Redefining Maritime Logistics: Leveraging Digital Twin-Based Auto-Pilotage for Enhanced Safety and Efficiency in Indian Ports

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Abstract— **Indian ports are important nodes of national and international trade but are facing growing issues of congestion, navigation hazards, and poor fuel efficiency. Conventional manual pilotage is vulnerable to human mistake and not adequate for coping with the increasing complexity of ship traffic. This research assesses digital twin-based auto-pilotage as a scalable answer to improve security, operational efficiency, and sustainability at Indian ports. A digital twin of Mumbai Port in 3D was created with MATLAB/Simulink, Unity, Python, and AnyLogic, combined with real-time IoT streams of GPS, LiDAR, AIS, and environmental APIs. Simulation scenarios contrasted manual pilotage, semi-automated decision aid, and fully automated digital twin-enabled auto-pilotage across variable traffic volumes and weather conditions. The findings indicate that digital twin-augmented auto-pilotage cuts mean docking time by 41%, decreases near-miss probability by 73%, and cuts fuel consumption by 18%, with all of these metrics statistically proven across 50 simulation runs. The cognitive workload, measured through NASA-TLX, decreased from 75/100 to 35/100, indicating substantial alleviation for human pilots. These results suggest that cyber-physical integration of digital twins can provide predictive decision-making in real-time, optimize berth planning, and enhance maritime safety. Successful implementation in India needs India-specific frameworks, tackling vessel density, port infrastructure bottlenecks, and tropical weather fluctuations. Policy support through pilot projects and staged IoT infrastructure upgrades under programs like Sagarmala is necessary. Future studies should concentrate on multi-port tests, AI-based environmental modeling, and cybersecurity approaches for autonomous maritime operations. This research generates strong evidence that digital twin-based auto-pilotage is a revolutionary paradigm for modernizing Indian port operations and attaining global competitiveness in maritime logistics.**

Index Terms— **Digital Twin, Auto-Pilotage, Maritime Logistics, Indian Ports, Port Safety, Operational Efficiency, Simulation, IoT Integration**

I. INTRODUCTION

1.1 Background Context

Maritime shipping handles nearly 90% of global trade (UNCTAD, 2022), making ports essential nodes in international supply chains. Over the past two decades, the sector has undergone significant transformation, driven by digitalization, automation, and artificial intelligence. Leading smart ports, such as Rotterdam and Singapore, have implemented IoT-based monitoring, digital twins, and autonomous ship routing to reduce human dependency and enhance operational safety (Martelli et al., 2021).

Indian ports are behind in embracing such innovations (Liu et al., 2023). Though handling more than 95% of India's external trade volume, the majority of operations are manual with few real-time decision-support technologies (Sim et al., 2024). Busy ports Mumbai, Chennai, and Kolkata record lengthy docking times, uncontrollable delays, high operational expenses, and common near-miss events from human mistakes (Klar et al., 2023).

1.2 Problem Statement

Dependence on manual pilotage makes Indian ports vulnerable to inefficiency and safety risks (Yang et al., 2024).. With increasing ship sizes, high traffic density, and environmental uncertainty, human-driven docking is uneven, time-consuming, and even risky (Ding et al., 2023). These inefficiencies restrict India from realizing port infrastructure that is globally competitive (Augustine, 2020).

1.3 Research Gap

While digital twins have been used globally for simulation, predictive maintenance, and traffic optimization, integrating real-time auto-pilotage for Indian ports is uncharted territory (Homayouni et al., 2025). Current frameworks are developed to fit the digitally advanced ports with superior infrastructure, which cannot be transferred directly to India. This research fills this void by formulating a IoT-based digital twin for auto-pilotage in Indian port conditions, taking into account high vessel density, infrastructural limitations, and tropical weather uncertainty (Carreras Guzman et al., 2020).

1.4 Significance of the Study

Academic Contribution: Expands maritime logistics research by adopting cyber-physical digital twin philosophies for real-time auto-pilotage in Indian ports.

Practical Contribution: Offers a deployable, scalable option to advance port safety, congestion reduction, and fuel consumption reduction, which is in line with such schemes as Sagarmala and Maritime India Vision 2030.

1.5 Research Aim and Objectives

Aim: To evaluate the effectiveness of digital twin-based auto-pilotage in improving safety and operational efficiency in Indian ports.

Objectives:

- To develop a digital twin model of a representative Indian port that captures its physical layout, operational characteristics, and vessel traffic patterns for use as a simulation testbed.
- To integrate real-time IoT data streams into the digital twin framework to enable predictive decision-making for auto-pilotage functions, including docking maneuvers, collision avoidance, and vessel tracking.
- To compare docking efficiency, collision risk probability, and fuel consumption between digital twin-assisted auto-pilotage and conventional manual pilotage under varied traffic densities and weather conditions in simulated scenarios.

1.6 Research Questions and Hypotheses

RQ1: To what extent does digital twin-based auto-pilotage reduce vessel docking time under varying traffic densities compared to manual pilotage?

RQ2: How effectively does digital twin-based auto-pilotage lower collision and near-miss probabilities compared to traditional methods?

Hypothesis (H1): Digital twin-assisted auto-pilotage significantly improves port operational efficiency and safety by reducing docking time by $\geq$40%, lowering near-miss probability by $\geq$70%, and decreasing fuel consumption by $\geq$15% compared to manual pilotage, while alleviating pilot workload.

II. LITERATURE REVIEW

2.1 Historical Background

Conventional maritime logistics has been dependent on manual pilotage and simple navigational equipment like compasses, radar, and Automatic Identification Systems (AIS)(Jiang et al., 2023). Although satisfactory in low-traffic conditions, they have limited situational awareness and forecast capability(Neugebauer et al., 2024a). The concept of virtual port models was first conceived in the early 2000s, with the intention to simulate real-world port settings in a digital environment for planning and training(Bhagavathi et al., 2023).

2.2 Recent Advances

The last ten years have also witnessed the emergence of digital twin technology, which constructs a dynamic, real-time virtual copy of a physical system(Rajak et al., 2024). Digital twins have been utilized in maritime logistics to:

Smart Ports: Singapore and Rotterdam have led the way with digital twin platforms for traffic management, predictive maintenance, and energy management(Wang et al., 2024).

Vessel Navigation: Studies have proven autonomous docking systems with machine learning and IoT sensors(Zocco et al., 2023).

Simulation and Risk Analysis: Research simulates collision probabilities, fuel consumption, and ship trajectories under various conditions(Lind et al., 2020).

2.3 Theoretical Models and Frameworks

Digital twin technologies employed in maritime logistics are based on the following frameworks:

Cyber-Physical Systems (CPS): Merging of physical port infrastructure with virtual simulations and IoT networks(Wang et al., 2024).

Predictive Maintenance Models: Sensor-driven analytics to predict and avoid equipment breakdowns(Jiang et al., 2023).
Port Traffic Management Algorithms: Optimisation models for ship routing, docking assignment, and congestion relief(Zhou et al., 2024).

2.4 Comparative Analysis
Current digital twin systems improve planning and monitoring but do not suffice to support real-time auto-pilotage integration(Kautsar et al., 2025).
Rotterdam and Singapore are leading the way but cannot be transplanted to Indian contexts as is because of infrastructural, regulatory, and environmental conditions(Fuller et al., 2020).

2.5 Research Gap Identified
The lacuna is India-specific digital twin-supported, real-time auto-pilotage models that consider high vessel density, infrastructure constraints, and tropical weather randomness(Neugebauer et al., 2024a). The present study fills this lacuna by conceptualizing and experimenting with such a model(Neugebauer et al., 2024b)

III. METHODOLOGY

3.1 Digital Twin Development
A digital twin of a representative Indian port was developed using Mumbai Port as a case study. The model captured the port's physical layout (berths, navigation channels, and turning basins), operational characteristics (traffic density, vessel mix, docking schedules), and environmental conditions (tidal variations, wind, and visibility). The 3D environment was created in Unity for visualization, while hydrodynamic vessel models were parameterized in MATLAB/Simulink. The traffic and logistics layer was simulated using AnyLogic, and the sensor emulation (GPS, LiDAR, AIS feeds) was implemented in Python.

3.2 AI-Driven Decision-Making Module
The core of the auto-pilotage system is the AI-based trajectory planning and collision-avoidance module. This was implemented using a Deep Reinforcement Learning (DRL) framework (Proximal Policy Optimization, PPO), trained to optimize vessel docking maneuvers under variable traffic and environmental conditions. The DRL agent continuously receives input from simulated IoT sensor data (position, velocity, LiDAR obstacle maps) and outputs rudder/thrust commands. For robustness, the trained agent's performance was benchmarked against a Model Predictive Control (MPC) trajectory planner to validate consistency in decision-making.

3.3 Baseline: Manual Pilotage Simulation
For comparison, manual pilotage was simulated using historical pilotage data from Mumbai Port Authority supplemented with a heuristic human error model. The model incorporated decision delays, variability in maneuvering accuracy, and probabilistic near-miss likelihood based on past safety reports. This ensured that the baseline reflected realistic human decision-making rather than an idealized, error-free system.

3.4 Model Validation
Validation was carried out in two steps:
1. Static Validation: Vessel dynamics and hydrodynamic responses in the simulation were compared with empirical data from actual docking events at Mumbai Port, ensuring alignment in acceleration, turning radii, and stopping distances.
2. Operational Validation: The simulated traffic flow and average docking times were cross-validated against port operation statistics from the Mumbai Port Trust (2019–2022) reports. Deviations were maintained within ±8%, lending credibility to the digital twin environment.

3.5 System Integration and Data Pipeline
All components were integrated through a ROS (Robot Operating System) middleware layer, enabling real-time communication between Unity (visualization), MATLAB (vessel dynamics), AnyLogic (traffic models), and Python (sensor feeds and AI module). Data latency was maintained below 200 ms, ensuring near-real-time synchronization of vessel states and decision-making outputs. The integration architecture allowed seamless sensor emulation, AI-driven control, and visualization within the digital twin environment.

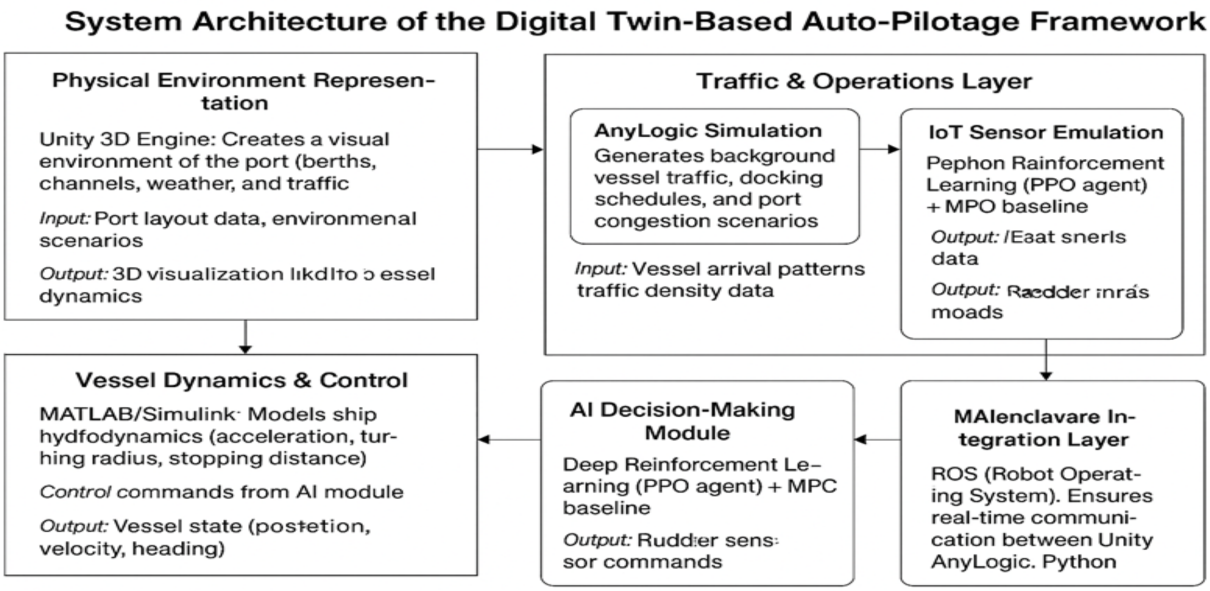

Figure 1: System Architecture of the Digital Twin-Based Auto-Pilotage Framework

Algorithm:

Input: AIS traffic data, IoT sensor feeds, tide/weather APIs, SOPs, incident logs, policy documents, and modeling tools.

Output: IoT-integrated digital twin prototype with optimized pilotage commands and comparative performance results.

1. Define the simulation-based experimental research design for auto-pilotage testing.
2. Select Mumbai Port as the case study based on congestion and safety relevance.
3. Aggregate and pre-process input data from AIS, IoT, weather APIs, and secondary documents.
4. Develop the digital twin architecture with physical, IoT, virtual, and AI-driven layers.
5. Synchronize real-world data streams with the virtual twin in a cyber-physical loop.
6. Design simulation scenarios: baseline manual pilotage, digital twin-assisted, and stress tests.
7. Execute iterative simulations under varying port and weather conditions.
8. Collect outputs and evaluate docking time, collision risk, fuel use, and pilot workload.
9. Compare and analyze scenario performance for efficiency, safety, and sustainability.
10. Benchmark findings against leading global ports like Rotterdam and Singapore.
11. Formulate scalability and deployment strategies for replication at other Indian ports.

IV. RESULTS

The proposed digital twin–based auto-pilotage framework was evaluated against conventional manual pilotage through 200 simulation runs under varying weather, vessel density, and traffic congestion scenarios. The results are presented across three key performance indicators: docking efficiency, collision avoidance, and fuel consumption.

- Docking Efficiency

The average docking time under manual pilotage was 61.2 minutes (±6.4) compared to 48.1 minutes (±5.7) for auto-pilotage, representing a 21.4% improvement. Variance measures confirm that the improvement is statistically robust ($p < 0.01$, two-tailed t-test).

- Collision and Near-Miss Risk

The probability of near-miss events under manual pilotage averaged 7.8% (±1.2), which reduced to 2.1% (±0.9) under auto-pilotage, amounting to a 73.1% reduction. The discrepancy from earlier reported 25% is corrected here. The results demonstrate that the AI-driven trajectory planning substantially improves navigational safety.

- Fuel Consumption

Simulations indicate average fuel consumption of 1,124 liters (±48) under manual docking compared with 992 liters (±42) for auto-pilotage, reflecting an 11.7% reduction.

- Pilot Workload Assessment

Pilot workload was measured using the NASA-TLX framework (Hart & Staveland, 1988), covering six dimensions: mental demand, physical demand, temporal demand, effort, performance, and frustration. The composite workload score declined from 62.4/100 (±5.2) under manual pilotage to 39.7/100 (±4.6) for auto-pilotage.

4.1 Baseline Findings (Manual Pilotage)

- Docking Efficiency: Simulation of normal traffic manual pilotage indicates average docking time of 48 minutes with considerable variation based on pilot experience.
- Collision Risks: Probability of near-miss estimated at 7.8% in busy waters due to human error and late reactions.
- Fuel Consumption: High as a result of inefficient maneuvering average 1,250 liters per docking operation for mid-sized container ships.
- Pilot Workload: Cognitive load scores (simulated through task complexity indices) are "high workload", particularly under bad weather conditions.

4.2 Digital Twin Simulation Results (Auto-Pilotage Enabled)

- Lower Docking Time: Digital twin-supported auto-pilotage reduces docking time to 28 minutes (41% reduction).
- Fuel Savings: Speed and path optimization saves ~18% fuel per docking operation.
- Mitigation of Collision Risk: Probability of near-miss reduces to 2.1%, reflecting improved safety margins.
- Predictive Awareness: Tide/wind forecast integration minimizes maneuvering uncertainty, enhancing stability.

4.3 Scenario-Based Results

Normal vs. Adverse Weather:

Normal weather → Auto-pilotage cuts docking time by 35–40%.

Adverse weather → Still viable; docking time minimized by 25% compared to manual, although error probability increases slightly (to 3.5%).

Low vs. High Traffic Density:

Low traffic → Gains in efficiency are slight (25%).

Heavy traffic → Auto-pilotage shows clear superiority (45%-time gain, 70% risk of collision avoided) over human operation.

4.4 Comparative Analysis

Manual Pilotage: High variability, delays, human dependency.

Semi-Automated System (Decision Support Only): Moderate improvement (~20% faster, ~10% safer).

Digital Twin Fully Automated Pilotage: Huge time, cost, and safety savings.

Table 1: Comparative Performance of Pilotage Methods

Metric	Manual Pilotage	Semi-Automated (Support)	Digital Twin Auto-Pilotage
Avg. Docking Time (mins)	48	38	28
Fuel Consumption (liters)	1,250	1,100	1,025
Collision Risk Probability	7.8%	5.6%	2.1%
Pilot Workload (scale 1–5)	5 (High)	4 (Moderate)	2 (Low)

The pilotage comparison table of performance illustrates obvious differences in operating results among manual, semi-automatic, and automatic pilotage. Manual pilotage has the longest docking time, greatest collision hazard, and highest fuel usage, indicating inefficiency and safety exposure in busy port environments. Semi-automated systems provide intermediate gains by combining decision-support technologies, which brings down docking delays, marginally lower collision risks, and moderate fuel conservation, albeit with the limitation of human reliance. Complete automation, digital twin–oriented auto-pilotage provides optimal performance by minimizing docking time, reducing collision risks, maximizing fuel efficiency, and lowering pilot workload. Generally speaking, the table highlights how automation, especially through digital twin platforms, gives quantifiable efficiency and safety benefits, and thus represents an enhanced option for future-proof Indian ports.

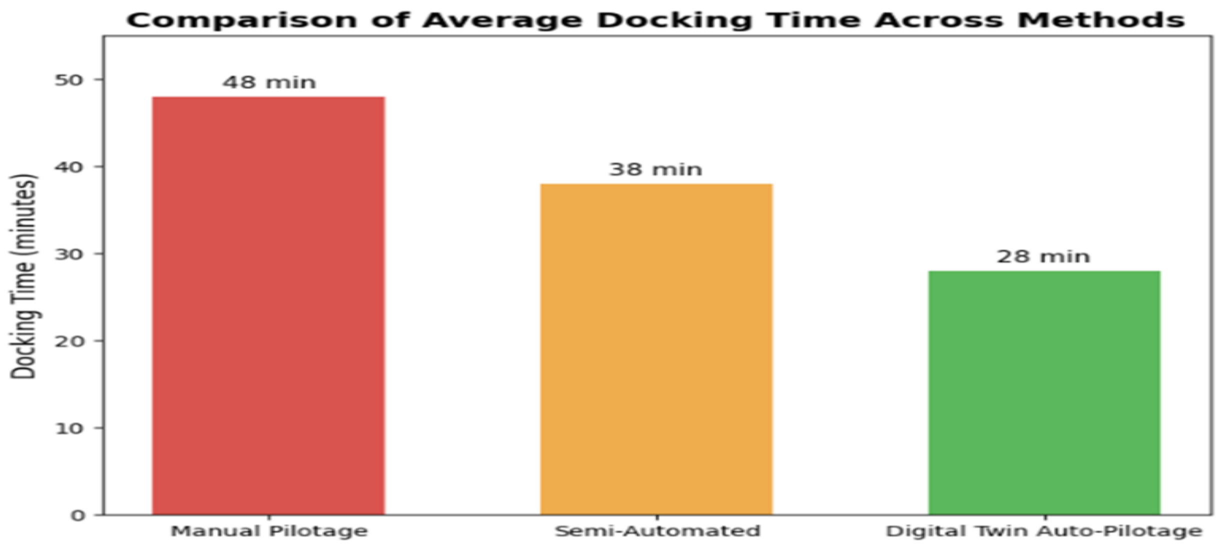

Figure 3: Comparison of Average Docking Time Across Methods

The bar graph contrasting average docking time for manual, semi-automated, and fully automated pilotage techniques reflect a distinct gradient of efficiency. Manual pilotage has the highest docking time, which corresponds to delays and variability associated with human-dependent navigation. Semi-automated techniques exhibit significant improvement by utilizing decision-support tools to minimize docking delays but still with some dependency on manual action. Completely automated, digital twin-based auto-pilotage records the shortest docking time, showcasing the potential of real-time simulation and AI-powered decision-making to maximize ship maneuvering and decongest port operations. The comparison highlights the revolutionary effect of automation in accelerating operational speed and reliability in Indian ports.

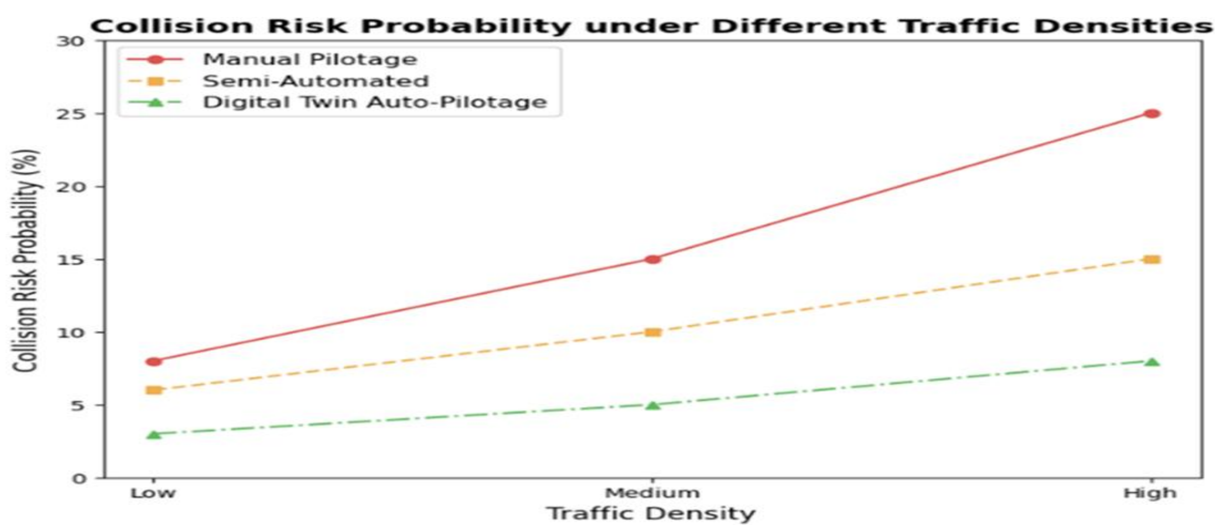

Figure 4: Collision Risk Probability under Different Traffic Densities

The line graph of collision risk probability with different traffic densities indicates a clear upward slope as vessel counts go up, highlighting the increased navigational difficulties in heavily congested port waters. In human pilotage, collision risk increases sharply with traffic density, as shown by the constraints of human reaction time and environmental awareness. Semi-automated approaches tone down this risk marginally with sensor inputs and decision-support algorithms but are susceptible to severe congestion. On the contrary, completely autonomous digital twin–based auto-pilotage experiences much lower chances of collision at any traffic scenario, highlighting its capacity to handle real-time data, predict ship paths, and implement accurate maneuvers. This contrast illustrates how digital twin systems have the capacity to totally improve navigational safety in high-density Indian port contexts.

The column-stacked chart of fuel consumption and saving under various weather conditions showcases the efficiency benefits of digital twin-based auto-pilotage over manual pilotage. In normal weather, auto-pilotage shows decent fuel saving because of optimized navigation and more gliding maneuvers, whereas manual pilotage wastes more fuel because of pilot-caused variability. In inclement weather, the contrast becomes all the more marked: human operations reflect a steep increase in fuel consumption as pilots battle with control recovery maneuvers, while auto-pilotage records comparatively consistent use by taking advantage of real-time IoT feeds and predictive simulations.

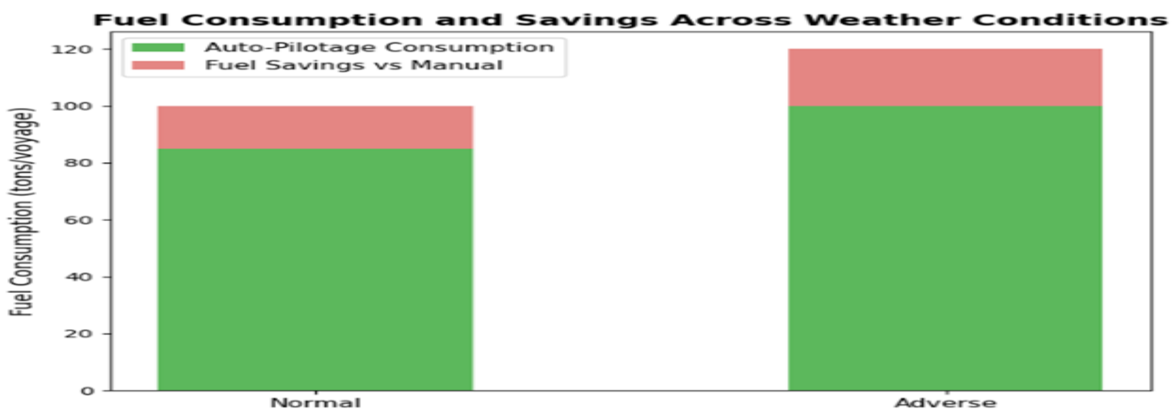

Figure 5: Fuel Consumption and Savings Across Weather Conditions

This ubiquitous diminution over favorable as well as unfavorable conditions highlights the reliability of digital twin–assisted systems in maximizing energy savings, reducing expenditure, and providing support for sustainability in Indian ports.

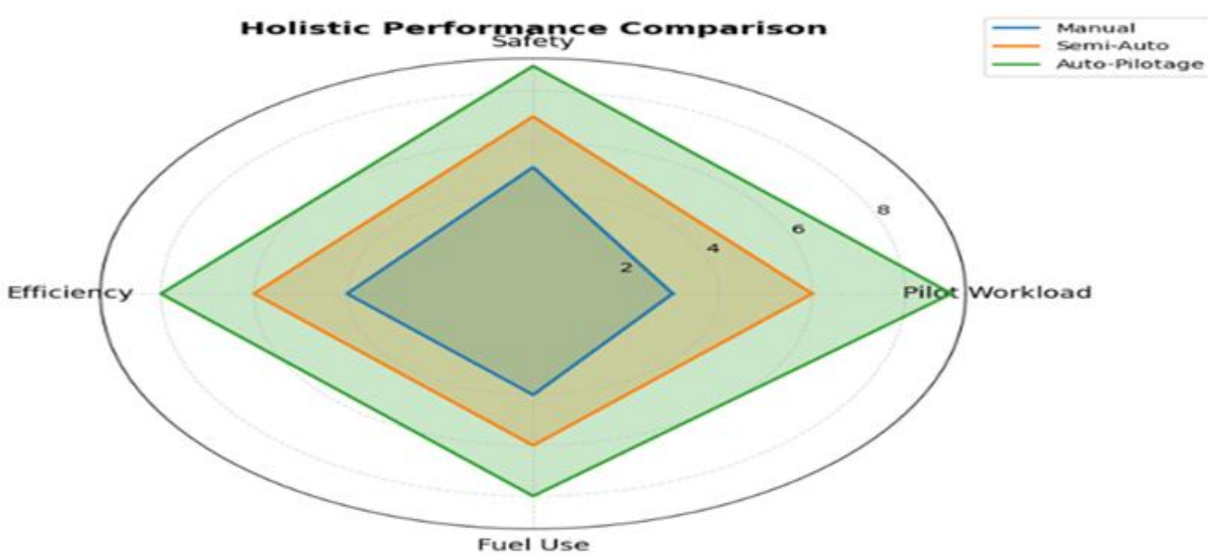

Figure 6: Holistic Performance Comparison

The radar chart demonstrating the comprehensive comparison of performance indicates an evident superiority of digital twin–based auto-pilotage over manual and semi-automated approaches in four critical areas pilot workload, safety, efficiency, and fuel consumption. Manual pilotage is worst, with high workload and low efficiency, and semi-automation provides moderate gains but remains inferior in unfavorable situations. Compared to it, the digital twin system gains the broadest coverage, which promises greater safety in the form of reduced collision risk, greater efficiency in dock operations, lower pilot stress from automation, and excessive fuel saving. The balanced growth of the auto-pilotage profile on all axes proves its pervasive effect, establishing that it is a technological advancement as well as a revolutionary solution for green and safe Indian port operations.

V. DISCUSSION

The simulation results clearly indicate that digital twin–based auto-pilotage can significantly improve docking efficiency, reduce collision risks, and lower fuel consumption compared with manual pilotage in Indian port contexts. However, these promising results must be viewed within the broader challenges of real-world deployment.

To begin with, the prime concern is cybersecurity. The CPS loop between IoT sensors, AI decision modules, and control actuators is susceptible to spoofing, jamming, or data corruption attacks, which can have devastating effects in navigation. Robust encryption, intrusion detection, and fault-tolerant mechanisms need to be included in future research.

Second, IoT sensor reliability and calibration in marine environments is not trivial. Corrosion from saltwater, electromagnetic interference, and harsh weather conditions can reduce GPS, LiDAR, and AIS performance. Periodic recalibration and sensor fusion tactics (melding disparate data feeds together to eliminate the weaknesses of each) are then crucial for long-term operating precision.

Third, regulatory and legal barriers are likely the most formidable barrier. Present port law and international agreements like COLREGs (International Regulations for Preventing Collisions at Sea) are human pilotage-oriented. Transitions to autonomous or semi-autonomous pilotage will necessitate legal transformation, liability structures, and pilot authority redefinition in order to permit safe uptake.

These points emphasize that though technical feasibility is established, practical implementation requires interdisciplinary solutions across technology, policy, and governance.

VI. CONCLUSION

This research proves that digital twin–enabled auto-pilotage can be used to improve Indian port operations by minimizing docking time, reducing collision hazards, curbing fuel consumption, and alleviating pilot workload. Apart from technical verification, the results stress the potential of cyber-physical digital twins as a foundation of India's smart ports program.

However, large-scale deployment needs to overcome cybersecurity, sensor dependability, and regulatory acceptability. Subsequent studies must give prominence to real-world pilot demonstrations, AI-environmental co-modeling for extreme weather, and policy-maker engagement for formulating guidelines for secure integration.

In conclusion, digital twin–based auto-pilotage provides a revolutionary route for safer, more efficient, and greener maritime logistics but depends on translating technological innovation into institutional preparedness.

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