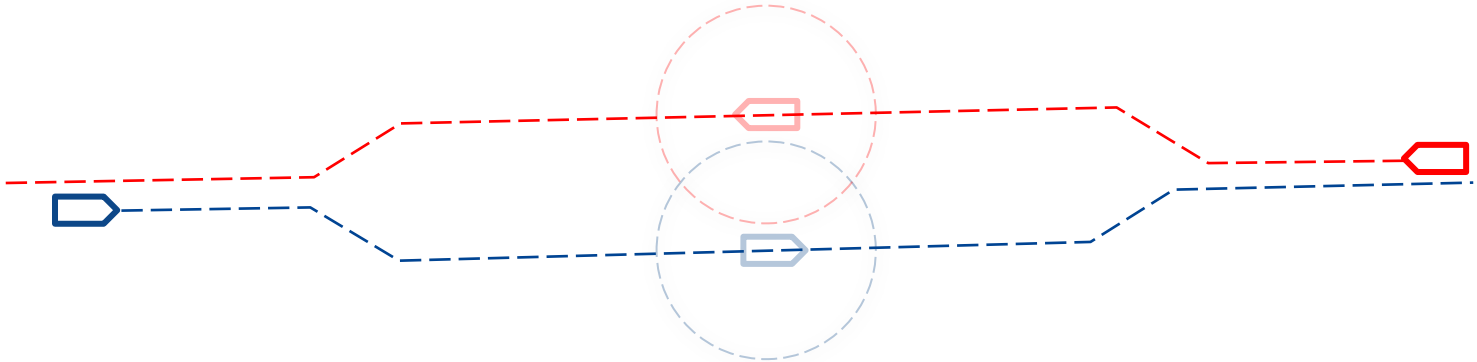


Changing course

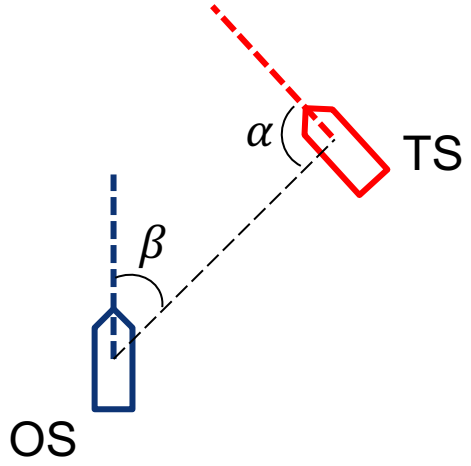
Implementation of the COLREG

Rule 8 – Action to avoid a collision

- Early planning
- Apparent course changes by discrete course sets
- Maintaining safe distance
- Course and speed change possibility



Implementation of the COLREG

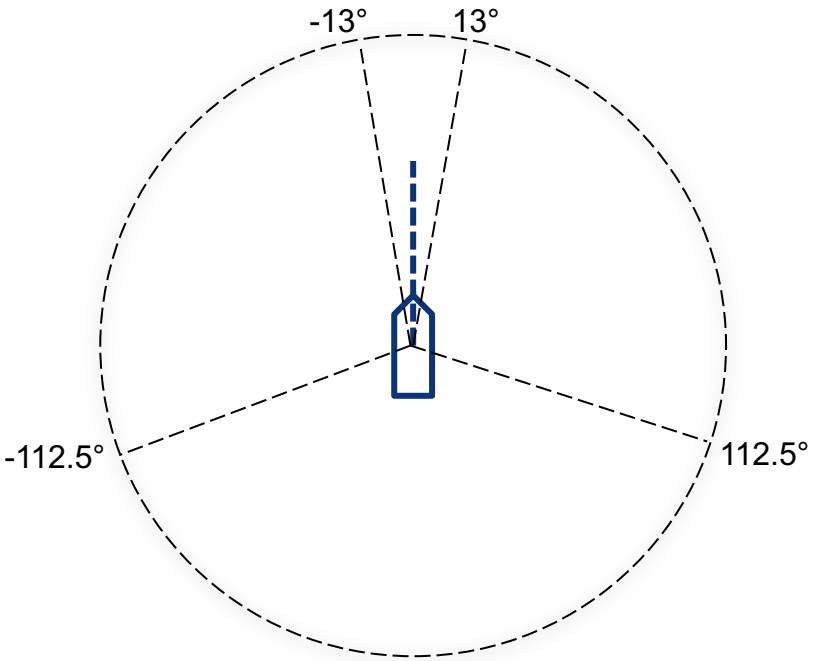


[4]

Algorithm 2 The COLREG Rule Evaluation

procedure THE COLREG RULES
  $\alpha_i \leftarrow$ Relative bearing of OS from TS_i
  $\beta_i \leftarrow$ Relative bearing of TS_i from OS
  $u_{OS} \leftarrow OS$ speed
  $u^i_{TS} \leftarrow TS_i$ speed
  if $(|\beta_i| < 13°) \wedge (|\alpha_i| < 13°)$ **then**
    Rule $\leftarrow$ Head-on (HO)
  else if $(|\beta_i| > 112.5°) \wedge (|\alpha_i| < 45°) \wedge (u^i_{TS} > u_{OS})$ **then**
    Rule $\leftarrow$ Overtaken (ON)
  else if $(|\alpha_i| < 112.5°) \wedge (|\beta_i| < 45°) \wedge (u_{OS} > u^i_{TS})$ **then**
    Rule $\leftarrow$ Overtaking (OG)
  else if $(-112.5° < \beta_i < 0°) \wedge (-10° < \alpha_i < 112.5°)$ **then**
    Rule $\leftarrow$ Crossing Stand-on (CR_{SO})
  else if $(-112.5° < \alpha_i < 0°) \wedge (-10° < \beta_i < 112.5°)$ **then**
    Rule $\leftarrow$ Crossing Give-way (CR_{GW})
  else
    Rule $\leftarrow$ None

Implementation of the COLREG



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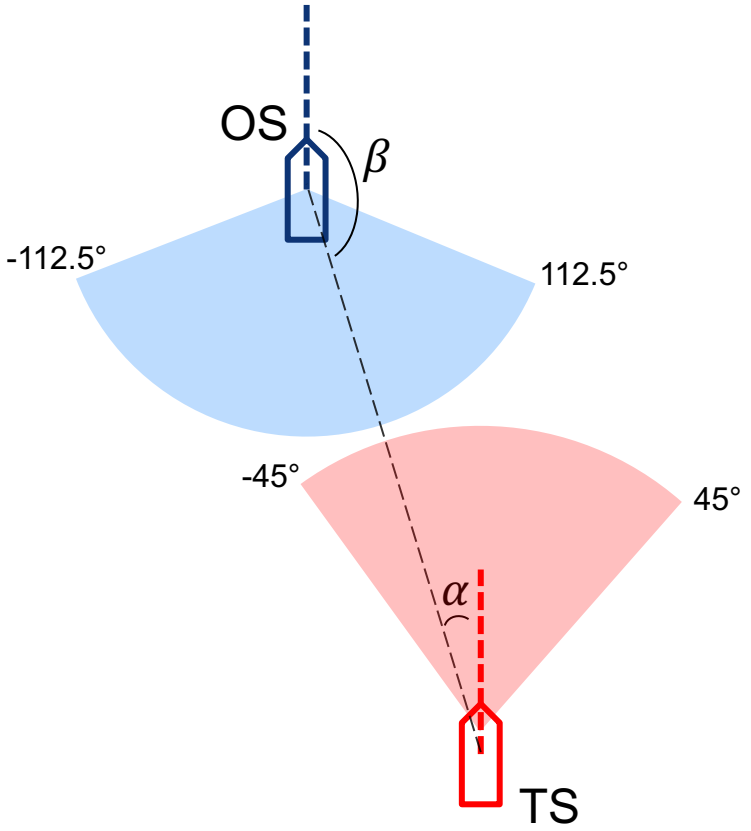
    Rule $\leftarrow$ Crossing Give-way (CR_{GW})
  else
    Rule $\leftarrow$ None

Implementation of the COLREG

Rule 13 - Overtaken

Algorithm 2 The COLREG Rule Evaluation

```
1:  procedure THE COLREG RULES
2:      α_i ← Relative bearing of OS from TS_i
3:      β_i ← Relative bearing of TS_i from OS
4:      u_OS ← OS speed
5:      u^i_TS ← TS_i speed
6:      if (|β_i| < 13°) ∧ (|α_i| < 13°) then
7:          Rule ← Head-on (HO)
8:      else if (|β_i| > 112.5°) ∧ (|α_i| < 45°) ∧ (u^i_TS > u_OS) then
9:          Rule ← Overtaken (ON)
10:     else if (|α_i| < 112.5°) ∧ (|β_i| < 45°) ∧ (u_OS > u^i_TS) then
11:         Rule ← Overtaking (OG)
12:     else if (−112.5° < β_i < 0°) ∧ (−10° < α_i < 112.5°) then
13:         Rule ← Crossing Stand-on (CR_SO)
14:     else if (−112.5° < α_i < 0°) ∧ (−10° < β_i < 112.5°) then
15:         Rule ← Crossing Give-way (CR_GW)
16:     else
17:         Rule ← None
```



Implementation of the COLREG

Rule 13 - Overtaking

Algorithm 2 The COLREG Rule Evaluation

```
1:  procedure THE COLREG RULES
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6:      if (|β_i| < 13°) ∧ (|α_i| < 13°) then
7:          Rule ← Head-on (HO)
8:      else if (|β_i| > 112.5°) ∧ (|α_i| < 45°) ∧ (u^i_TS > u_OS) then
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11:         Rule ← Overtaking (OG)
12:     else if (−112.5° < β_i < 0°) ∧ (−10° < α_i < 112.5°) then
13:         Rule ← Crossing Stand-on (CR_SO)
14:     else if (−112.5° < α_i < 0°) ∧ (−10° < β_i < 112.5°) then
15:         Rule ← Crossing Give-way (CR_GW)
16:     else
17:         Rule ← None
```

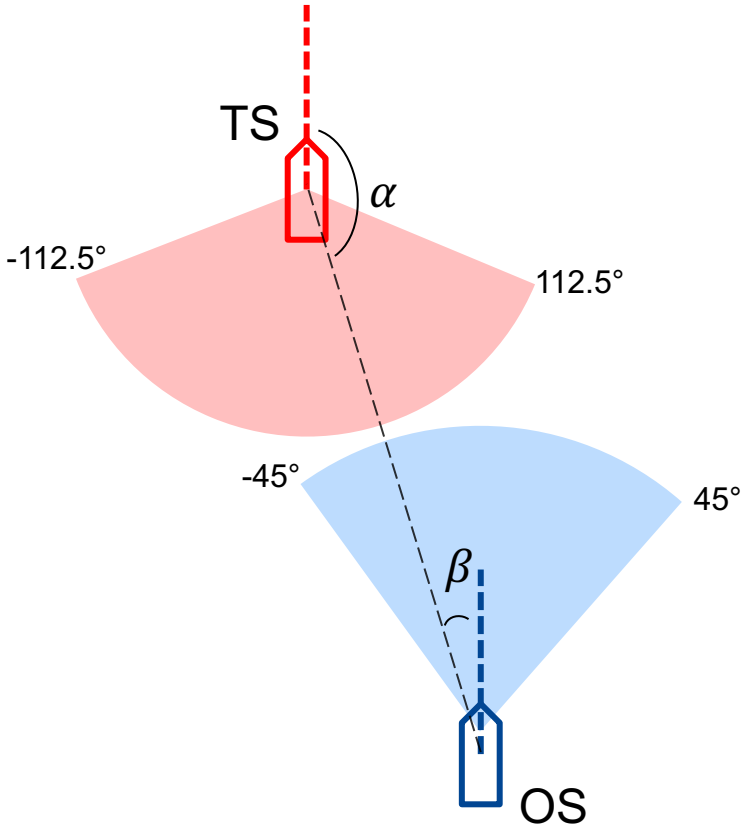

Implementation of the COLREG

Rule 14 - Head-on

Algorithm 2 The COLREG Rule Evaluation

procedure THE COLREG RULES
  $\alpha_i \leftarrow$ Relative bearing of OS from TS_i
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  else if $(|\beta_i| > 112.5°) \wedge (|\alpha_i| < 45°) \wedge (u^i_{TS} > u_{OS})$ **then**
    Rule $\leftarrow$ Overtaken (ON)
  else if $(|\alpha_i| < 112.5°) \wedge (|\beta_i| < 45°) \wedge (u_{OS} > u^i_{TS})$ **then**
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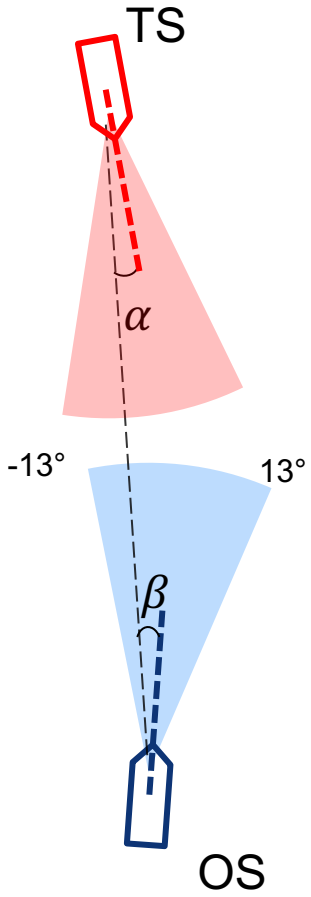
  else if $(-112.5° < \beta_i < 0°) \wedge (-10° < \alpha_i < 112.5°)$ **then**
    Rule $\leftarrow$ Crossing Stand-on (CR_{SO})
  else if $(-112.5° < \alpha_i < 0°) \wedge (-10° < \beta_i < 112.5°)$ **then**
    Rule $\leftarrow$ Crossing Give-way (CR_{GW})
  else
    Rule $\leftarrow$ None

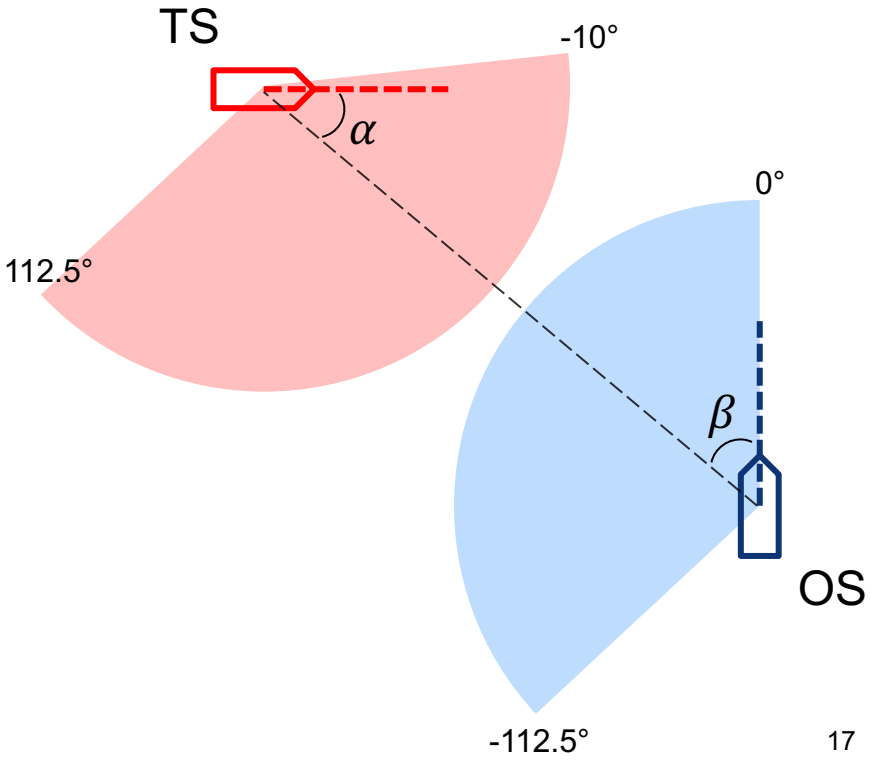


Implementation of the COLREG

Rule 15 - Crossing stand-on

Algorithm 2 The COLREG Rule Evaluation

```
1:  procedure THE COLREG RULES
2:      α_i ← Relative bearing of OS from TS_i
3:      β_i ← Relative bearing of TS_i from OS
4:      u_OS ← OS speed
5:      u^i_TS ← TS_i speed
6:      if (|β_i| < 13°) ∧ (|α_i| < 13°) then
7:          Rule ← Head-on (HO)
8:      else if (|β_i| > 112.5°) ∧ (|α_i| < 45°) ∧ (u^i_TS > u_OS) then
9:          Rule ← Overtaken (ON)
10:     else if (|α_i| < 112.5°) ∧ (|β_i| < 45°) ∧ (u_OS > u^i_TS) then
11:         Rule ← Overtaking (OG)
12:     else if (−112.5° < β_i < 0°) ∧ (−10° < α_i < 112.5°) then
13:         Rule ← Crossing Stand-on (CR_SO)
14:     else if (−112.5° < α_i < 0°) ∧ (−10° < β_i < 112.5°) then
15:         Rule ← Crossing Give-way (CR_GW)
16:     else
17:         Rule ← None
```



Implementation of the COLREG

Rule 15 - Crossing give-way

Algorithm 2 The COLREG Rule Evaluation

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15: Rule $\leftarrow$ Crossing Give-way (CR_{GW})
16: **else**
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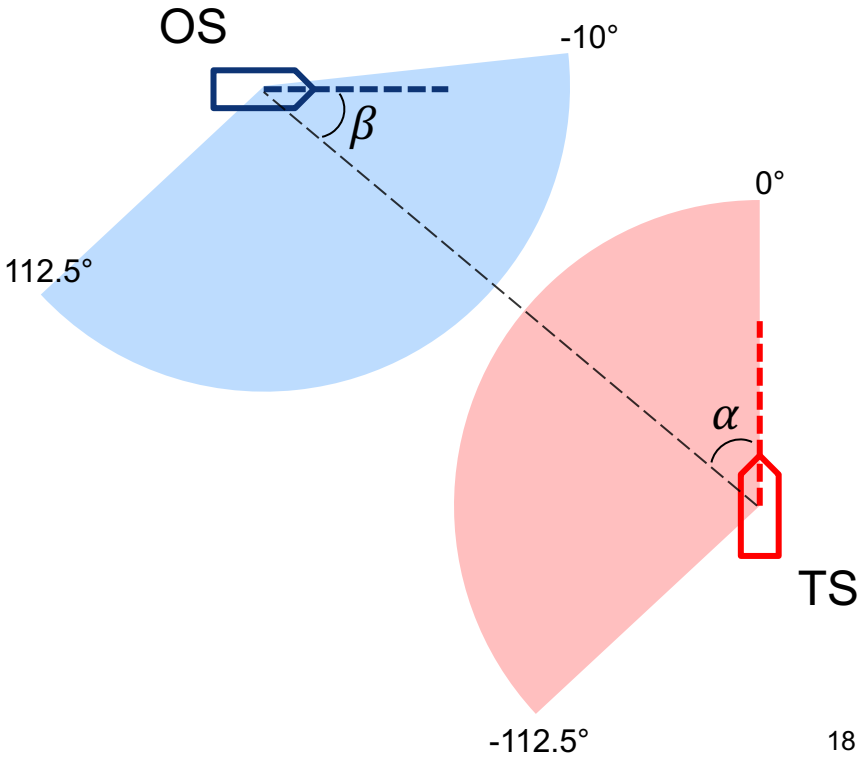
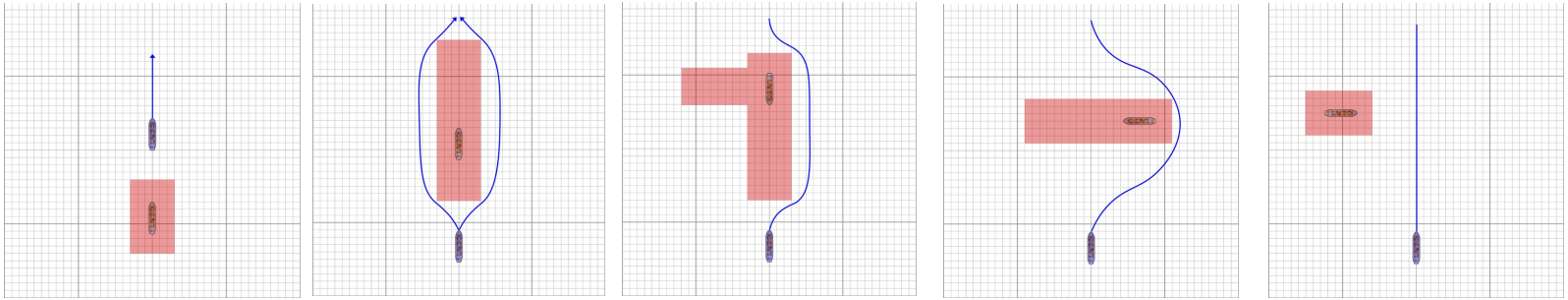


Implementation of the COLREG

Rule 16, 17 – Actions by give-way and stand-on vessels

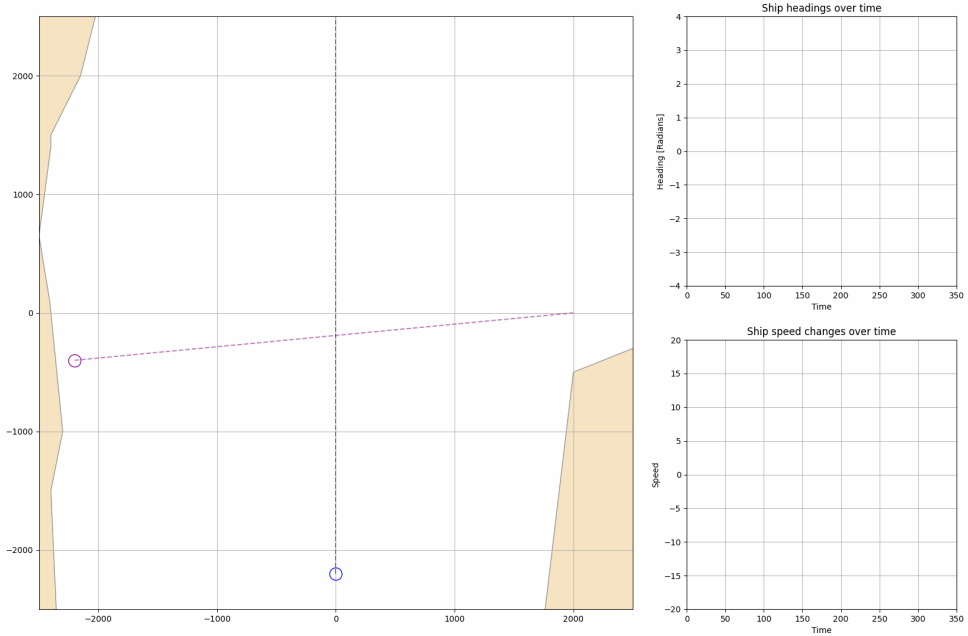
Trajectory Planning with the A* algorithm	Trajectory optimization with the Proactive MPC	Trajectory planning with the Informed SB-MPC
Blocking additional areas to guide planning	Port turn is penalized in the cost function	Penalizing actions against the rules in the cost function



Overtaken | Overtaking | Head-on | Crossing GW | Crossing SO

Implementation of the COLREG

Rule 2 – Responsibilities and Rule 17 – Actions by stand-on vessel

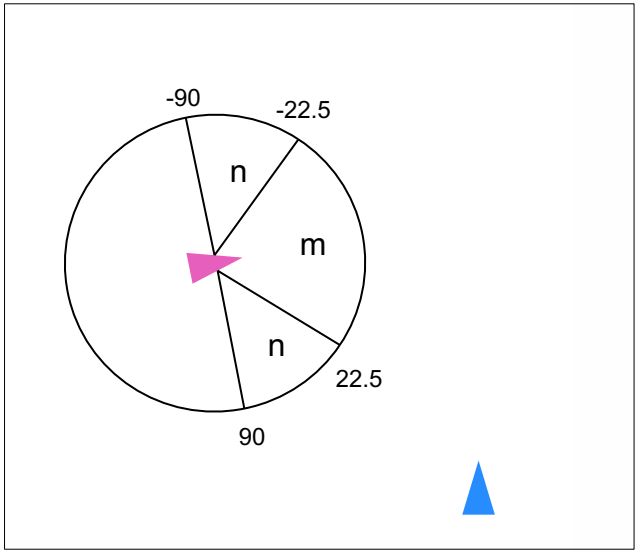


SB-MPC and deviation from the SO responsibility.

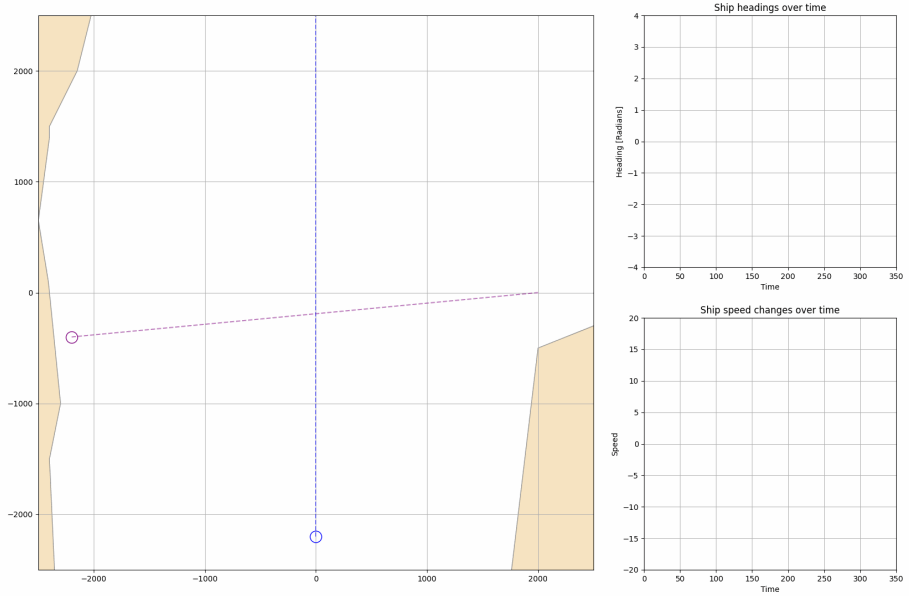
Implementation of the COLREG

Rule 18 – Responsibilities between vessels

Hierarchy between different types of vessels



$$\zeta_i^k(t) = \begin{cases} m, & \text{if } |\beta_i| \leq 22.5^\circ \vee |\alpha_i| \leq 22.5^\circ \\ n, & \text{if } 22.5^\circ < |\alpha_i| \leq 90^\circ \\ 0, & otherwise \end{cases}$$



R18 implementation in Informed SB-MPC.

Conclusion

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		Rule 6	Safe speed
		Rule 7	Risk of collision
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[5]

References

[1] IMO, “Convention on the International Regulations for Preventing Collisions at Sea, 1972, (COLREGs),” London: IMO., 1972

[2] Öztürk, Ülkü, Melih Akdağ, and Tarık Ayabakan. "A review of path planning algorithms in maritime autonomous surface ships: Navigation safety perspective." *Ocean Engineering* 251 (2022): 111010.

[3] Burmeister, Hans-Christoph, and Manfred Constapel. "Autonomous collision avoidance at sea: A survey." *Frontiers in Robotics and AI* (2021): 297.

[4] Woerner, Kyle. Multi-contact protocol-constrained collision avoidance for autonomous marine vehicles. Diss. Massachusetts Institute of Technology, 2016.

[5] Akdağ, Melih, Thor I. Fossen, and Tor A. Johansen. "Collaborative Collision Avoidance for Autonomous Ships Using Informed Scenario-Based Model Predictive Control." IFAC-PapersOnLine 55.31 (2022): 249-256.

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