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I. Problem Statement

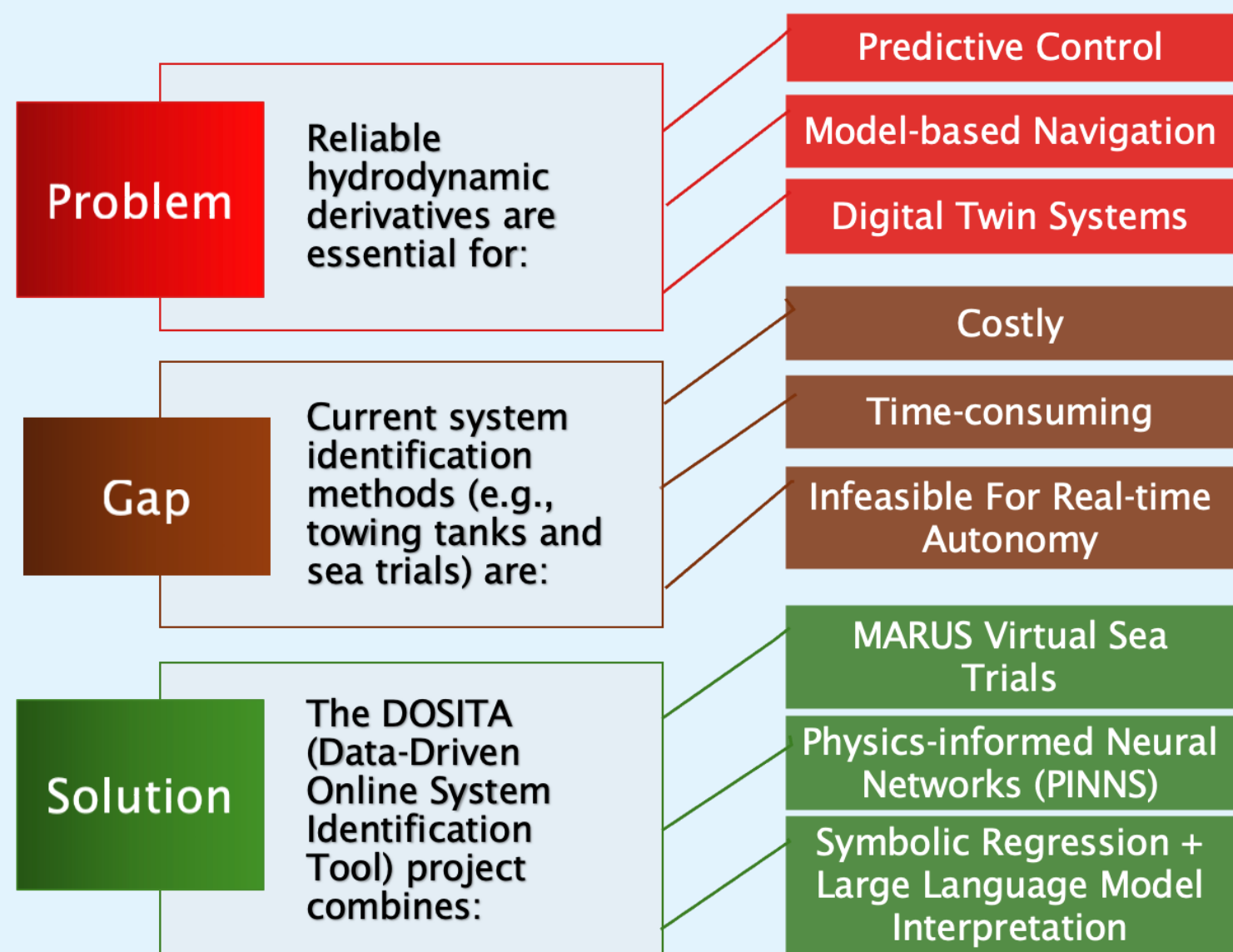


Fig. 1: Problem-gap-solution overview of the DOSITA framework, highlighting MARUS (Marine Robotics Unity Simulator)-enabled virtual sea trials and hybrid learning components.

II. Hybrid MARUS-PINN-LLM Pipeline

This section introduces the hybrid MARUS-PINN-LLM pipeline for data-driven hydrodynamic system identification.

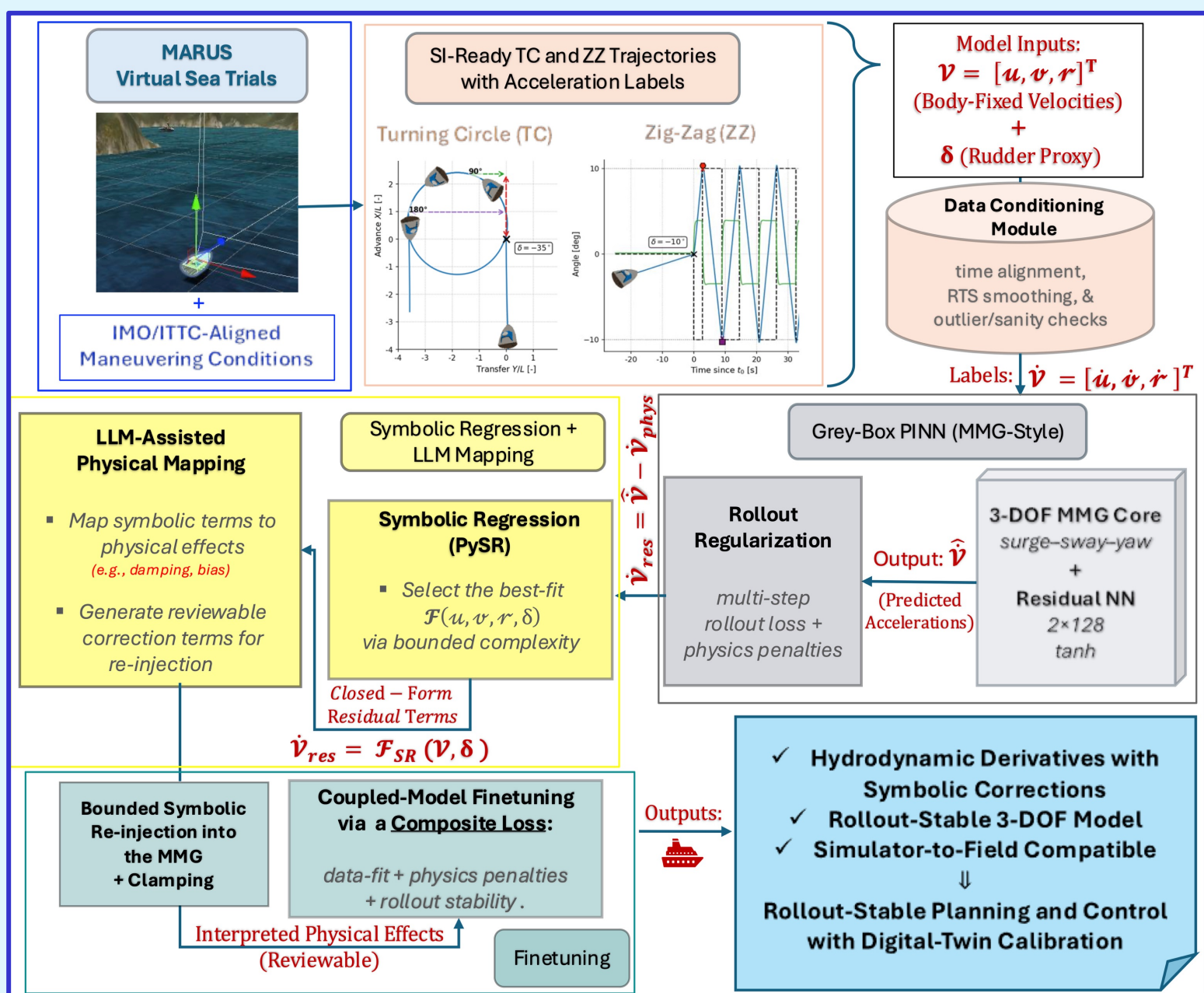


Fig. 2. Derivative-estimation workflow: MARUS-based Turning Circle (TC) and Zig-Zag (ZZ) manoeuvres, Manoeuvring Modelling Group (MMG)-structured grey-box PINNs, symbolic residual discovery, and rollout-stable hydrodynamic modelling.

The core of the framework is a GreyBox PINN combining an MMG-inspired physics model with a learned neural residual correction.

$$\dot{v}_{pred} = f_{MMG}(v, \delta) + f_{res}(v, \delta) \quad (1)$$

Where:

f_{MMG} : physics-based MMG core

f_{res} : learned neural residual correction

Key Features:

Physics-consistent → Rollout-stable → Interpretable → Digital-twin-ready

III. Virtual Sea Trials and Experimental Validation

i. IMO/ITTC Maneuvering Validation

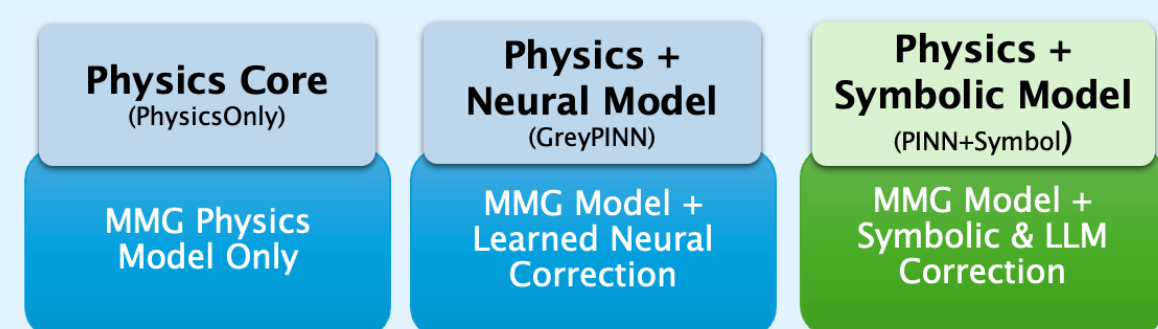
Representative TC and ZZ maneuvers satisfied International Maritime Organization (IMO) criteria under International Towing Tank Conference (ITTC) procedures, preserving actuation traceability.

Manoeuvre	Advance	Tactical Diameter	IMO Criteria
Turning Circle to Starboard	2.49	3.59	Advance ≤ 4.5 , Tactical Diam. $\leq 5.0 \rightarrow$ PASS
Manoeuvre	Overshoot Excess	Peak Yaw Rate	IMO Criteria
ZZ 20°/20° (Port-first)	0.49 / 0.54	5.78	Overshoot Exc. $\leq 25^\circ$, Peak YR $\leq 40^\circ \rightarrow$ PASS

Table I. Representative MARUS-based IMO/ITTC Turning Circle and Zig-Zag Execution Validation Results. All extracted manoeuvrability metrics pass the prescribed IMO criteria.

ii. Rollout-Stability and Hydrodynamic Prediction Performance

Three models were tested on held-out MARUS TC and ZZ manoeuvres:



The results are as follows:

Accuracy	PhysicsOnly	GreyPINN	PINN+Symbol
Stability	PhysicsOnly	GreyPINN	PINN+Symbol
Generalizability	PhysicsOnly	GreyPINN	PINN+Symbol

Model	RMSE _u	RMSE _v	RMSE _r	Rollout _r	Rollout _v
PhysicsOnly	0.0929 ± 0.0003	0.0274 ± 0.0000	0.1779 ± 0.0001	9999 ± 0	9999 ± 0
GreyPINN	0.0130 ± 0.0003	0.0154 ± 0.0087	0.0191 ± 0.0004	476 ± 881	481 ± 881
PINN+Symbol	0.0130 ± 0.0002	0.0039 ± 0.0009	0.0056 ± 0.0011	0.031 ± 0.004	1.44 ± 0.61

Table 2. Rollout-Stability and Prediction Performance.

To illustrate the practical implications of these results, predicted TC trajectories from each model are compared with the ground truth.

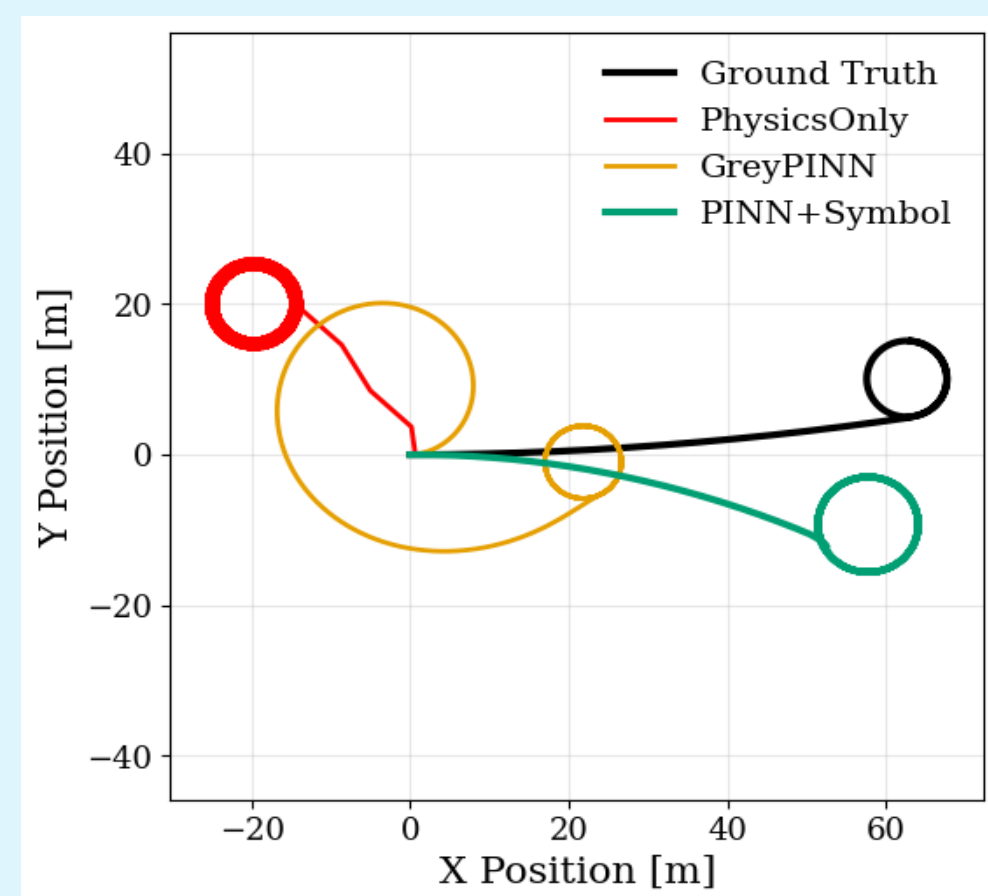


Fig. 3: TC trajectory reconstructions. PhysicsOnly converges to a tight orbit with the thicker line depicting overlapping loops. GreyPINN drifts and loses the overall manoeuvre shape. In contrast, PINN+Symbol follows the turning-circle more closely and produces smoother, more consistent behaviour over longer rollouts.

IV. Conclusions

This work demonstrates that hybrid MARUS-based system identification can produce traceable, rollout-stable, and interpretable hydrodynamic models, enabling reliable marine vessel autonomy. This research was supported through Graduate Teaching Assistant (GTA) funding from Sheffield Hallam University's School of Engineering and Built Environment.