

# Intelligent, Rule-aware, and Fault-Tolerant solutions for Seamless Short-sea and Inland Waterway Navigation

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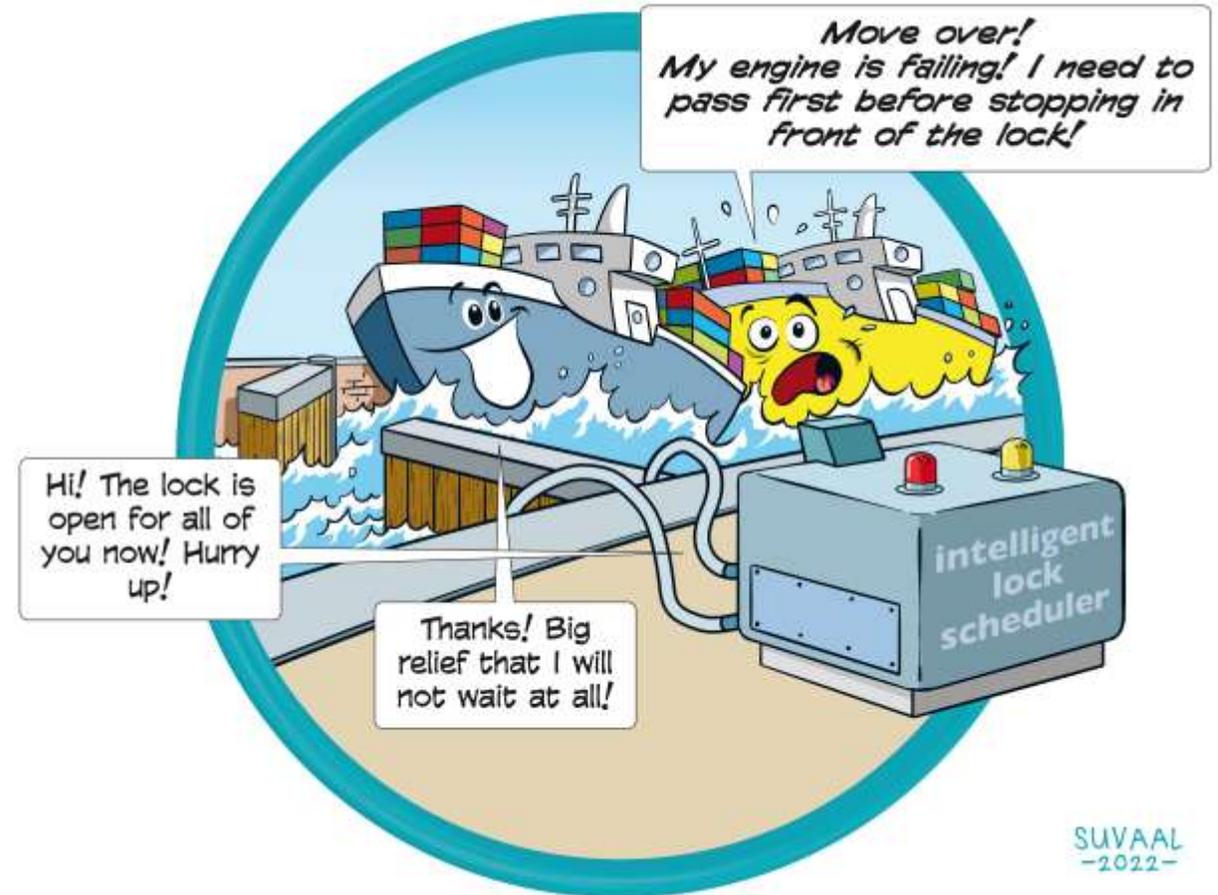
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# Safe Autonomous Maritime Transport



Maritime and  
Transport  
Technology

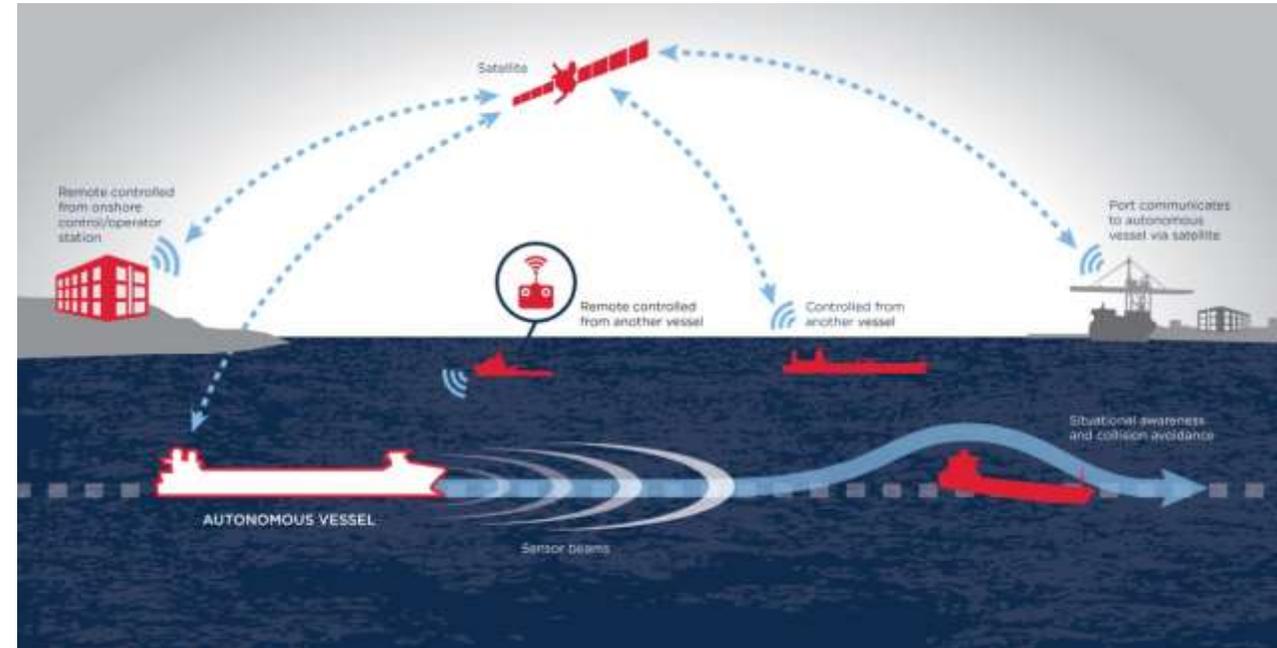


SUVAAL  
-2022-

# Maritime Autonomy & Safety



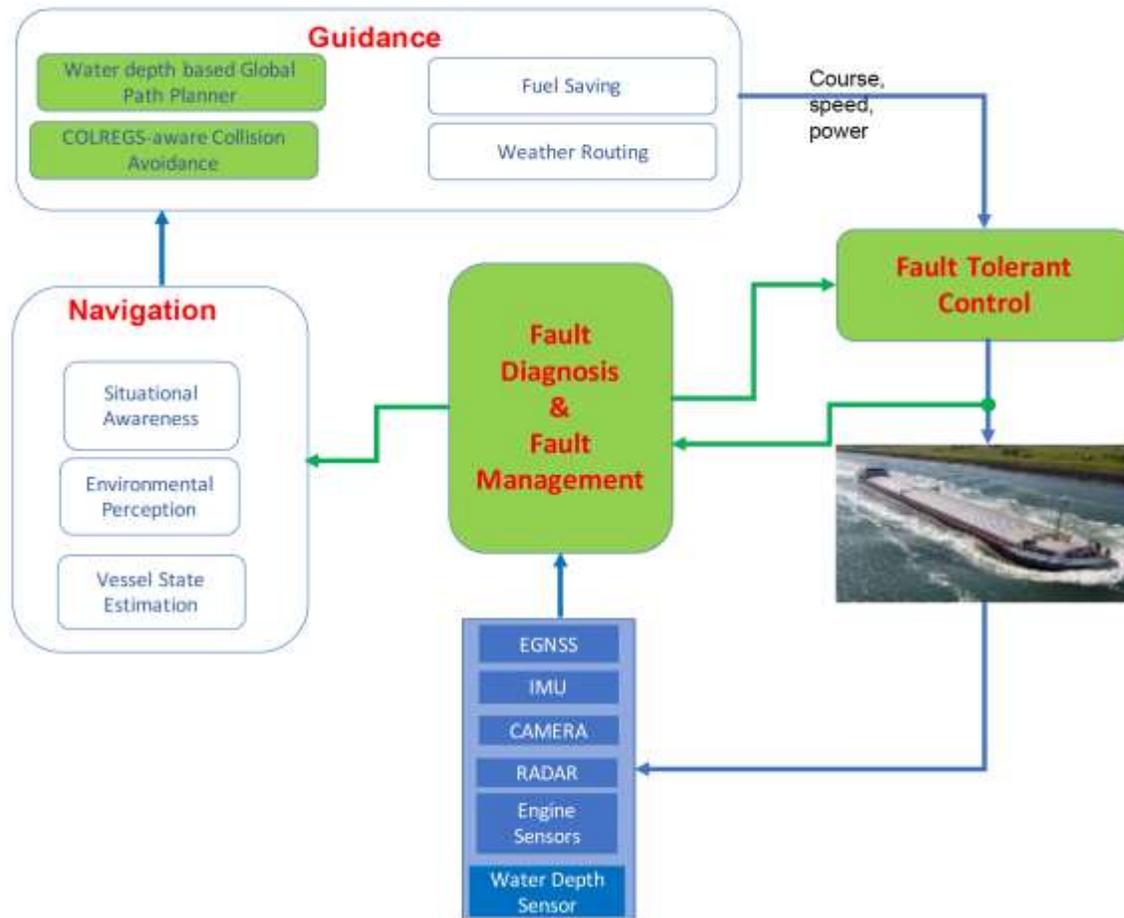
(a)



(b)

Fig. 1 Maritime Safety in (a) conventional vessels, and (b) autonomous vessels

# The GNC System



- **Guidance system:**
  - generation of the desired path/trajectory/energy consumption using high-level information & local information
  - Defines safe path/speed (e.g., collision avoidance)
- **Navigation system:** situational awareness, state estimation, environmental perception
- **Control system:** computes the signals to the actuators to make the system achieve the desired safe behavior

# What is missing?

1. Multi-environment operation not considered (e.g., change of physical constraints, dynamics)
2. Rule awareness using both regional and international traffic rules (e.g., COLREGS, BPR/ CCNR)
3. Consideration of both vessel-to-vessel (V2V) and vessel-to-infrastructure (V2I) collisions
4. Handling of navigation sensor inaccuracies and faults, is required for precise path following



# The SEAMLESS Approach

**Objectives:** Develop a **Guidance, Navigation & Control** scheme:

- ✓ **Adaptive to both** short sea and inland waterway navigation
- ✓ **Safe against** physical (e.g., static obstacles, grounding) and cyber (e.g. faults) threats
- ✓ **Compliant to various collision avoidance regulations** (e.g., COLREGS, CCNR, BPR)
- ✓ **Fault-Tolerant against sensor and actuator faults**



**Model 1**  
**inland**  
**waterways**  
**navigation**

**switch**  
↔

**Model 2**  
**short sea**  
**navigation**

**Environmental Disturbances**

- **Current**
- **Water depth**
- **Bank effects**

- **Wind**
- **Waves**

# Manoeuvring Model Formulation

$$\begin{aligned} \Sigma : \dot{\mathbf{x}} &= \gamma(\mathbf{x}, \mathbf{u}) \\ &= R(\mathbf{x}) \cdot \begin{bmatrix} u \\ v \\ r \\ (m + m_y)v_m r + x_G m r^2 + X_H(\mathbf{x}) + X_P(\mathbf{x}) + X_R(\mathbf{x}, \mathbf{u}) \\ Y_H(\mathbf{x}) + Y_R(\mathbf{x}, \mathbf{u}) + (m + m_x)ur \\ N_H(\mathbf{x}) + N_R(\mathbf{x}, \mathbf{u}) - x_G m ur \end{bmatrix} \end{aligned} \quad (1)$$

- ✓ Based on the Maritime Modelling Group (MMG) model due to its inherent modularity
- ✓ Transformed into state-space format

# Sensor inaccuracies modelling

$$\mathcal{S} : \mathbf{y}(t) = C\mathbf{x}(t) + \overset{\text{noise}}{\mathbf{d}(t)} + \overset{\text{faults}}{\mathbf{f}(t)} \quad (2)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

# Semantic Database

$$\mathcal{F} = \mathcal{F}_d \cup \mathcal{F}_s \cup \mathcal{F}_e \cup \mathcal{F}_r$$

## Database component

$\mathcal{F}_d$ : vessel design

$\mathcal{F}_s$ : vessel sensors

$\mathcal{F}_e$ : operational environment

$\mathcal{F}_r$ : traffic rules

## Examples of stored information

$L_{bp}, U_d, \textit{name of vessel}$

sensor name, noise level

wave height, current speed

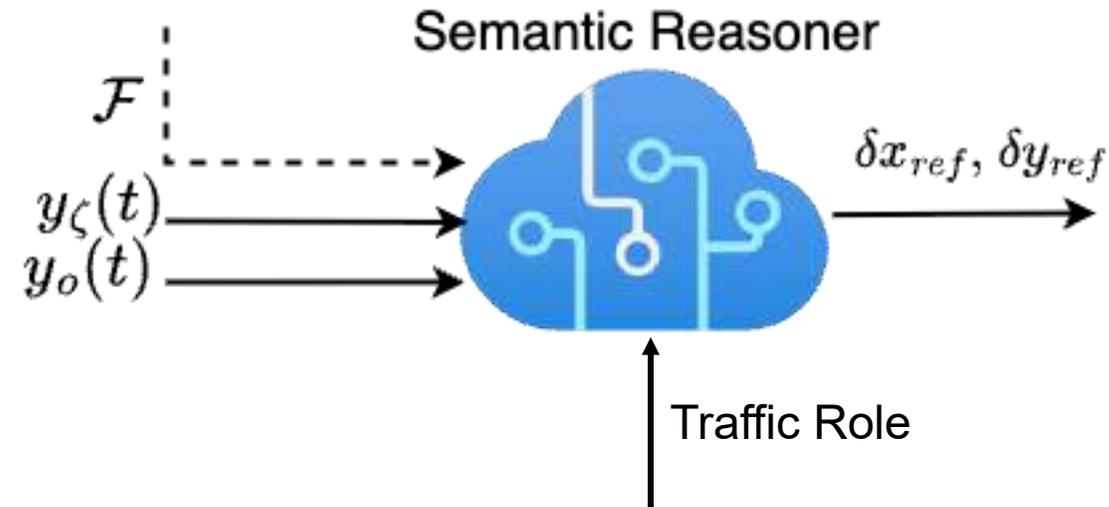
BPR, COLREGS

# Database Implementation

The screenshot displays an ontology editor interface with several key sections:

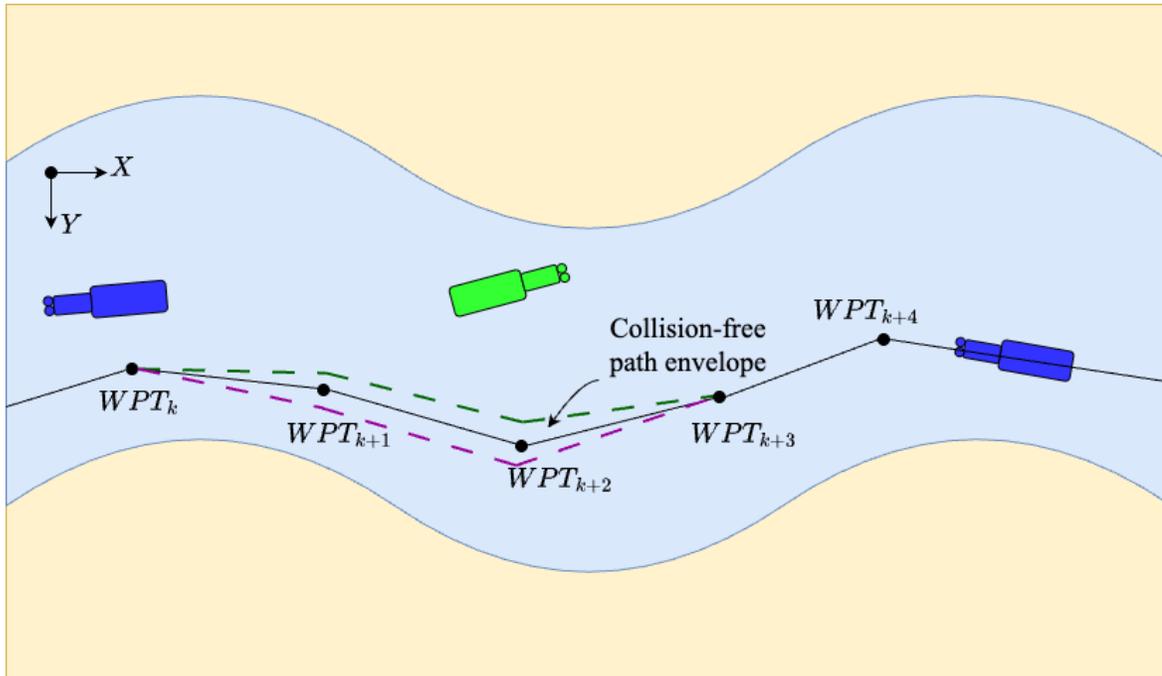
- Classes:** A tree view on the left shows the class hierarchy, including `owl:Thing`, `Control`, `Design_space`, `Encounter_situations`, `Environment`, `Operational_actions`, `Operators`, `Regulations` (highlighted), `Sensors`, and `Vessel`.
- Comments/ Context:** A panel on the right shows the `rdfs:comment` for `Rule_8e`: "if necessary to avoid collision or allow more to assess the situation, a vessel shall slacken her speed or take all way off by stopping or reversing her means of propulsion."
- Instances:** A panel at the bottom left lists direct instances of `Regulations`, including `COLREGS/Rule_14` through `COLREGS/Rule_8d`, with `COLREGS/Rule_8e` selected.
- Class information:** A central panel shows the description of `COLREGS/Rule_8e` as `Regulations` and its relationship to `COLREGS/Situation_Dependent`.
- Dependencies:** A panel on the right shows property assertions for `COLREGS/Rule_8e`, including `inputFrom Camera`, `inputFrom Radar`, `reg_active 0`, and `safespeed "0.0"^^xsd:double`.

# Semantic Reasoning: Decision on safe reference trajectory deviation

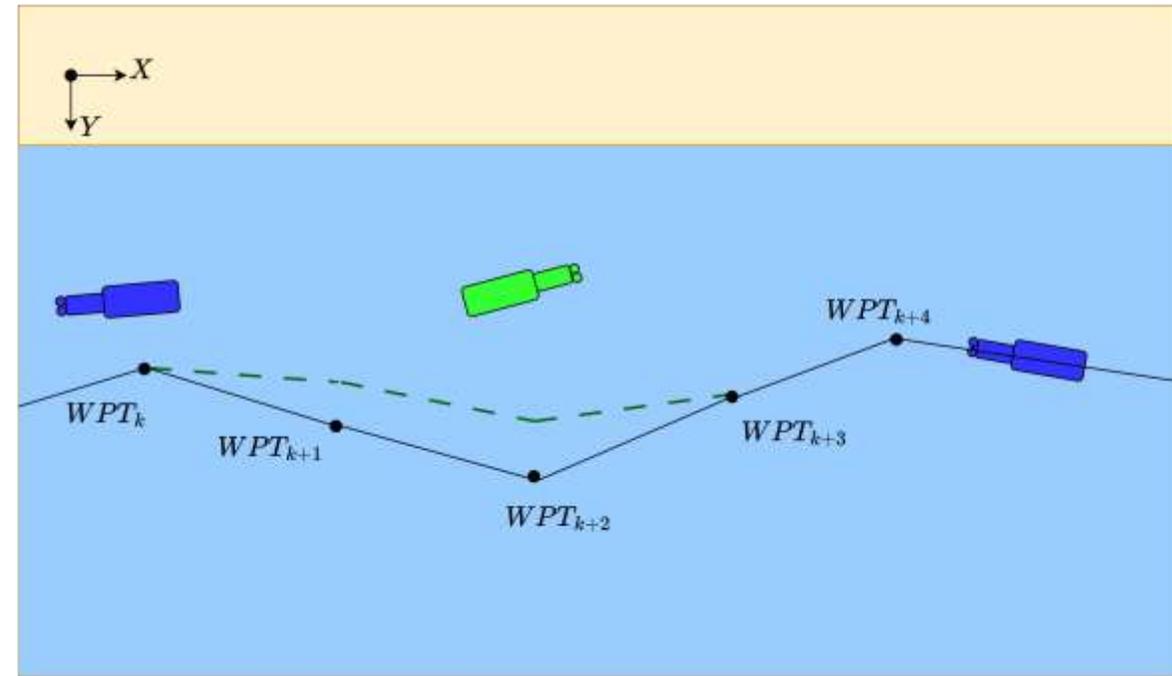


- **(Give-way Vessel)** Determination of safe trajectory deviation based on safe distance from other vessels, safe lane distance (in case of waterway), and VTS information on other vessel's position and heading
- **Generation of collision-free envelope** for inland waterway and short-sea operations

# Examples of collision free envelopes



(a) Inland waterways



(b) Short sea

# Semantic Reasoning: Decision on traffic rules and role

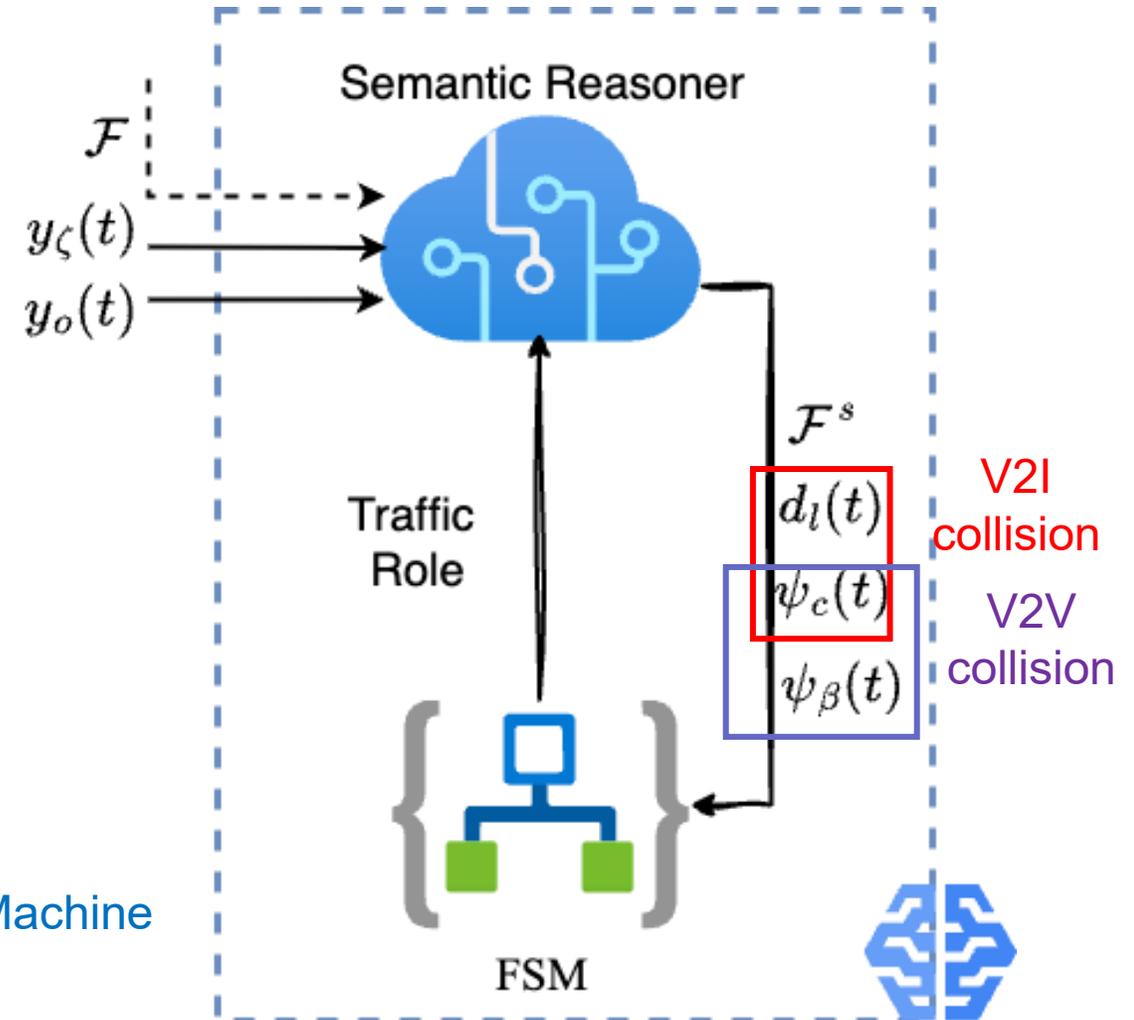
Determination of applicable traffic rules  
(based on operational area)

$$\mathcal{V}_{GPS} \times \mathcal{F} \mapsto \mathcal{F}^s$$

Calculation of relative heading and  
bearing

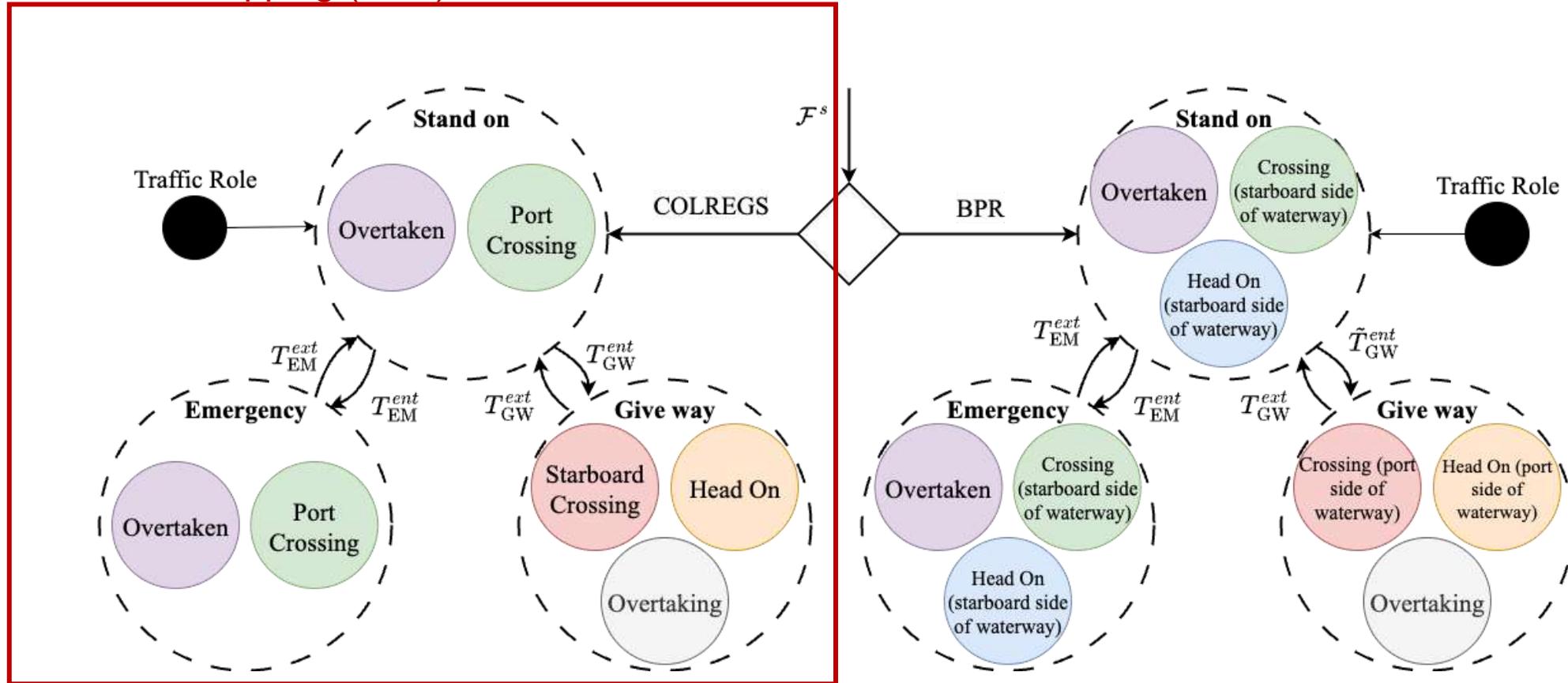
based on (Tsolakis et al., 2024)

Traffic role generated through the use of Finite State Machine



# Modular Finite State Machine

## Short-sea Shipping (SSS)



# Modular Finite State Machine

## Inland waterway Transport (IWT)

Traffic |



- **Head-on situation (Article 6.04)**: If two vessels are approaching each other on opposite courses in such a way that there is a risk of collision, the vessel not following the starboard side of the fairway shall give-way to the vessel following the starboard side of the fairway. If neither vessel follows the starboard side of the fairway, each shall give-way to vessels on the starboard side so that they pass each other port to port.

En |

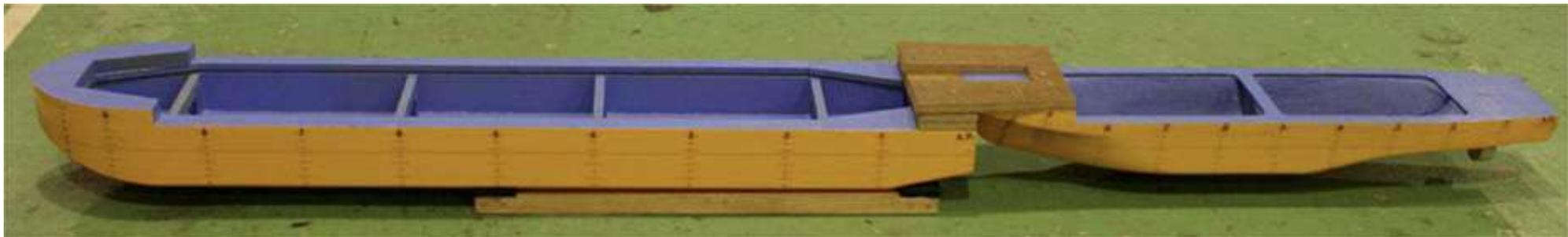


Overtake

- **Crossing situation (Article 6.17)**: If the courses of two ships cross each other in such a way that there is a risk of collision, the vessel not following the starboard side of the fairway shall give way to the vessel following the starboard side of the fairway. In case none of the ships follows the starboard side of the fairway, the ship approaching from the port side gives way to the vessel approaching from starboard side.

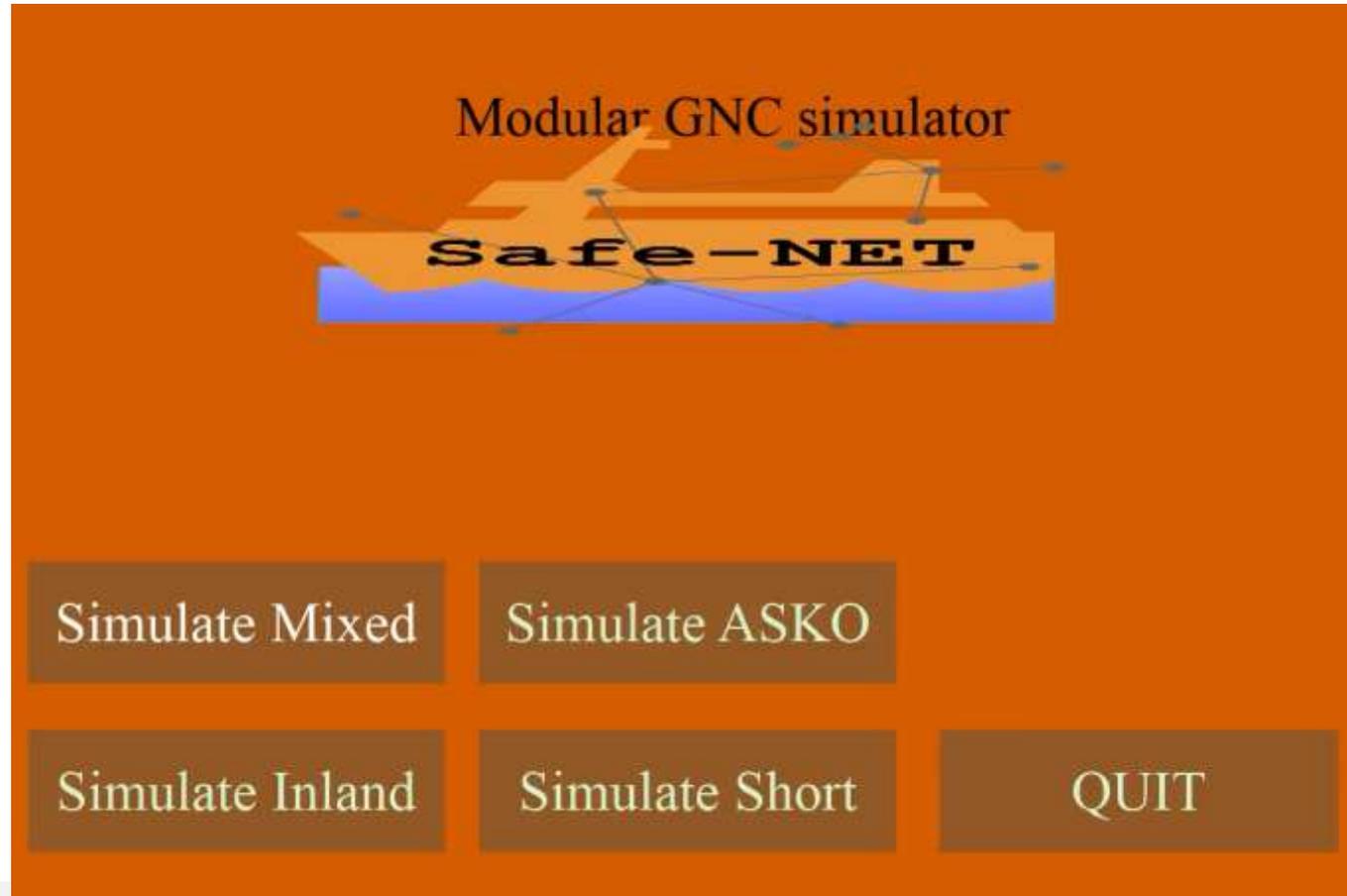
# Case study: Head-On Scenarios in a mix of SSS and Dutch IWT Environments

- Two head-on scenarios
- Implementation of Semantic Database, Reasoner and Modular FSM to prevent collision
- Consideration of COLREGs and BPR Regulations
- Pusher-Barge vessels are simulation (3 vessels/ 1 own and 2 other vessels)

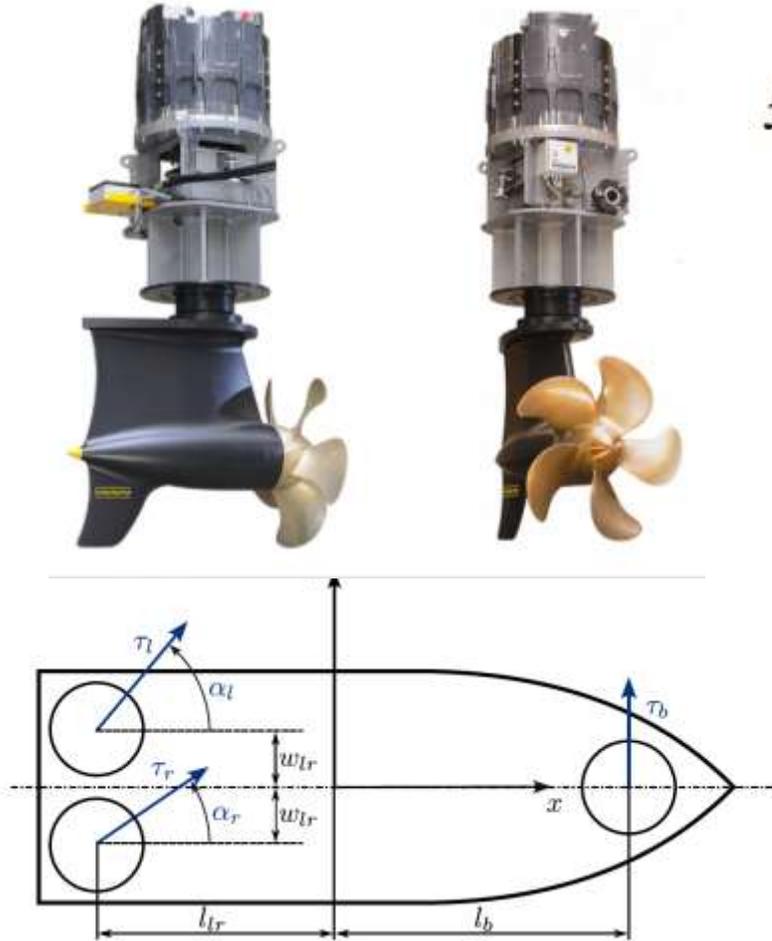


*Image credits: K.K. Koh and H. Yasukawa. "Comparison study of a pusher-barge system in shallow water, medium shallow water and deep water conditions". In: Ocean Engineering 46 (June 2012), pp. 9–17. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2012.03.002.*

# Example: Intelligent and Rule-Aware Capabilities



# Vessel Motion under Thruster Faults

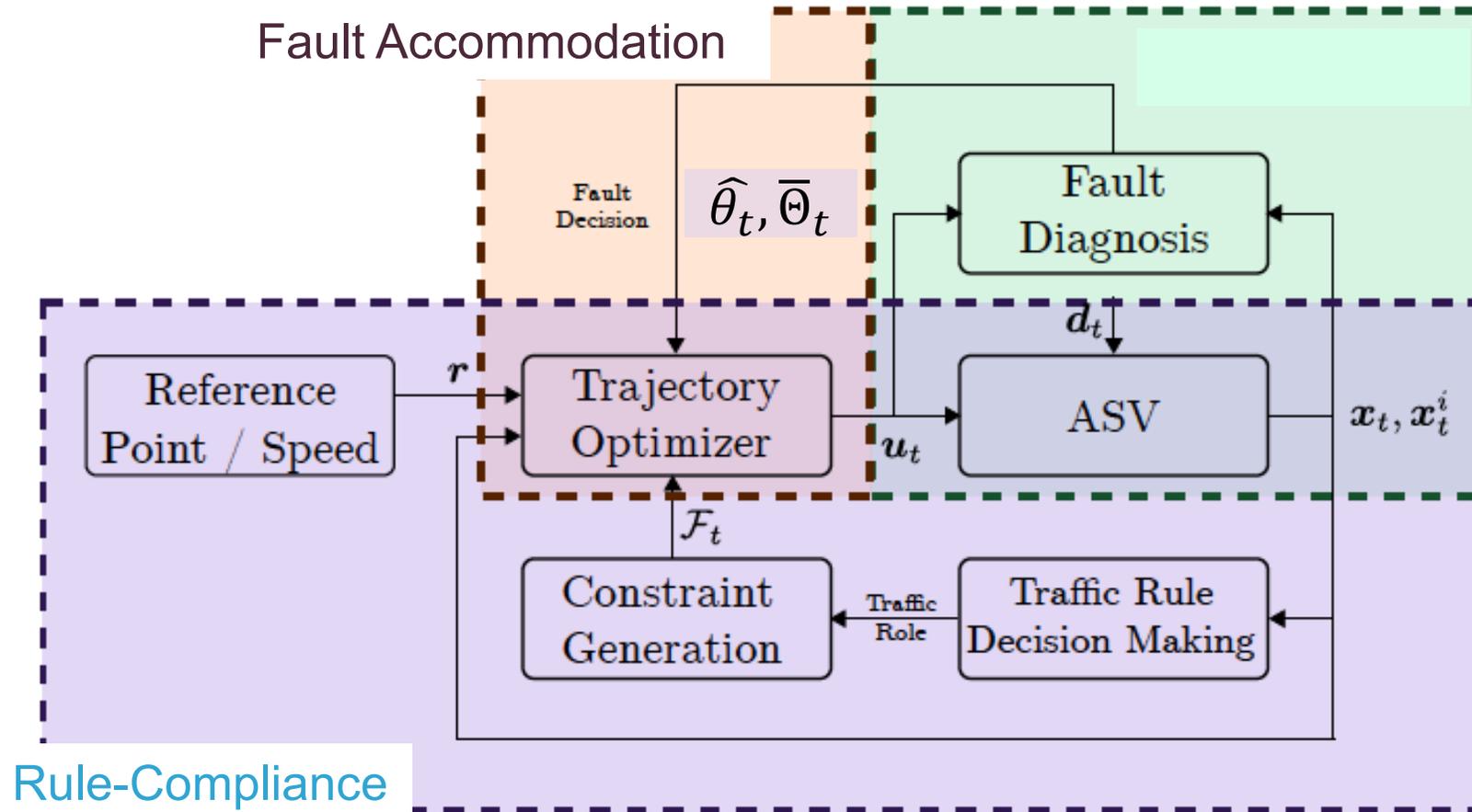


$$\dot{x} = \underbrace{\begin{bmatrix} \mathbf{0}_{3 \times 3} & R(x) \\ \mathbf{0}_{3 \times 3} & -M^{-1}(C(x) + D(x)) \end{bmatrix}}_{f(x)} x + \underbrace{\begin{bmatrix} \mathbf{0}_{3 \times 3} \\ M^{-1} \end{bmatrix}}_{g(u)} \tau(u) + \underbrace{\begin{bmatrix} \mathbf{0}_{3 \times 3} \\ M^{-1} \end{bmatrix}}_d \tau_d$$

$$g(u) = \underbrace{\begin{bmatrix} \mathbf{0}_{3 \times 3} \\ M^{-1} \end{bmatrix} \begin{bmatrix} \tau_l \cos \alpha_l & \tau_r \cos \alpha_r & 0 \\ \tau_l \sin \alpha_l & \tau_r \sin \alpha_r & 0 \\ -w_{lr} \tau_l \cos \alpha_l & w_{lr} \tau_r \cos \alpha_r & l_b \tau_b \\ -l_{lr} \tau_l \sin \alpha_l & -l_{lr} \tau_r \sin \alpha_r & 0 \end{bmatrix}}_{G(u)} \underbrace{\begin{pmatrix} \theta_l \\ \theta_r \\ \theta_b \end{pmatrix}}_{\theta}$$

$$[I_p \quad -I_p] \theta \leq [1 \quad 0] \text{ Loss of Effectiveness}$$

# Rule-Compliant & Fault-Tolerant Motion Planning



# Fault Diagnosis

❑ **Fault Detection Logic:** if  $\bar{\Theta}_{t-1} \cap \Delta_t = \emptyset$ , a fault is guaranteed to have occurred.

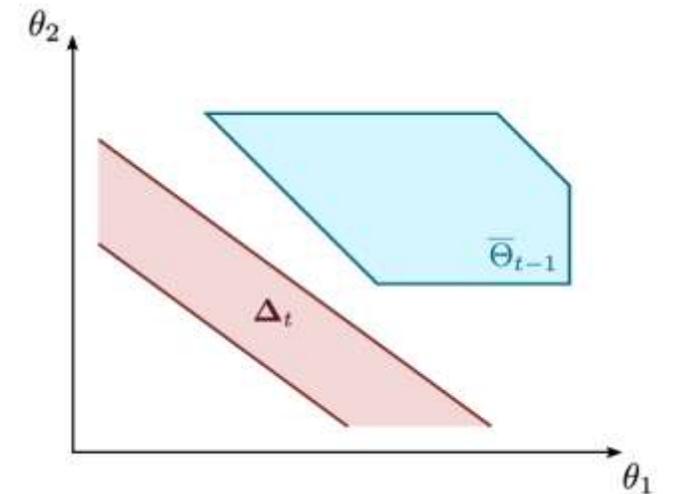
❑ **Time of Detection:**  $t_D = \min\{t \mid \bar{\Theta}_{t-1} \cap \Delta_t = \emptyset, t > t_F\}$

❑ **Fault Isolation Logic:** if  $\text{Proj}_{\theta_i}(\Theta_t) \cap \text{Proj}_{\theta_i}(\Theta_{t_D-1}) = \emptyset$ , where

$$\text{Proj}_{\theta_i}(\Theta_t) = \left[ \min_{v \in \mathcal{V}}(e_{\theta_i}^\top v), \max_{v \in \mathcal{V}}(e_{\theta_i}^\top v) \right]$$

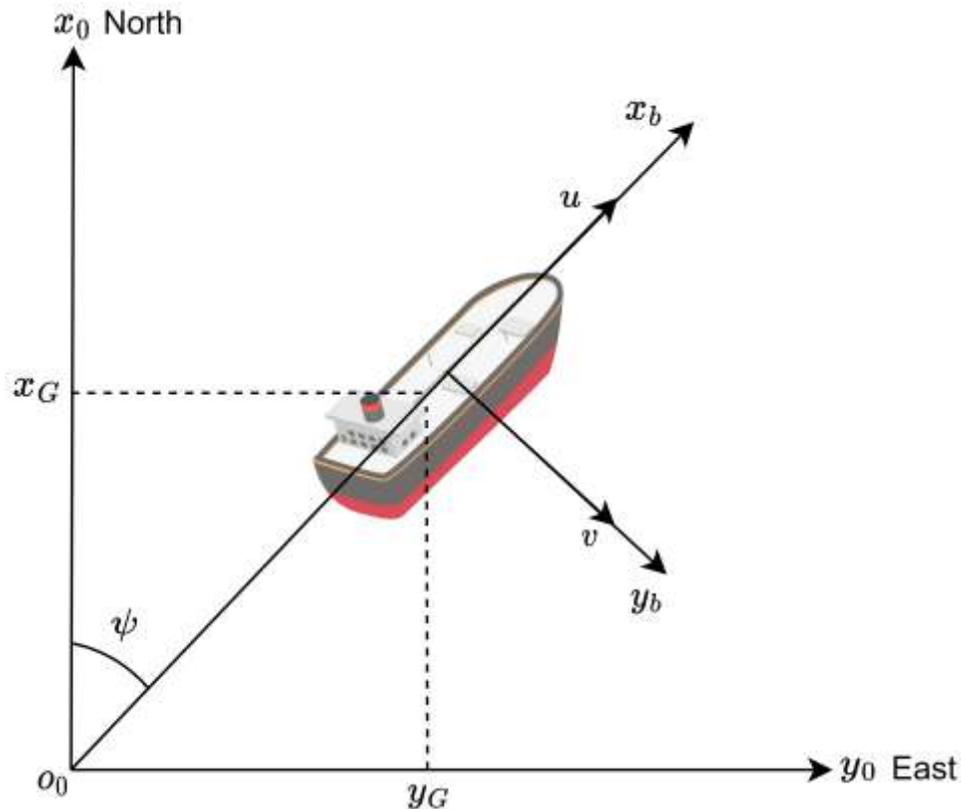
then parameter  $\theta_i$  is faulty (i.e.  $< 1$ )

❑ **Time of Isolation:**  $t_I^i = \min\{t \mid \text{Proj}_{\theta_i}(\Theta_t) \cap \text{Proj}_{\theta_i}(\Theta_{t_D-1}) = \emptyset, t > t_D\}$



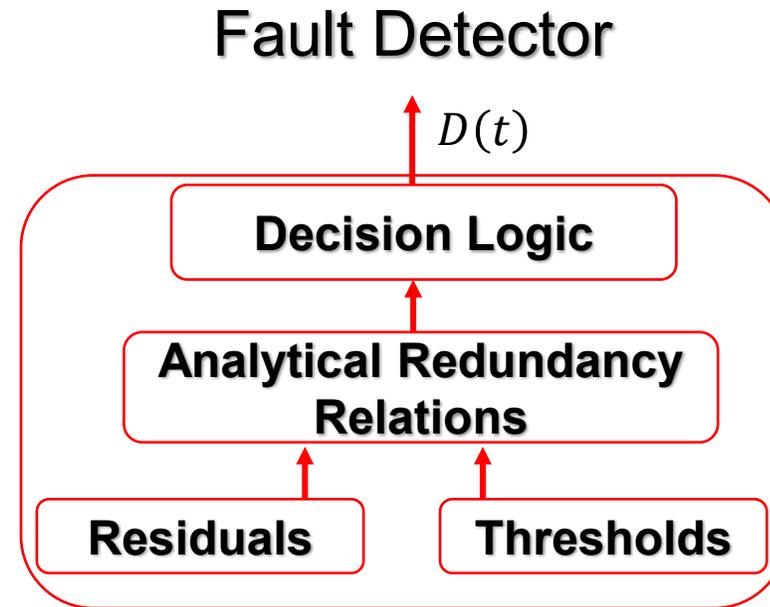
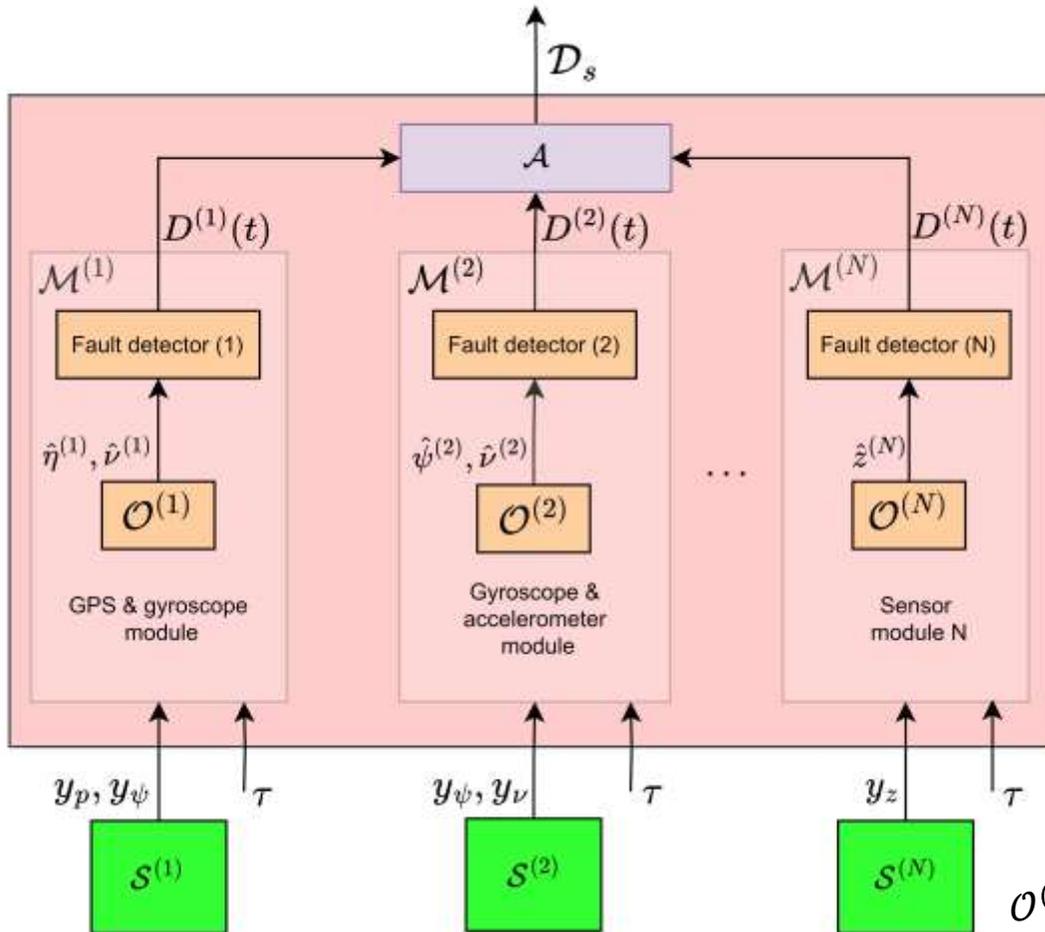
# Navigational Sensor Fault Diagnosis

*How to diagnose sensor faults affecting multiple navigational sensors considering modelling uncertainty?*



- ❑  $S_p$ : GPS/GNSS measuring position  $(x_p, y_p)$
- ❑  $S_\psi$ : Gyroscope measuring heading  $(\psi)$
- ❑  $S_v$ : accelerometer measuring velocities  $(v)$

# Sensor Fault Diagnosis



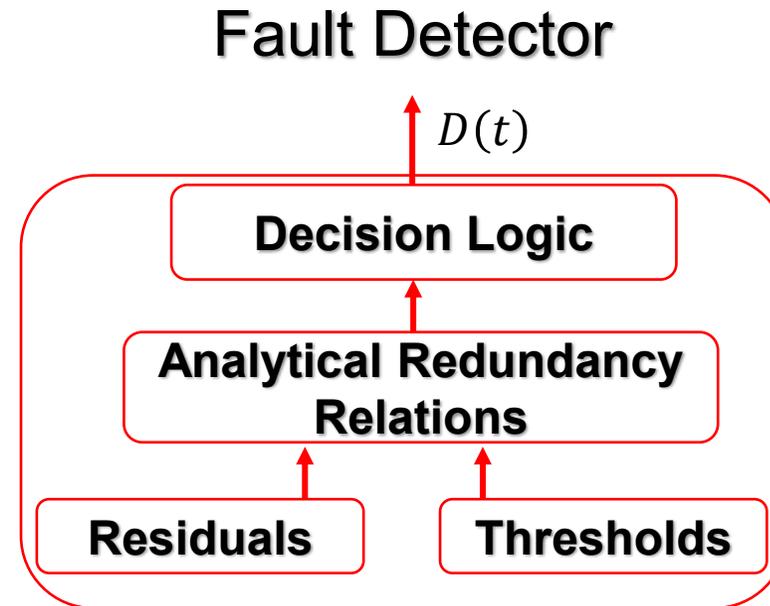
$$O^{(1)}: \begin{cases} \dot{\hat{\eta}}^{(1)} = R(\hat{\psi}^{(1)})\hat{\nu}^{(1)} + K^{(1)}\tilde{\eta}^{(1)}, \\ \dot{\hat{\nu}}^{(1)} = M^{-1}(-C(\hat{\nu}^{(1)})\hat{\nu}^{(1)} - D(\hat{\nu}^{(1)})\hat{\nu}^{(1)} + \tau) + K^{(2)}R^T(\hat{\psi}^{(1)})\tilde{\eta}^{(1)}. \end{cases}$$

# Sensor Fault Diagnosis

- ARR:  $\forall i \in \{1, 2, \dots, n\}$   
 $\varepsilon_i: |r_i(t)| = |y_i(t) - \hat{y}_i(t)| \leq \bar{y}_i(t)$
- **Detection** Decision Logic: assuming permanent sensor faults

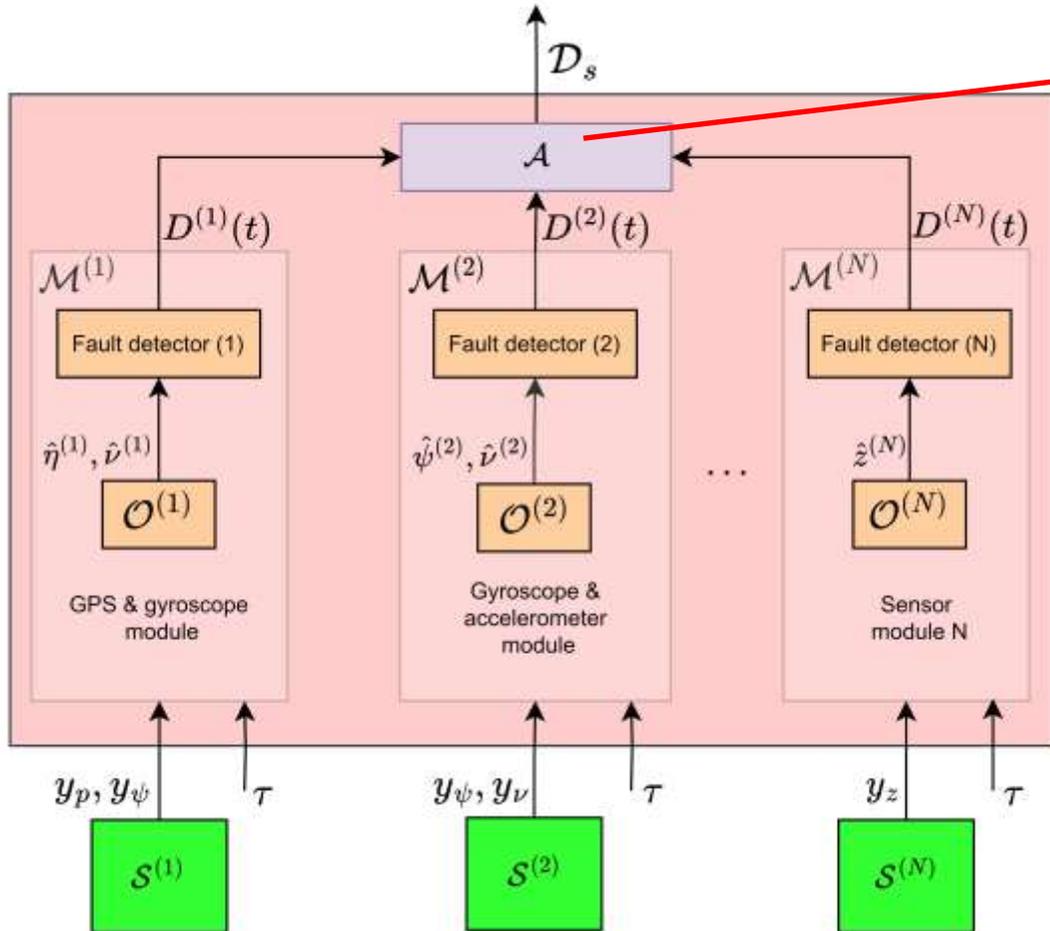
$$D(t) = \begin{cases} 0, & t \leq t_D \\ 1, & t > t_D \end{cases}$$

$t_D$ : **first time** that  $|r_i(t)| > \bar{y}_i(t)$   
for at least one  $i$



$$\mathcal{O}^{(1)}: \begin{cases} \dot{\hat{\eta}}^{(1)} = R(\hat{\psi}^{(1)})\hat{\nu}^{(1)} + K^{(1)}\tilde{\eta}^{(1)}, \\ \dot{\hat{\nu}}^{(1)} = M^{-1}(-C(\hat{\nu}^{(1)})\hat{\nu}^{(1)} - D(\hat{\nu}^{(1)})\hat{\nu}^{(1)} + \tau) + K^{(2)}R^T(\hat{\psi}^{(1)})\tilde{\eta}^{(1)}. \end{cases}$$

# Multiple Sensor Fault Isolation



	$f_p$	$f_\psi$	$f_\nu$	$\{f_p, f_\psi\}$	$\{f_p, f_\nu\}$	$\{f_\psi, f_\nu\}$	$\{f_p, f_\psi, f_\nu\}$
ARRs -1	1	*	0	1	1	*	1
ARRs -2	0	1	0	1	0	1	1
ARRs -3	0	1	1	1	1	1	1
ARRs -4	0	0	1	0	1	1	1

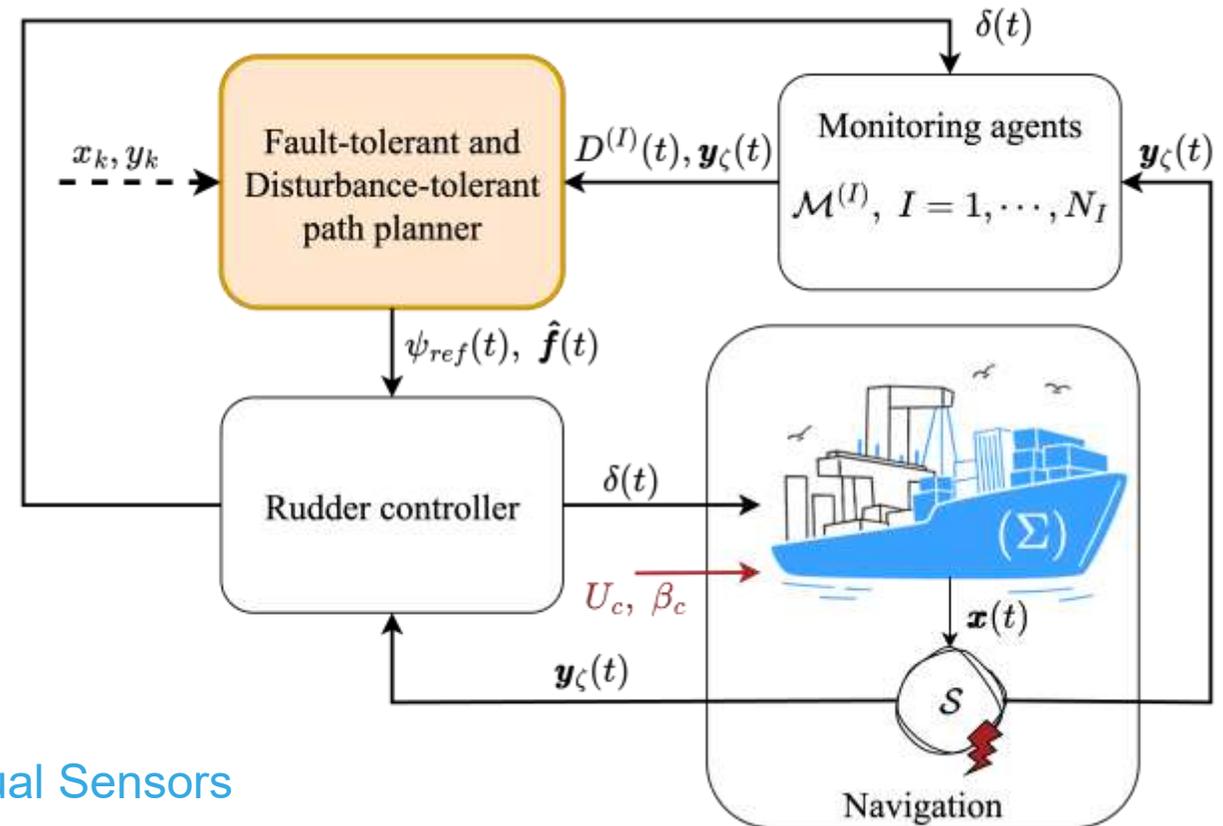
Observed pattern

$$D(t) = \begin{bmatrix} D_1(t) \\ D_2(t) \\ D_3(t) \\ D_4(t) \end{bmatrix}$$

- **Consistency test:** Compare at every time instant the observed pattern to the **theoretical patterns (columns of FSM)**

# Fault-tolerant Guidance system design

- Faults in the navigation sensors negatively affect Guidance decisions
- Novel Virtual Sensor Line-Of-Sight (VS-LOS) Guidance Law for Sensor Fault effect mitigation
- Monitoring agent interconnection



VS-LOS = Adaptive LOS (drift compensation) + Virtual Sensors

# Virtual sensor-informed LOS (VS-LOS) Guidance

$$\left\{ \begin{array}{l} \dot{\hat{x}} = \gamma(\hat{x}, u) + L(y - \hat{y}) + \Omega \dot{\hat{f}}, \\ \dot{\Omega} = -L, \\ \hat{y} = \hat{x} + \hat{f}, \\ \dot{\hat{\beta}} = \frac{\Gamma_1 U \cdot X_D}{\sqrt{X_D^2 + (e + X_D \hat{\beta})^2}} e, \\ \dot{\hat{f}} = \Gamma_2 (\Omega + 1) \mathcal{D}[y - \hat{x} - \hat{f}], \end{array} \right.$$

## Design

Estimator Gain

Learning rate

## Stability and Computation

Filtering Term

Parameters

Cross-tracking error

Deadzone

# Thank you

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27