Den Danske Maritime Fond — Final Project Report

SAFEMARVEL

A SAfety-critical control FramEwork for roll stabilization of MARine VEsseLs

Full project period · March 2024 – February 2026

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Grantee / Lead	SDU Mechatronics, Sønderborg	Project leader	Prof. Jerome Jouffroy
Consortium	SDU Mechatronics · Dacoma ApS · SDU Physics	Prepared by	Shouvik Chaudhuri, Postdoc (SDU CIM)

Project summary. The marine industry has traditionally restricted itself to conservative, robust controllers, foregoing the performance of high-performance (adaptive / AI-based) controllers because of the risk that such controllers may drive a vessel beyond safe limits while adapting to unforeseen conditions at sea. **SAFEMARVEL** resolves this tension by developing a practical safety-critical control framework that admits any controller, including high-performance and learning-based ones, while formally guaranteeing vessel stability and safety through barrier functions. Over 24 months the consortium delivered the complete chain: a control-oriented **digital twin** of a vessel with a canting/air-keel; a **CLF–CBF–QP** safety-enhanced framework that augments (rather than redesigns) a nominal controller; a first-of-its-kind recasting of the IMO Second-Generation Intact Stability Criteria as online control constraints; a **reinforcement-learning** roll controller trained inside the digital twin (SDU Physics); and a **real-time validation on a representative physical laboratory experiment**, carried out with the industrial partner Dacoma ApS. The framework was thereby advanced to a laboratory-validated technology readiness level, with the full on-vessel demonstration identified as the immediate follow-on.

Project at a glance

12/12 Milestones achieved (M1–M12)	**8/8** Work packages completed	**16/16** Deliverables realised (D1–D16)	**TRL 3→5** Concept to lab-validated system
2 + 2 Papers pub./accepted + in prep.	**1** Postdoc position created	**1** MSc thesis (RL, SDU Physics)	**4 + 2** Bi-annual mtgs + kickoff/closure

Contents

1. Introduction and objectives

Roll stabilization in marine vessels is challenging because of the complex, dynamic nature of the marine environment — waves, wind, and loading/unloading scenarios. Two criteria govern the problem and are not naturally aligned: (i) safety constraints such as a maximum heel angle and lateral acceleration must always be satisfied; and (ii) the rolling motion induced by environmental factors must be compensated. A fast-acting stabilizer optimised for (ii) can breach (i). The marine industry therefore compromises performance, prioritising safety with conservative, robust controllers that are safe but slow.

The control community has developed safety-critical control, widely adopted in automotive and robotics, that places a formal safety barrier around control actions so that the system always remains within safe limits. The barrier leaves a high-performance controller free to act when solutions are safe, and becomes dominant only as the controller approaches unsafe regions. This two-fold behaviour: performance and a guarantee of safety, is what SAFEMARVEL brings to the roll-stabilization problem.

1.1 Project objectives

O1. Develop a safety-critical control framework for roll stabilization, using barrier functions to always guarantee vessel stability and safety.

O2. Design a high-performance learning-based controller within this framework, with particular focus on reinforcement learning for various sea conditions.

O3. Develop, simulate and test the concept using digital-twin technology.

O4. Validate the real-time capability of the concept on a representative physical experimental platform.

1.2 Consortium and lineage

The work was carried out by a consortium led by SDU Mechatronics, with Dacoma ApS (industrial partner, canting/air-keel stabilizer) and the SDU Department of Physics, Chemistry and Pharmacy (reinforcement learning). SAFEMARVEL builds directly on the consortium's track record in the Eurostars/EUREKA project AMCOSTSAR (2021–2023), in which SDU Mechatronics and Dacoma developed and demonstrated an adaptive control system for a new type of ship stabilizer, establishing the modelling expertise, hardware, and working relationship that SAFEMARVEL extends with formal safety guarantees and learning-based control.

1.3 The framework at a glance

The conceptual architecture of the delivered system is shown below: an existing performance-tuned (nominal) controller and a reinforcement-learning agent propose control actions; a single quadratic program (QP) then minimally modifies that proposal so that a Control Lyapunov Function (CLF) certifies stability and Control Barrier Functions (CBFs), derived from IMO stability criteria and actuator limits, certify safety, before the command is sent to the canting/air-keel of the vessel (digital twin or representative physical platform).

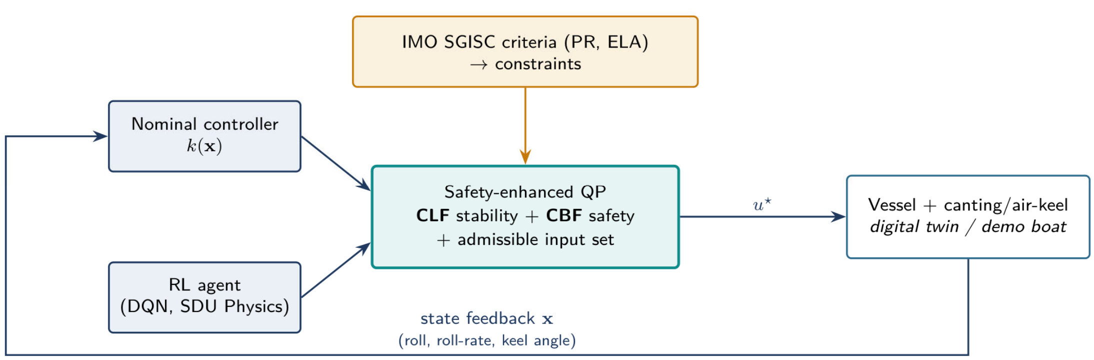


Figure 1. Graphical abstract of the SAFEMARVEL safety-enhanced control framework.

2. Work-package outcomes: tasks, results and partner roles

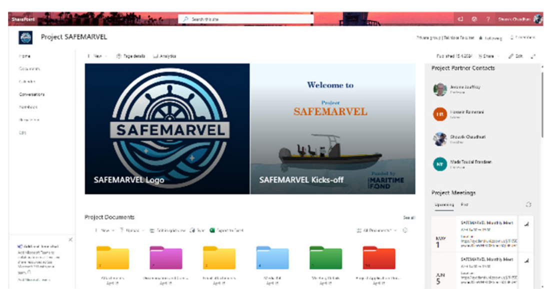
This section reports each work package against the plan in the project application. For every WP a Planned versus Delivered comparison is given, followed by a boxed breakdown of the individual tasks, the industrial-partner contribution where relevant, the key result, and a placeholder grid for the supporting figures to be inserted. The industrial partner Dacoma ApS played a central, hands-on role across the modelling, safety-specification and validation work packages. SDU Mechatronics led WP1–WP4, WP6, WP7 and WP8; SDU Physics led WP5; Dacoma contributed to WP2, WP3 and WP7.

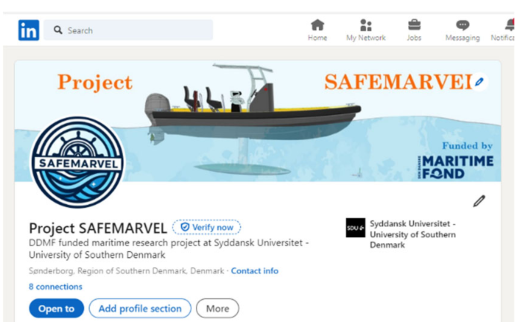
2.1 WP1 — Project management & administration (SDU Mechatronics · M1, M2)

PLANNED	Launch the project, execute agreements, run the kick-off meeting, and coordinate partners and schedule over the full duration (T1.1–T1.3).
DELIVERED	Project launched 1 March 2024; online kick-off 9 April 2024. SharePoint workspace, monthly-meeting calendar and project LinkedIn page established; coordination sustained for 24 months through regular monthly meetings. **M1, M2 achieved (Month 1).**

Detailed tasks

Task T1.1	**Project launch & kick-off.** The kick-off meeting was held online on 9 April 2024 (11:00–12:00) according to partner and supporter availability, and a project logo was created beforehand. Its outcomes set the project's operating rhythm: monthly partner meetings (first Wednesday, 14:00–15:00), a shared SharePoint workspace for information exchange, and a LinkedIn dissemination plan via the SDU CIM page and a dedicated project page.
Task T1.2	**Overall management.** Using the T1.1 outcomes as guidelines, the SharePoint folder involving all partners was created for sharing information and technical progress, the monthly-meeting calendar was set up, and the project LinkedIn page (see link) was launched to keep partners aligned and the project on schedule
Task T1.3	**Progress monitoring & coordination.** The project coordinator maintained continuous oversight of technical progress, outcomes and deadlines for the full 24 months, including the joint supervision of one in-company project (with Dacoma) and one MSc thesis (with SDU Physics)





WP1 : Supporting figures for Project management and administrative tasks performed during the project

2.2 WP2 — Mathematical modelling, validation & digital twin (SDU Mechatronics + Dacoma · M3, M4)

PLANNED	Build an advanced, disturbance-aware mathematical model of a vessel with its roll-stabilizer, implement it in MATLAB/Simulink, add parameter estimation, and validate it into a control-oriented digital twin (T2.1–T2.4).
DELIVERED	Full model delivered (vessel equations of motion, vessel torques, keel model, keel actuator), implemented as a Simulink digital twin, with parameter estimation and validation against in-house boat data collected with Dacoma. **M3, M4 achieved (Month 6).**

Detailed tasks

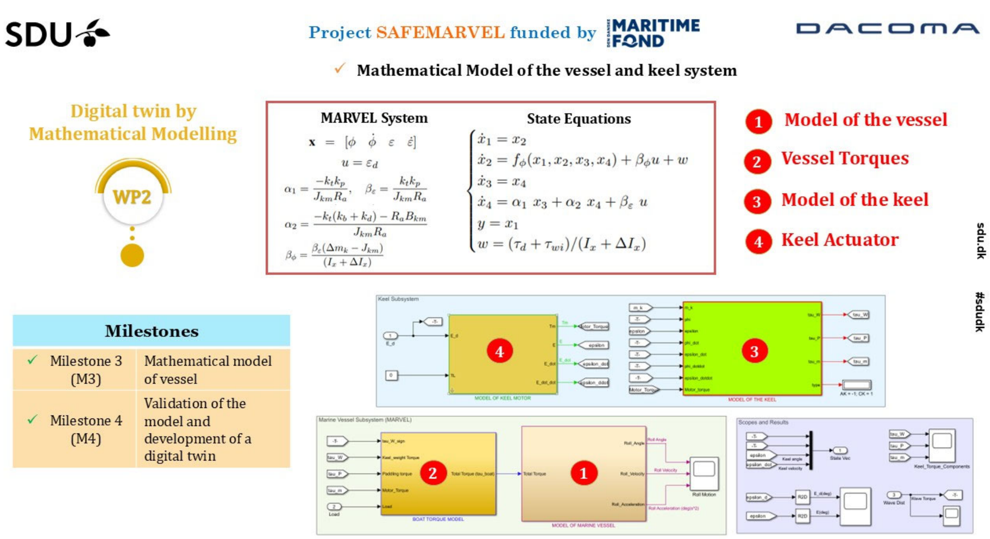
Task T2.1	**Mathematical modelling.** Detailed models representing the vessel dynamics, including the roll-stabilization (canting/air-keel) mechanism, were formulated while explicitly incorporating external disturbances such as waves and wind. The model is composed of four coupled parts: the vessel equations of motion, the vessel torques, the keel model, and the keel-actuator dynamics
Task T2.2	**Simulink implementation.** The T2.1 models were implemented in MATLAB/Simulink to build a digital-twin environment that mirrors the real-world behaviour of the vessel, enabling rapid control-design prototyping and testing
Task T2.3	**Parameter estimation.** Estimation techniques were designed and integrated into the twin so that it remains accurate under varying operating conditions using real-time data.
Task T2.4	**Validation.** The digital twin was validated against experimental / field data obtained in-house using a catamaran model boat together with Dacoma through standard validation methods, confirming its fidelity for control design and simulation.

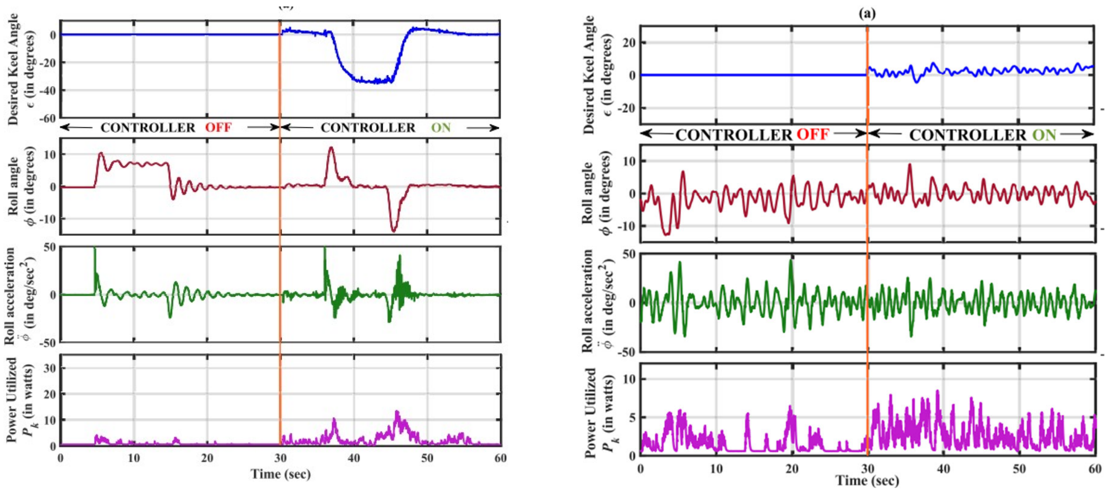
DACOMA ApS — INDUSTRIAL PARTNER ROLE

Dacoma supplied the keel stabilizer concept and hardware together with the model boat, and shared the real-time field data that underpinned the validation of the digital twin (T2.4). Dacoma's maritime-engineering input directly shaped the disturbance representation and the keel-actuator model, ensuring the twin reflects a realistic, deployable stabilizer rather than a generic one.

KEY RESULT

A validated, control-oriented digital twin of a monohull vessel with a canting/air-keel was delivered and used as the common simulation and training environment for every subsequent work package.





WP2: Supporting figures for control-oriented digital twin of the vessel with keel mechanism, validated against in-house model boat data (with Dacoma).

2.3 WP3 — Design & specification of the safety-control framework (SDU Mechatronics + Dacoma · M5)

PLANNED	Survey safety-critical control from other sectors, compile maritime safety protocols (with Dacoma) into mathematical form, and produce an outline framework admitting any high-performance controller while ensuring safety (T3.1–T3.3).
DELIVERED	Literature survey completed (basis of the ECC 2025 paper); maritime safety requirements translated into mathematical constraints; framework formulated and verified on representative benchmark systems before application to a vessel with conventional and air-keel. **M5 achieved (Month 9).**

Detailed tasks

Task T3.1	**Literature survey.** Existing research and methodologies on safety-critical control were surveyed, especially from automotive and robotics, to extract concepts and techniques transferable to marine vessels. This survey later formed part of the article communicated to IEEE ECC 2025 (under WP8)
Task T3.2	**Maritime safety protocols.** Safety standards and operational protocols specific to the maritime industry were collected with input from Dacoma ApS and translated into mathematical constraints that define the control barrier functions used in WP4
Task T3.3	**Framework outline.** Drawing on T3.1 and T3.2, a structured outline of the safety-critical control framework was formulated, defining how high-performance controllers operate within safe limits under practical environmental constraints. It was first verified on representative benchmark systems (an actuated pendulum and a pendulum-cart) before being applied to a marine vessel equipped with a roll-stabilizing keel (conventional and air-keel)

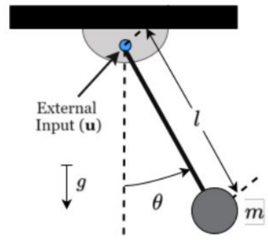
DACOMA ApS — INDUSTRIAL PARTNER ROLE

Dacoma provided the industrial safety protocols as per IMO standards and operational limits specific to the maritime domain, permissible heel angles, lateral-acceleration limits and actuator constraints, which SDU translated into the mathematical safety conditions at the heart of the barrier scheme. This grounding ensured the framework targets constraints that matter in real maritime operation.

SCIENTIFIC NOVELTY

The framework augments an existing nominal controller with safety protocols rather than redesigning it, guaranteeing global stability with minimal interference while preserving the nominal controller's tuned performance.

Example 4: Actuated Pendulum (Proposed CLF-CBF-QP)



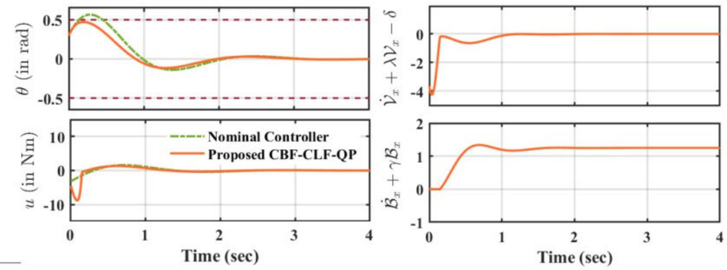
Proposed CLF-CBF-QP

$$\mathbf{u}^*(\mathbf{x}) = \underset{\mathbf{u}\in\mathbb{R}^m,\, \delta\in\mathbb{R}}{\text{argmin}} \quad \frac{1}{2}(\mathbf{u}-\mathbf{k}(\mathbf{x}))^T\mathbf{H}(\mathbf{u}-\mathbf{k}(\mathbf{x})) + p\,\delta^2$$

s.t. $\mathbf{u} \in \mathcal{U}(\mathbf{x})$ (Input Constraint)

$L_\mathbf{f}\mathcal{V}(\mathbf{x}) + L_\mathbf{g}\mathcal{V}(\mathbf{x})\mathbf{u} \leq \delta$ (CLF Constraint)

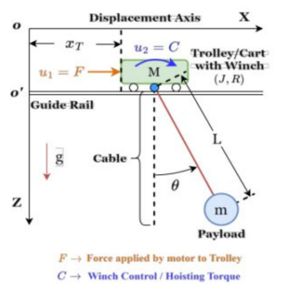
$L_\mathbf{f}\mathcal{B}(\mathbf{x}) + L_\mathbf{g}\mathcal{B}(\mathbf{x})\mathbf{u} \geq -\gamma\mathcal{B}(\mathbf{x})$ (CBF Constraint)



Simulation Conditions

- Initial Conditions, $\mathbf{x_0} = (0.3\ [rad],\ 2\ [rad/s])$
- Safe Limits, $\theta_{safe} = \pm 0.5\ [rad]$
- Nominal Controller: **LQR** => $\mathbf{Q}_{lqr} = 10I_2$; $\mathbf{R}_{lqr} = 1$
- **CLF form**, $\mathcal{V} = \mathbf{x}^T\mathbf{P}_l\,\mathbf{x}$ with $\mathbf{P}_l$ => $\mathbf{Q} = I_2$ (as in Example 3 - Case2)
- **CBF form**, $\mathcal{B}(\mathbf{x}) = \left(\theta_{safe}^2 - \theta^2\right) - (k_1\,\dot{\theta}^2/2\dot{\theta}_{max})$; $k_1 = 0.015$
- Class k_∞ function, $\gamma = 5.0$

Case Study: Safe Tracking Control of an Overhead Crane



Reference trajectories

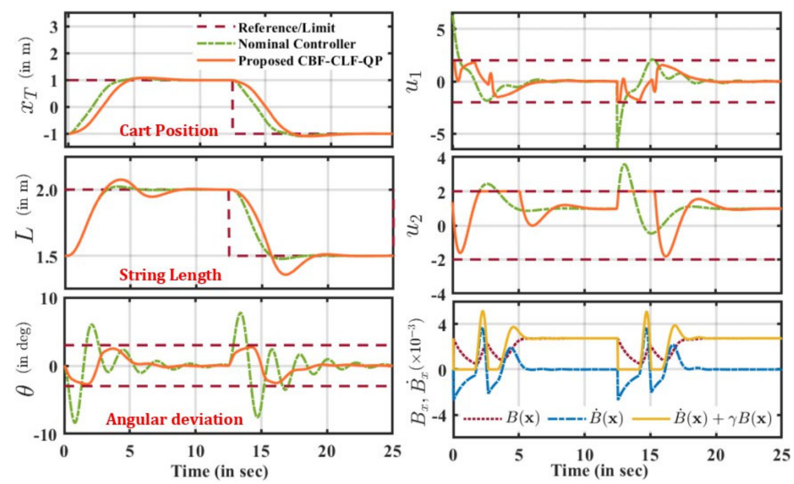
x_T^d => cart position (1 to -1)

L^d => cable length (2.0 to 1.5)

Constraints to follow

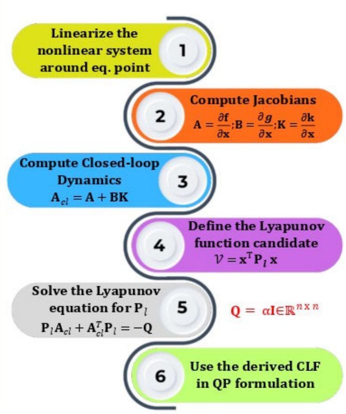
$u_1 = \pm 2$ [N] and $u_2 = \pm 2$ [Nm]

$\theta_{safe} = \pm 3\ [degrees]$



Safety-enhanced Control Framework: QP Formulation

Part 1: CLF Systematic Selection



Part 2: CBF Selection by formalizing IMO criteria

Considering a dynamical system and a safe set $\mathcal{C}_s$, a function $\mathcal{B}: \mathcal{C}_s \to \mathbb{R}$, can be a Control Barrier Function (CBF), if there exists an extended class k_∞ function γ such that,

$$\frac{\partial \mathcal{B}}{\partial \mathbf{x}} \neq 0,\ \forall\, \mathbf{x} \in \partial C_s$$

$$\dot{\mathcal{B}}(\mathbf{x},\mathbf{u}) = \mathcal{L}_\mathbf{f}\mathcal{B}(\mathbf{x}) + \mathcal{L}_\mathbf{g}\mathcal{B}(\mathbf{x})\mathbf{u} \geq -\gamma\mathcal{B}(\mathbf{x})$$

where, $L_f\mathcal{B}(\mathbf{x})$ and $L_g\mathcal{B}(\mathbf{x})$ are the Lie derivatives of $\mathcal{B}(\mathbf{x})$ along $\mathbf{f}(\mathbf{x})$ and $\mathbf{g}(\mathbf{x})$

Part 3: Admissible Input Set

$$\mathcal{U}(\mathbf{x}) = u \in \mathbb{R}^m : u_{min} \leq u \leq u_{max}$$

u_{min} and u_{max} are the actuator saturation bounds

Final: Safety-Enhanced QP Formulation

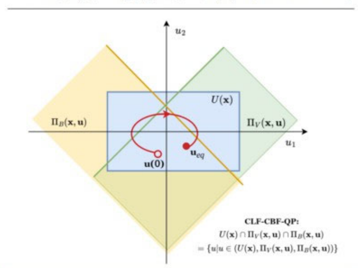
Proposed Safety-Enhanced QP

$$\mathbf{u}^*(\mathbf{x}) = \underset{\mathbf{u}\in\mathbb{R}^m,\, \delta\in\mathbb{R}}{\text{argmin}} \quad \frac{1}{2}(\mathbf{u}-\mathbf{k}(\mathbf{x}))^T\mathbf{H}(\mathbf{u}-\mathbf{k}(\mathbf{x})) + p\,\delta^2$$

s.t. $\mathbf{u} \in \mathcal{U}(\mathbf{x})$ (Input Constraint)

$L_\mathbf{f}\mathcal{V}(\mathbf{x}) + L_\mathbf{g}\mathcal{V}(\mathbf{x})\mathbf{u} \leq \delta$ (CLF Constraint)

$L_\mathbf{f}\mathcal{B}(\mathbf{x}) + L_\mathbf{g}\mathcal{B}(\mathbf{x})\mathbf{u} \geq -\gamma\mathcal{B}(\mathbf{x})$ (CBF Constraint)



WP3: Supporting figures for the safety-enhanced CLF–CBF–QP framework verified on benchmark systems before the marine-vessel case study.

2.4 WP4 — Safety-barrier scheme (SDU Mechatronics · M6)

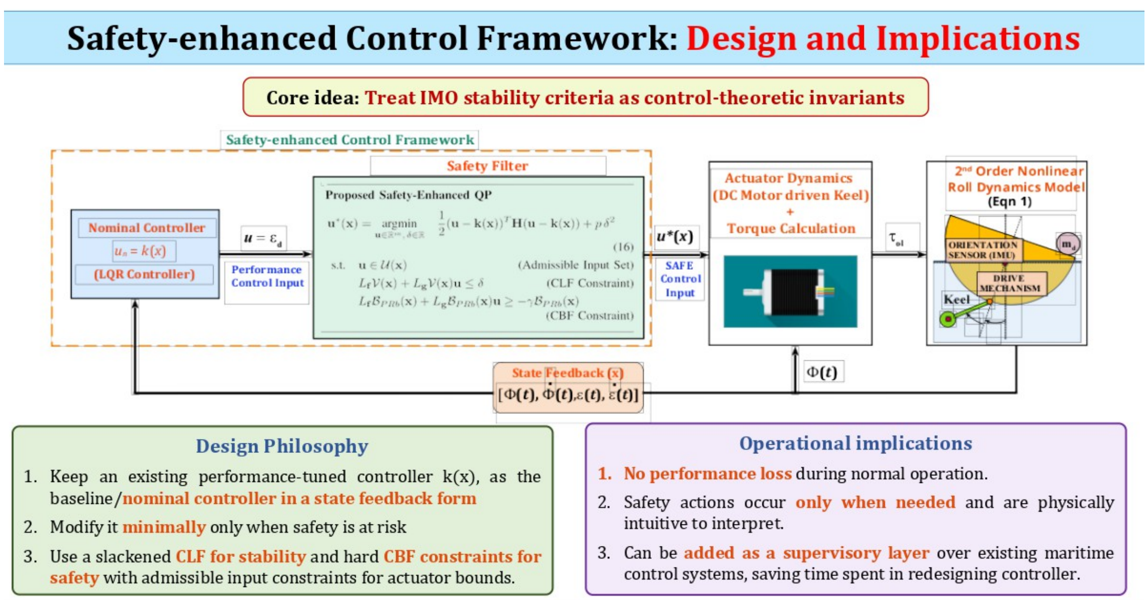
PLANNED	Convert WP3 safety objectives into control barrier functions, design suitable CBF candidates for roll stabilization, and add a real-time scheme to update constraints from the learning controller (T4.1–T4.3).
DELIVERED	Safety conditions formalised; a squared "braking" CBF adopted to ensure forward invariance in high seas; real-time constraint adaptation coupled to the WP5 RL controller; the IMO Second-Generation Intact Stability Criteria recast as online constraints. **M6 achieved (Month 12).**

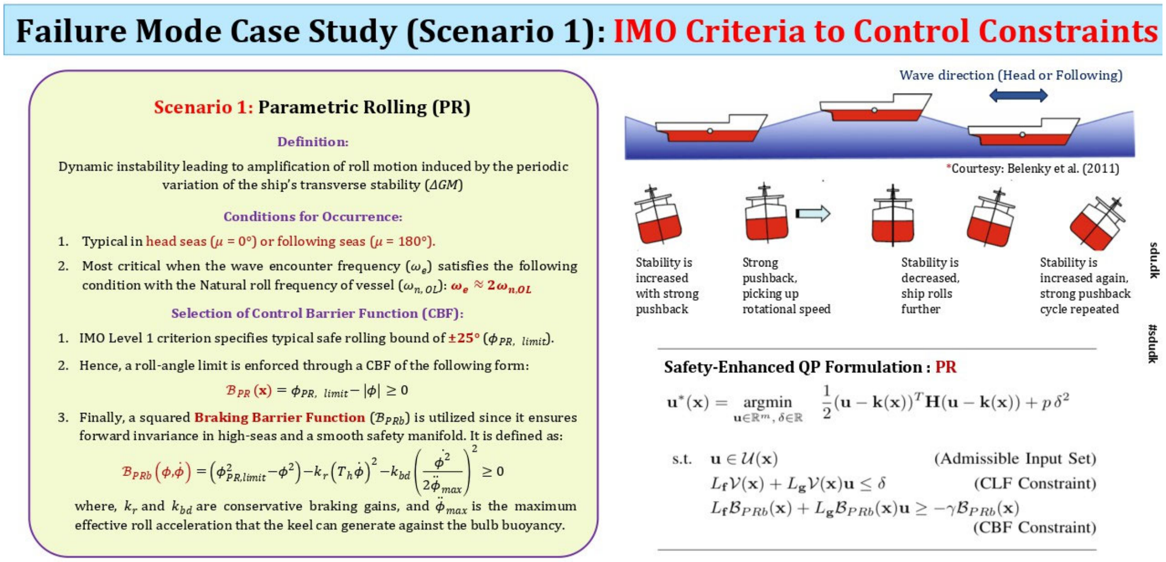
Detailed tasks

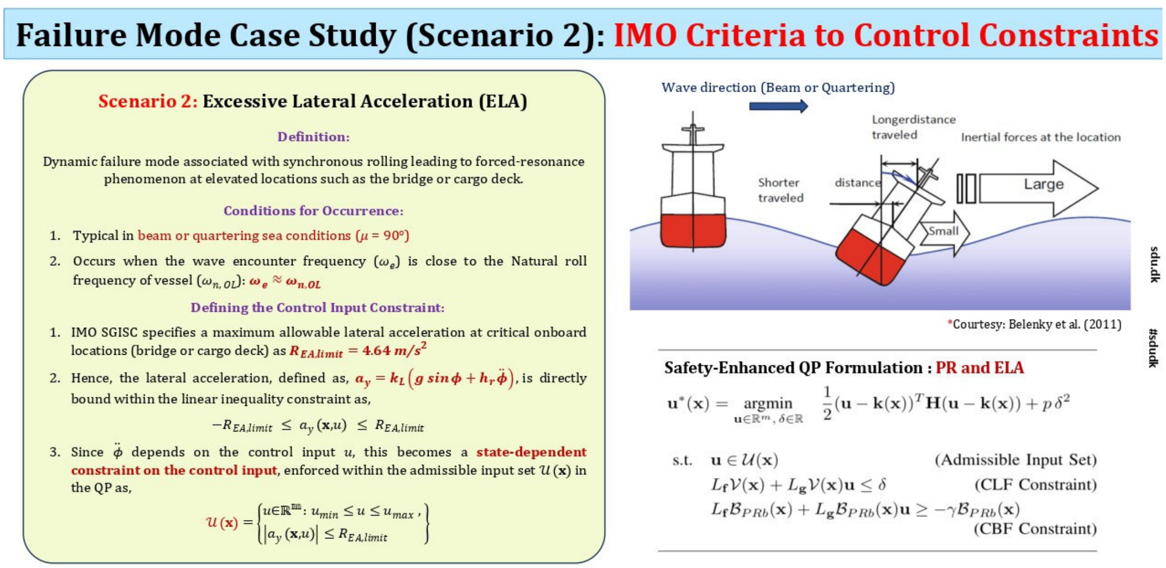
Task T4.1	**Safety conditions.** the industrial safety protocols and constraints identified in WP3 were translated into precise, mathematically defined safety conditions that form the foundation for the control barrier functions
Task T4.2	**CBF construction.** appropriate CBF candidates tailored to the roll-stabilization problem were identified and constructed to act as formal safety filters; a squared ``braking'' barrier function was adopted because it ensures forward invariance in high seas and a smooth safety manifold
Task T4.3	**Real-time adaptation.** a mechanism allowing the safety constraints to adapt in real time, informed by the WP5 learning-based controller, was developed — closing the loop between learning-based performance and barrier-based safety

SCIENTIFIC NOVELTY

First-of-its-kind formulation that embeds two IMO SGISC roll-driven failure modes directly in the control loop: Parametric Rolling as a roll-angle CBF (IMO Level-1 limit ±25°) and Excessive Lateral Acceleration as a state-dependent affine input constraint (IMO limit 4.64 m/s^2), moving maritime stability from post-hoc compliance to active enforcement.







WP4: Supporting figures for control barrier function enforcing the safe roll envelope, with IMO SGISC criteria recast as online constraints.

2.5 WP5 — Learning-based controller (SDU Physics + SDU Mechatronics · M7)

PLANNED	Develop reinforcement-learning controllers within the safety framework that both update safety constraints in real time and act as high-performance roll controllers, trained on prior experimental/field data (T5.1–T5.2).
DELIVERED	A “pure” RL agent commanding the air-keel was built and trained entirely inside the Simulink digital twin. DDPG failed to converge; a discrete DQN agent trained well, and a smoothing reward term markedly reduced output jitter and accelerated roll arrest. **M7 achieved (Month 14).**

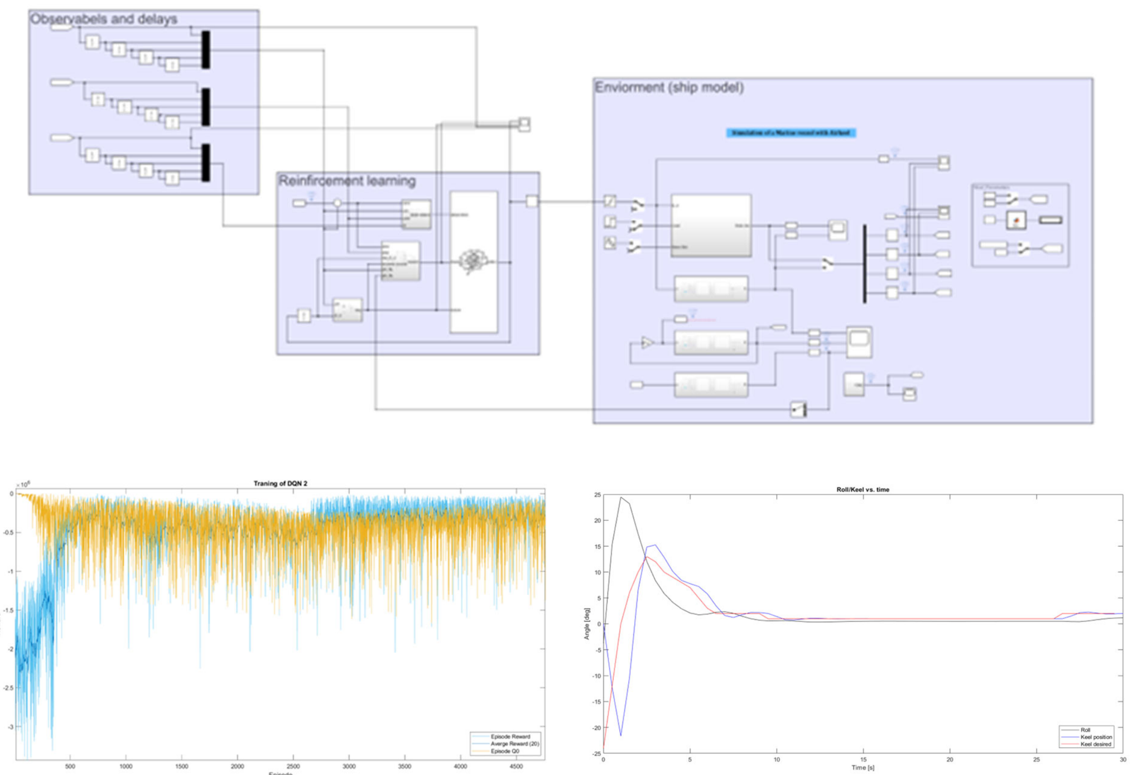
Detailed tasks

Task T5.1	**RL algorithm design.** reinforcement-learning algorithms were developed that learn from data collected in earlier experiments and field tests. A ``pure'' agent that directly commands the air-keel was trained entirely within the Simulink twin, keeping the whole system in one software environment for later deployment. Two agents were compared: a continuous

	DDPG and a discrete DQN , with the DQN converging reliably; the reward penalises squared tracking error, roll velocity and aggressive steering, terminates and penalises keel-limit violations (±60°), and rewards outperforming an open-loop baseline, with an added smoothing term to suppress jitter
Task T5.2	**Integration.** the trained controller was coupled with the WP4 safety-barrier scheme so that high-performance learning-based control is achieved without compromising safety

KEY RESULT

A reinforcement-learning roll controller (smoothed DQN) was trained inside the digital twin and integrated with the WP4 safety barrier, achieving smoother actuation and faster roll arrest than an open-loop baseline while remaining within the safety envelope. Documented in the Appendix 3 technical note and a conference paper in preparation.



WP5: Supporting figures for Reinforcement-learning roll controller (smoothed DQN) trained inside the digital twin

2.6 WP6 — Implementation & validation on the digital twin (SDU Mechatronics + SDU Physics · M8, M9)

PLANNED	Implement the full framework on the WP2 digital twin, estimate critical safety-barrier parameters, and validate the learning controllers under conditions that push the safety bounds (T6.1–T6.3).
DELIVERED	Framework integrated with the digital twin (M8) and learning controllers validated across sea states (M9). Two IMO failure modes stress-tested: Parametric Rolling (±25° limit) and Excessive Lateral Acceleration (4.64 m/s^2 limit), with the safety controller holding both where open-loop/nominal-LQR violated them. **M8, M9 achieved.**

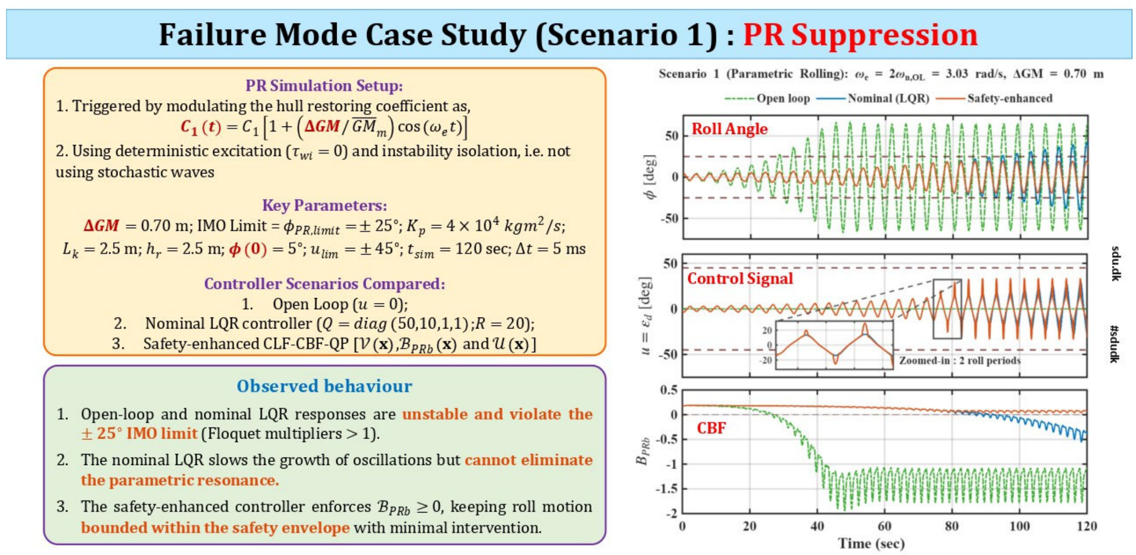
Detailed tasks

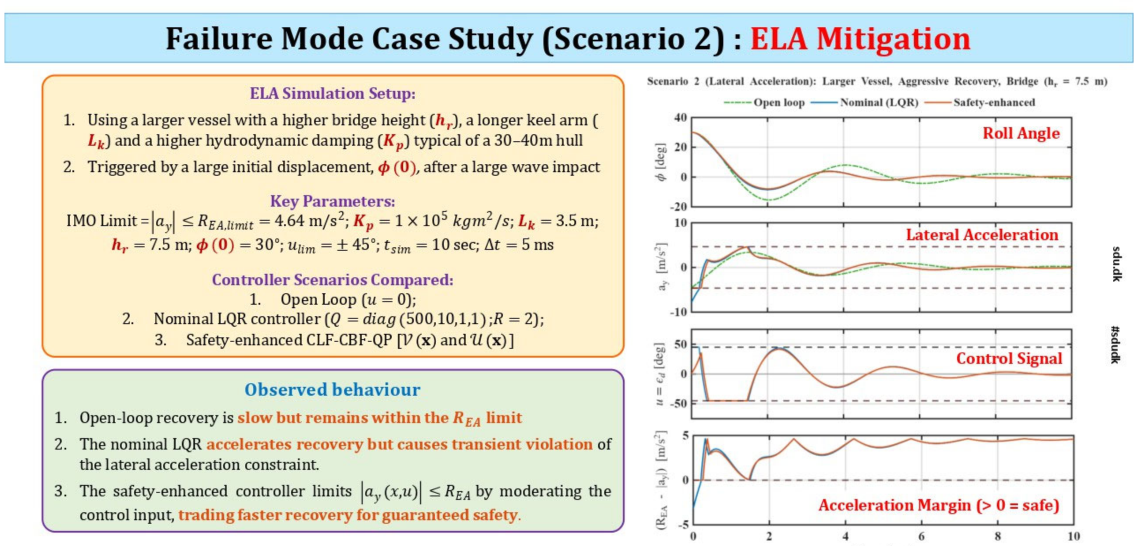
Task T6.1	**Implementation.** the developed safety-critical controller was implemented on the WP2 digital twin within the MATLAB/Simulink environment, integrating the

	nominal controller, CLF stability augmentation, CBF safety filter and the WP5 learning controller
Task T6.2	**Critical-parameter estimation.** parameters critically affecting the safety-barrier performance were identified and estimated using novel techniques, improving the reliability of the barrier under varying conditions
Task T6.3	**Testing & validation.** the learning-based controllers were tested under conditions that push the safety bounds. Under Parametric Rolling, open-loop and nominal-LQR responses violated the ±25° limit (Floquet multipliers > 1) while the safety-enhanced controller stayed bounded; under Excessive Lateral Acceleration, the safety controller held the lateral acceleration within 4.64 m/s^2 where nominal LQR transiently violated it

KEY RESULT

On the digital twin the safety-enhanced controller enforced both IMO-derived limits with minimal intervention, trading a marginally slower recovery for a guaranteed safety margin, which is the central proof-of-concept of the project. **M8, M9 achieved.**





WP6: Supporting figures for validation on the digital twin of parametric-rolling suppression and excessive-lateral-acceleration mitigation against IMO limits.

2.7 WP7 — Real-time validation on a representative platform (SDU Mechatronics + Dacoma · M10, M11)

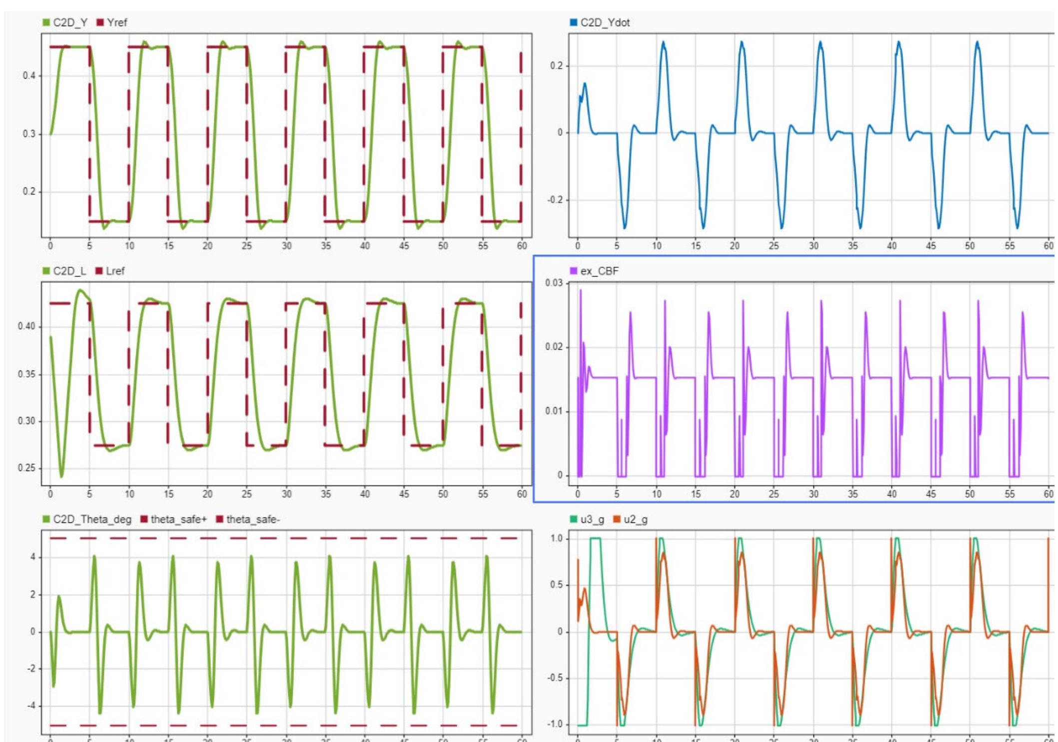
PLANNED	Implement the framework on a representative system with an embedded platform, run real-time experiments, and perform a full-scale test on a demo vessel against current standards (T7.1–T7.4).
DELIVERED	The framework was implemented on a representative physical experimental platform with an embedded computer interfaced with MATLAB, and its real-time capability was validated against realistic sensor noise, actuator saturation and timing constraints, confirming feasibility on hardware (TRL 5). **M10, M11 achieved (lab validation).**

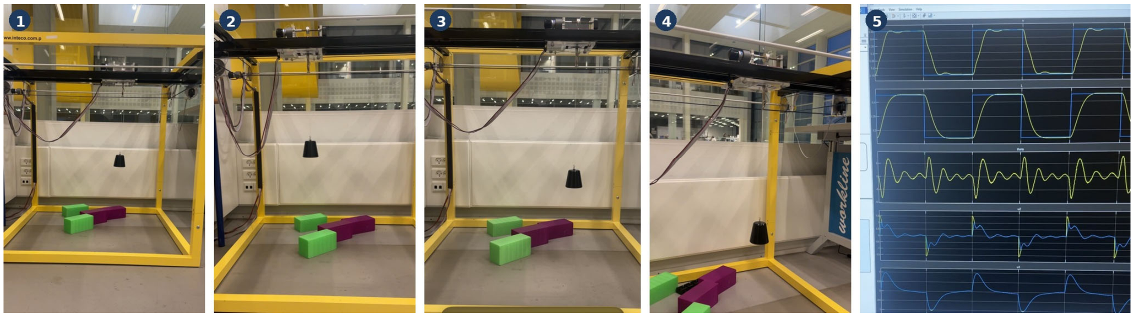
Detailed tasks

Task T7.1	**Embedded implementation.** The framework was implemented on a representative physical platform with the aid of an embedded computer interfaced with MATLAB, bringing the controller from simulation onto real hardware.
Task T7.2	**Disturbance experiments.** The influence of destabilizing factors and disturbances was investigated through controlled experiments on the representative physical setup.
Task T7.3	**Real-time validation.** The framework was exercised in real time on the representative experimental platform for testing and validation against the WP6 baseline and the relevant operational standards.
Task T7.4	**Data collection & analysis.** Performance data were collected and analysed, confirming real-time feasibility and quantifying the safety margins achieved relative to the WP6 simulation baseline.

KEY RESULT

The framework was validated in real time on a representative physical laboratory experiment, confirming real-time feasibility on hardware and raising the technology to TRL 5. **M10, M11 achieved (laboratory validation).**





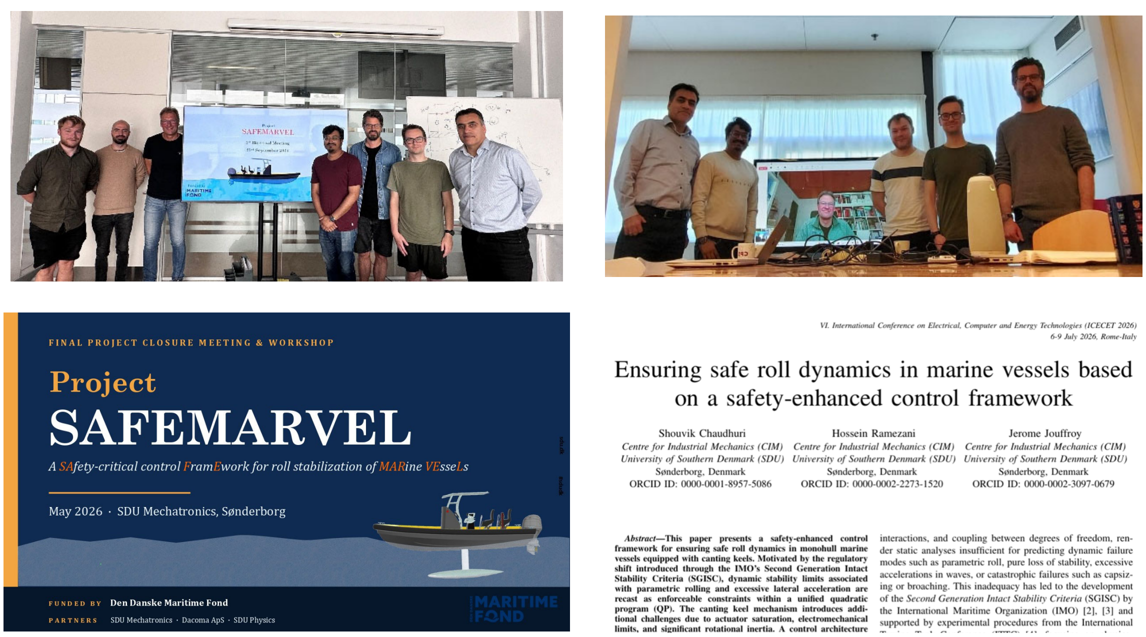
WP7: Supporting figures for real-time validation of the framework on a representative physical experimental platform.

2.8 WP8 — Dissemination & communication (all partners · M12)

PLANNED	Run two bi-annual meetings, hold a final closure meeting/workshop, and publish in journals/conferences with continuous social-media communication (T8.1–T8.4; D-series).
DELIVERED	Four bi-annual meetings plus kick-off and a final project closure meeting; ECC 2025 published and ICECET 2026 accepted; active LinkedIn presence; a supporter article by the Blue Tech Centre. **M12 achieved (Month 24).**

Detailed tasks

Task T8.1	**Bi-annual meetings.** In-person/online partner meetings were held in Sønderborg (23 September 2024) and Odense (21 March 2025), with two further meetings in the second project year, each reviewing progress and the roadmap for the upcoming work packages.
Task T8.2	**Final workshop.** A joint final closure meeting for partners and supporters was held as the project closure meeting in the May'2026.
Task T8.3	**Scientific publications.** contributions to prestigious conferences and journals — one paper published at IEEE ECC 2025, a second accepted at ICECET 2026, a third on the RL scheme in preparation with SDU Physics, and a journal extension in preparation.
Task T8.4	**Social-media communication.** regular posts on LinkedIn through the project and partner/supporter pages; the project supporter Blue Tech Centre published an article about SAFEMARVEL on its website



WP8: Supporting figures for dissemination activities — bi-annual partner meetings, the final closure meeting, LinkedIn communication and scientific publications.

3. Milestone and deliverable ledger

3.1 Milestones (M1–M12)

ID	Milestone	Plan	Status
M1	Project start	M1	**Done**
M2	Contract, co-operative agreement & kick-off meeting	M1	**Done**
M3	Mathematical model of vessel with roll-stabilizer	M3	**Done**
M4	Model validated & control-oriented digital twin implemented	M6	**Done**
M5	Outline of the safety-critical framework	M9	**Done**
M6	Safety-barrier (CBF) functionality developed	M12	**Done**
M7	Learning-based (RL) control algorithm within the framework	M14	**Done**
M8	Integration of the safety framework with the digital twin	M16	**Done**
M9	Testing of learning controllers on the integrated digital twin	M20	**Done**
M10	Implementation & test on a representative experimental platform	M22	**Done**
M11	Real-time validation of the framework on a representative platform	M24	**Done**
M12	Project end	M24	**Done**

3.2 Deliverables / dissemination (D1–D16)

ID	Dissemination / deliverable	Status
D1	Communication of project start (LinkedIn / partner pages)	**Done**
D2	First bi-annual meeting (Sønderborg, Sep 2024)	**Done**
D3	Communication of the framework outline	**Merged with D4**
D4	First scientific article on WP3 results	**Published in ECC 2025 (IEEE)**
D5	Second bi-annual meeting (Odense, Mar 2025)	**Done**
D6	Communication of WP4 results	**Done**
D7 + D8	Preparation of the RL Schema and Communication of WP5 results	**Done**
D9	Third bi-annual meeting (Online, Nov'2025)	**Done**
D10	Second scientific article on WP6 results	**ICECET 2026 (Presented)**
D11	Communication of WP6 results	**Done**
D12 + D13	Fourth bi-annual and Final project closure meeting (May 2026)	**Done**
D14	Third scientific article combining WP6 & WP7	**Journal in prep.**
D15	Communication of WP6/WP7 results	**Done**
D16	Final project reporting & communication	**Done**

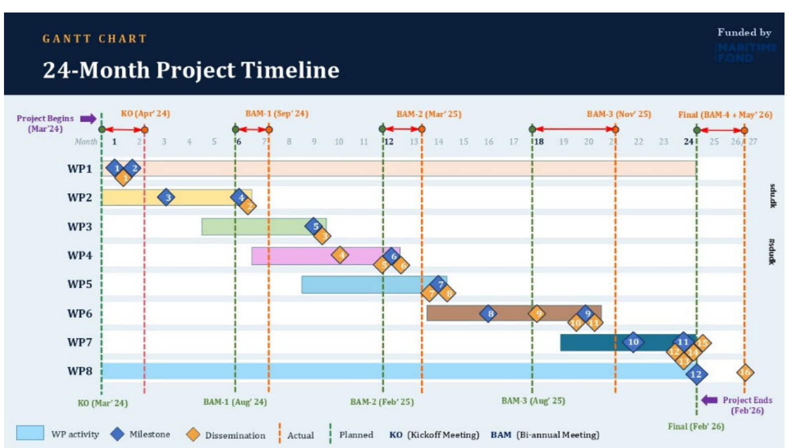


Figure 2. Project timeline: milestones (M1–M12) and dissemination (D1-D16) across the full period (Refer to Appendix 3)

4. Technology readiness and partner contributions

4.1 Technology-readiness progression

SAFEMARVEL advanced the safety-enhanced roll-stabilization concept from an idea on paper to a technology validated in a relevant laboratory environment — a real-time experiment on a representative physical system, reaching TRL 5 over the 24-month period.

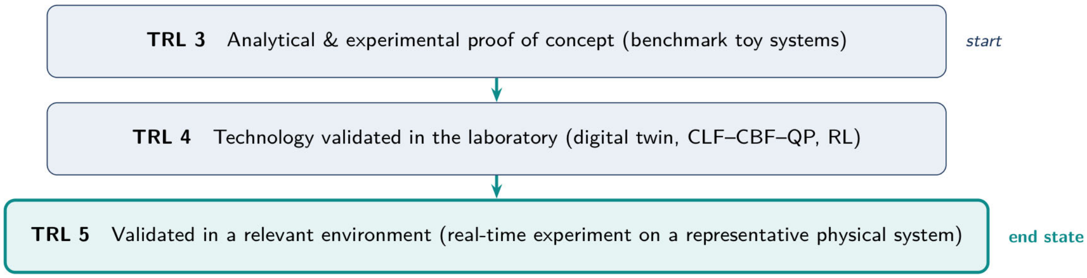


Figure 3. Technology-readiness progression from TRL 3 to TRL 5.

4.2 Partner contribution matrix

Partner	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8
SDU Mechatronics (lead)	L	L	L	L	C	L	L	C
Dacoma ApS		C	C				C	C
SDU Physics		C			L	C		C

L = lead · C = contributor

SDU Mechatronics (lead) delivered the mathematical modelling and digital twin, the CLF–CBF–QP safety framework and barrier scheme, and the integration and real-time experimental validation, alongside project management and dissemination. SDU Mechatronics hosted the postdoc for this project.

Dacoma ApS (industrial partner) provided the canting/air-keel stabilizer, the maritime domain expertise and safety requirements that shaped the barrier scheme, the model-boat data used to validate the digital twin, embedded-systems support for the representative validation. Dacoma also supervised an associated in-company project.

SDU Physics (academic partner) led the learning-based control work package, developing and training the reinforcement-learning roll controller inside the digital twin and coupling it to the safety barrier, and supervised the associated MSc thesis.

5. Scientific contributions and publications

The project produced a coherent body of work moving roll-stabilization safety from passive compliance to active, controller-level enforcement.

1. A safety-enhanced control framework that augments a nominal controller with systematically derived CLF stability and CBF safety guarantees via a single QP (ECC 2025).
2. A recasting of the IMO SGISC dynamic-stability criteria (parametric rolling, excessive lateral acceleration) as enforceable online control constraints for vessels with canting keels (ICECET 2026).
3. A reinforcement-learning roll controller trained inside the digital twin and coupled to the safety barrier (conference paper in preparation).

5.1 Publication record

Title / venue	Type	Status
Remarks on augmenting stability and safety in nominal controllers: a practical perspective — ECC 2025, Thessaloniki	Conference	**Published**
Ensuring safe roll dynamics in marine vessels based on a safety-enhanced control framework — ICECET 2026, Rome	Conference	**Presented**
Reinforcement learning for roll stabilization within a safety framework	Conference	**Prepared**
Journal extension with experimental/validation results	Journal	**In prep.**

6. Management, impact and sustainability

Cooperation. Collaboration between the three partners was constructive throughout: real-time data shared between Dacoma and SDU for digital-twin development; simulation files exchanged between SDU Mechatronics and SDU Physics via SharePoint for the RL work; joint work between Dacoma and SDU on the representative experimental setup; monthly all-partner meetings plus four bi-annual meetings and a final project closure meeting.

Impact. One postdoctoral position was created at SDU Sønderborg. The project produced one completed in-company project (with Dacoma) and one MSc thesis on Reinforcement Learning (with SDU Physics), and delivered active dissemination through LinkedIn, international conferences and a supporter article.

Sustainability and follow-on. The immediate next step is the full-scale on-vessel demonstration with Dacoma, advancing the technology beyond the laboratory-validated TRL 5 reached in the project. In addition, a spin-off involving AI-driven power-flow optimization at ferry charging stations in Denmark is under discussion among the partners, and the journal extension of the conference work is in preparation, extending the scientific and industrial reach of SAFEMARVEL beyond its funded period.

7. Conclusion

SAFEMARVEL met every objective and all twelve milestones within its 24-month period. It delivered a validated digital twin, a safety-enhanced CLF–CBF–QP framework that is the first to embed IMO Second-Generation Intact Stability Criteria as online constraints, a reinforcement-learning roll controller operating within that framework, and a real-time validation on a representative physical laboratory experiment carried out with the industrial partner Dacoma. The result is a practical, laboratory-validated route for the marine sector to adopt high-performance and learning-based controllers without sacrificing the formal safety guarantees on which the industry depends, with a clear path to a full-scale on-vessel demonstration.

Bottom line. A complete, laboratory-validated path from concept to a representative physical experiment: any controller can now be made provably safe for vessel roll stabilization, with safety expressed directly in the language of international maritime stability regulation.

Note: Please refer to the appendices below for the official financial reporting, publications and some technical notes on the project