From Classification to Prediction

A Physically-Aware Deep Learning Framework for Maritime Near-Miss Detection

Author: Polly Chen-GOUJARD
MSc AI for Business (Neoma/INSA de ROUEN)
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https://github.com/pollyxinjei-byte/Near-Miss_Project.git

Regional Motivation: The Piraeus Port Case Study

- **Environmental Constraints:**

The **Mediterranean basin,** specifically Piraeus, is characterized by negligible tidal variations.

- **Motion Drivers:**

In this environment, vessel movement is almost exclusively governed by human intent and physical inertia rather than external environmental forces.

- **The Opportunity:**

This predictable kinematic environment allows for a high-precision, physically-aware prediction model that outperforms general-purpose global models.

- **Strategic Goal:**

Transitioning from reactive safety monitoring to a proactive, predictive **"Glass Box"** system.

Problem Discovery: The Circular Logic Trap

- **The "False" Success:**

Initial baseline models (MLP) appeared to achieve an unrealistic 98% accuracy in risk classification.

- **Data Leakage:**

Analysis revealed that these models were "cheating" by using future risk indicators (CPA/TCPA) as input features.

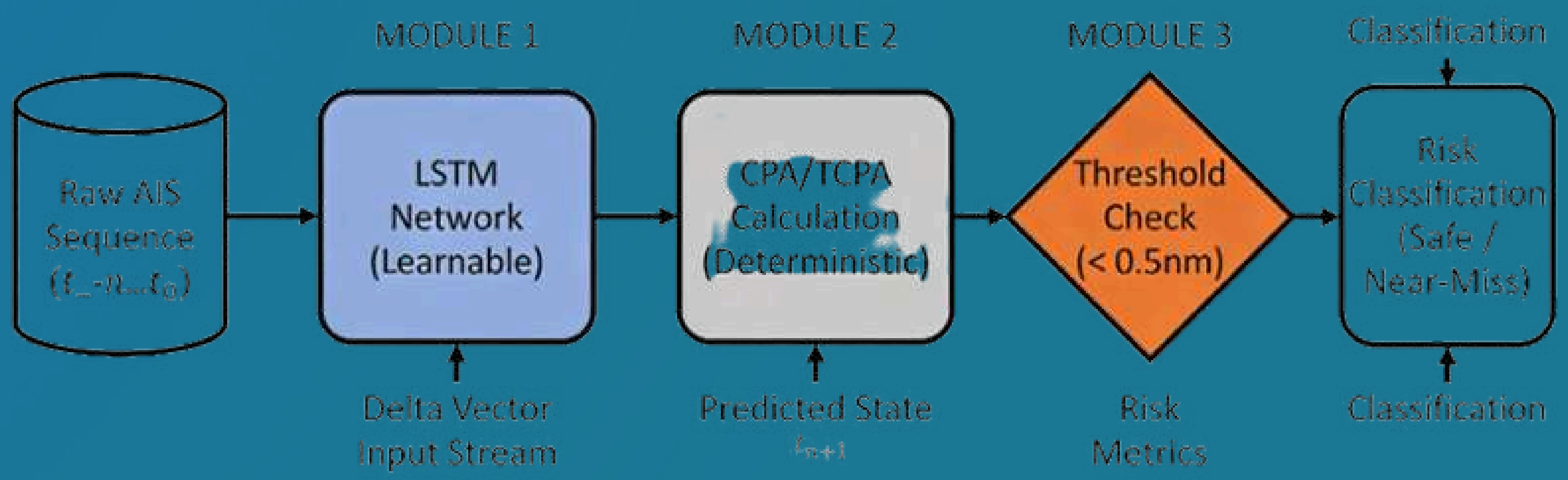
- **Structural Flaw:**

This created a Circular Logic loop where the model was memorizing outcome labels instead of learning vessel movement patterns.

- **The Redesign:**

To solve this, the framework was rebuilt to completely decouple Kinematic Prediction from Safety Judgment.

Solution Architecture: the Hybrid Framework



- **Module 1 (AI Prediction):** A 2-Layer LSTM engine specialized in predicting short-term vessel trajectories through delta-displacement.

- **Module 2 (Physics Computation):** A deterministic layer that calculates CPA and TCPA using the predicted kinematic states from Module 1.

- **Module 3 (Safety Logic):** A rule-based classifier that triggers "Near-Miss" alerts based on established maritime safety thresholds (CPA < 0.5 nm).

- **The "Glass Box" Advantage:** This modular design ensures that every safety alert is traceable, auditable, and physically justifiable.

Technical Breakthrough
7.98m Precision: A 500x Accuracy Gain

- **The Challenge:**

Traditional absolute coordinate prediction resulted in average errors exceeding 4,000 meters.

- **The Innovation:**

The model implements Delta-Prediction(Δ) by shifting the focus from absolute positions to relative displacement between time steps.

- **Model Configuration:**

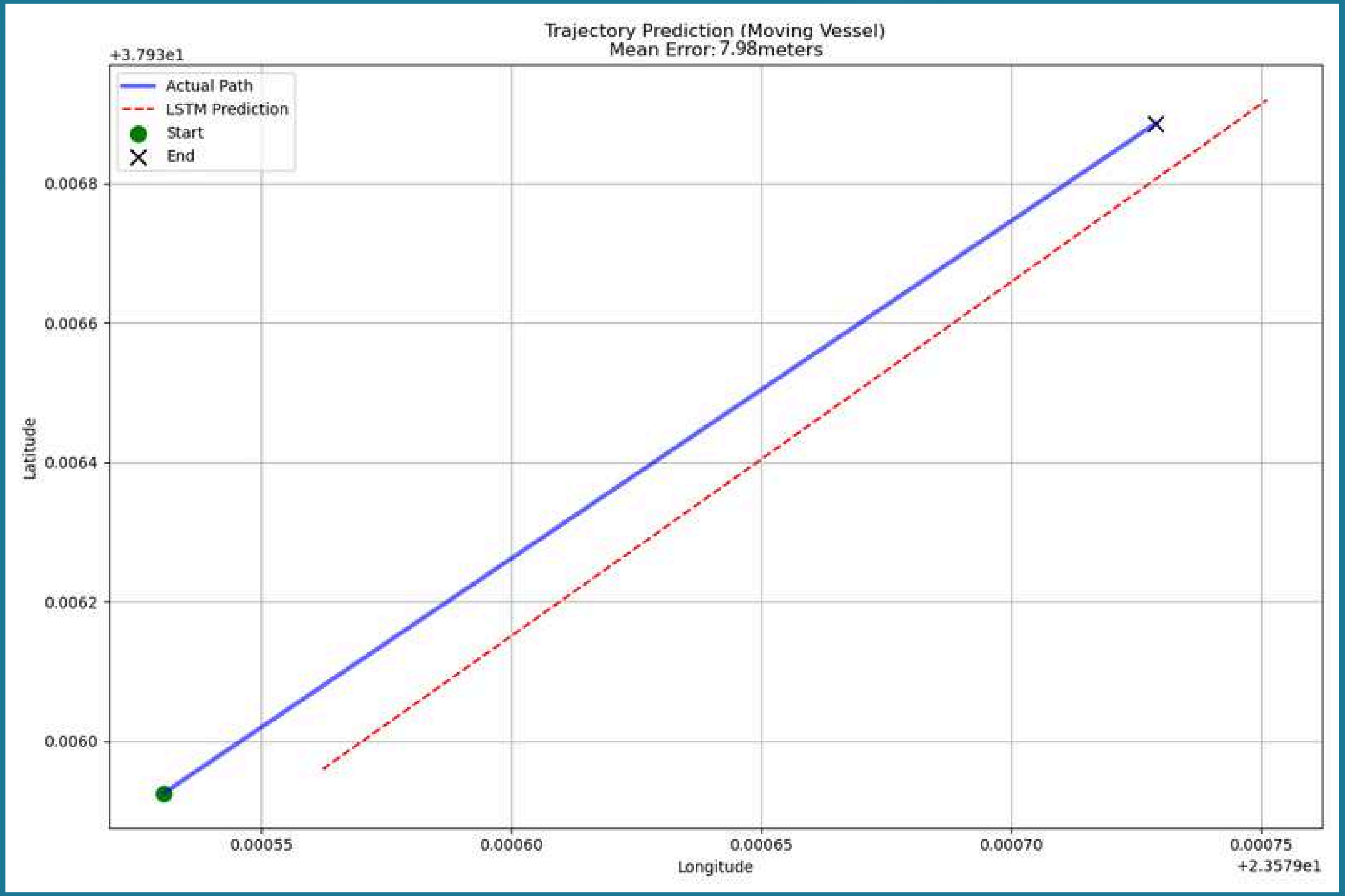
2-Layer LSTM architecture featuring **128** hidden units and a **0.2** Dropout rate for robust generalization.

- **The Result:**

Prediction error was reduced to **7.98 meters**, representing a **500-fold precision** improvement over baseline approaches.

Kinematic Reliability
Visual Validation: Trajectory Fidelity

- **The Comparison:** The plot demonstrates the high degree of overlap between predicted trajectories (Red) and actual vessel paths (Blue).
- **Dynamic Capture:** The model successfully captured complex vessel intent and momentum during maneuvering phases within the Piraeus port area.
- **Reliability:** This spatial alignment confirms that the **7.98m** mathematical error translates to high-fidelity physical realism.
- **Foundation:** This kinematic reliability provides a trustworthy baseline for the subsequent Physics and Logic modules.



Aware Safety Logic
The Physics Layer: Deterministic Risk Logic

- **Explainable Criteria:**

The framework utilizes deterministic Newtonian mechanics to judge risk instead of relying on opaque AI intuition.

- **The Formula:**

Every predicted state is processed through the CPA and TCPA equations to identify potential near-miss encounters.

- **Safety Thresholds:**

Alerts are triggered only when **CPA < 0.5 nm** and **TCPA > 0**, ensuring adherence to maritime navigational standards.

- **Auditable Alerts:**

This layer provides bridge officers with a clear physical justification for every safety notification.

Automated Risk Detection
System Results: Automated Near-Miss Detection

- **Detection Rate:**

The integrated system successfully identified high-risk encounters with a **15% Near-Miss rate** across the validated dataset.

- **Operational Efficiency:**

By applying deterministic logic, the system effectively filters out **85% of safe traffic** as "Non-Risky."

- **Alarm Fatigue Mitigation:**

This selective filtering reduces cognitive load for bridge officers by ensuring only physically-justifiable threats trigger alerts.

- **Proactive Horizon:**

The system provides a tactical safety window based on future predicted states rather than just historical positions.

Performance Benchmarking
Benchmark: Competitive Performance Analysis

- **Model Comparison:**

The framework was benchmarked against the TrAISformer model using the Piraeus Port dataset.

- **Efficiency Gains:**

The proposed system demonstrates superior computational efficiency for short-term tactical horizons.

- **Optimization:**

By focusing on kinematic delta-prediction, the model achieves lower inference latency without sacrificing spatial precision.

- **Regional Superiority:**

The physically-aware design proves more robust for specific Mediterranean navigation patterns than generalized global architectures.

Approach	Strength	Limitation	This Work
TrAISformer	Long-horizon accuracy	Overkill for tactical decisions	✓ Right-sized architecture
MLP Classifier	Simplicity	Circular logic vulnerability	✓ Eliminated via decoupling
Pure DL	Flexibility	Physics-ignorant	✓ Physics-integrated

Harmonizing AI and Physics
Conclusion and Future Outlook

- **System Summary:**

The project successfully transitioned maritime safety from reactive classification to a proactive **"Glass Box"** prediction framework.

- **Key Contribution:**

By integrating LSTM-based delta-prediction with Newtonian logic, the system achieved a significant **7.98m** accuracy threshold.

- **Future Work:**

Next iterations will explore Graph Neural Networks (GNNs) to model complex multi-vessel interactions and environmental forces.

- **Portfolio Access:**

Detailed code implementation and datasets are available on the project repository.

https://github.com/pollyxinjei-byte/Near-Miss_Project.gitt