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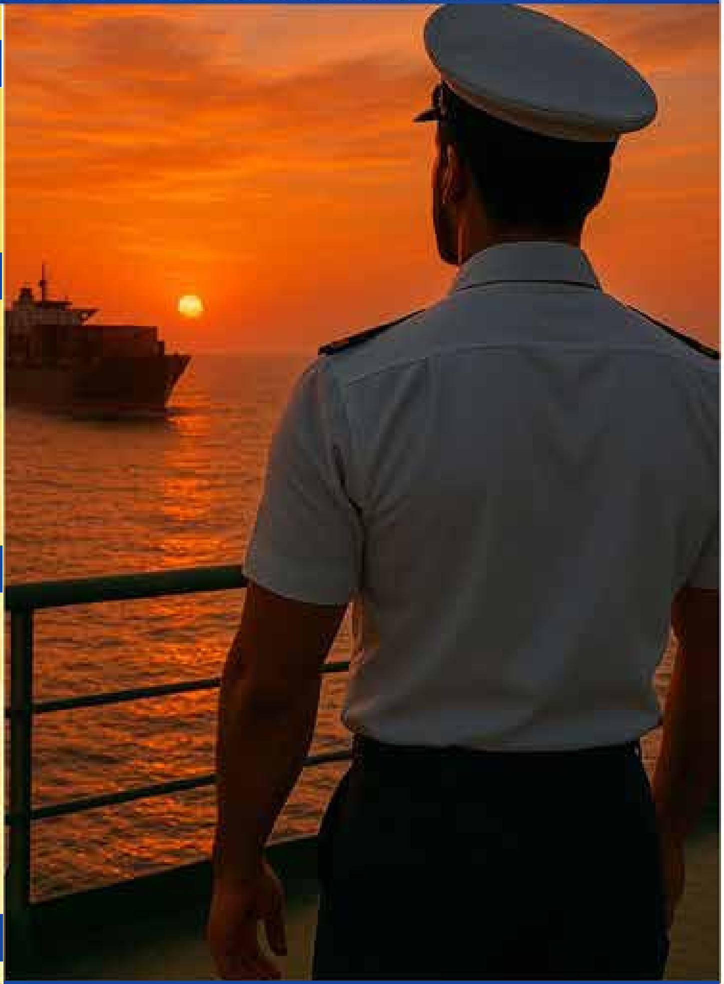

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EDITORIAL

The best way to predict the future is to create it.” — *Peter Drucker*

The Price of a Missile, the Cost of a War

In maritime history, wars are often described through maps, alliances, tonnage losses, and oil prices. Yet for the marine engineer, the ship operator, and the port planner, war is experienced differently: delayed arrivals, emergency surcharges, war-risk clauses, anxious underwriters, and engines pushed harder on longer diversion routes. When conflict erupts near critical maritime corridors—from the Strait of Hormuz to the Red Sea—the consequences are immediate and deeply operational.

The maritime sector is not merely a spectator to geopolitics; it is the transmission system through which geopolitical shocks enter the global economy. Nearly ninety percent of world trade moves by sea. When tankers hesitate, routes lengthen, insurance premiums rise, and cargoes are repriced, the ripple effect spreads rapidly across supply chains and energy markets. A missile fired in a strategic corridor rarely remains a local event, its economic shock travels across oceans.

This raises a fundamental question: how do we assign value to missiles and the destruction caused by uncalled-for wars? While the manufacturing cost of a missile is measurable, its true economic footprint is far greater. A single strike can damage a vessel, destroy cargo, disrupt port infrastructure, or halt offshore energy operations. Beyond this visible damage lies a cascading chain of consequences—higher war-risk premiums, rerouted services, rising bunker costs, delayed deliveries, and volatile markets.

For maritime transport, these impacts multiply quickly. Diversions increase voyage distances, fuel consumption, emissions, and operational stress. Insurance markets tighten and premiums escalate. Ports face congestion as shipping patterns shift unpredictably. Ultimately, the cost of instability is absorbed by global trade and passed on to societies through inflation and economic uncertainty.

There is also a deeper, less visible cost. Each conflict strains the international governance structures that ensure safe and predictable seas. Frameworks built on cooperation—UNCLOS principles, IMO conventions, and shared maritime norms—depend on stability. When commercial shipping becomes a target or collateral risk, confidence in these systems weakens.

For the maritime community, the lesson is stark. Ships may be engineered for efficiency and resilience, but they operate within a fragile geopolitical environment. Every missile launched in a strategic corridor carries a price far beyond its procurement cost.

Missiles may be counted in millions. Their impact on global shipping, energy flows, and trade stability is measured in billions—and in consequences that endure long after the conflict subsides.

* * *

The first article explains how Korea and China built globally competitive shipbuilding industries through strong marine equipment ecosystems, shipyard–supplier collaboration, localisation and policy support. It offers valuable lessons for India in developing clusters, strengthening engineering capability and building a sustainable maritime industrial ecosystem—an informative read for shipbuilding stakeholders.

* * *

The second article explains how AI and machine learning are transforming vessel performance management by replacing manual fuel-estimation methods with data-driven analytics. Using high-frequency operational data and predictive models, ships can optimise fuel use, enhance efficiency, support decarbonisation goals and enable smarter operational decisions across modern fleets—a must-read for every marine engineer.

* * *

The third article introduces the AI-enabled Cognitive Digital Twin “Chaitanya” supporting India’s Matsya6000 deep-ocean submersible by modelling interactions between crew, engineering systems and ocean environment. The narrative combines historical evolution with system design context, demonstrating strong technical rigour and interdisciplinary depth relevant to deep-sea exploration safety.

* * *

The fourth article examines how maritime law, ocean science, climate change and marine robotics are reshaping global shipping and ports. With strong interdisciplinary rigour, it integrates legal frameworks, oceanographic insights and technological trends, highlighting the evolving skillset required for maritime professionals navigating the decarbonised and digitally transformed ocean economy.

* * *

The fifth article in the *Marine Engineering Accident Investigation Series* demonstrates how vibration and condition-monitoring data can serve as forensic evidence in marine casualty investigations. Through practical engineering examples and regulatory context, it highlights strong technical rigour and shows how early vibration trends can reveal developing faults and prevent machinery failures.

* * *

The sixth article, Part 3 of the dual-fuel engine technology series, explores combustion principles, fuel systems, control architecture, safety systems and engine performance. Supported by strong technical rigour and real engine examples, it highlights the importance of dual-fuel engines in maritime decarbonisation and their growing relevance in the industry’s energy transition. The article is very informative and well presented by the authors.

Here is the April 2026 issue for your reading pleasure and intellectual rumination.

Mani Ganapathi Ramachandran
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Development of the Korean Shipbuilding Equipment Ecosystem and Implications for the Indian Shipbuilding Industry

Dae-Yeon Mun

Abstract

The global shipbuilding industry is supported by a complex ecosystem involving shipyards, equipment manufacturers, engineering capabilities and integrated supply chains. The success of South Korea and China in the global shipbuilding market has been closely linked to the systematic development of strong marine equipment industries. This article examines the evolution of the Korean and Chinese shipbuilding equipment ecosystems, highlighting the role of localisation strategies, shipyard–supplier collaboration and long-term national policy support.

Through industrial case examples and development pathways, the study analyses how engineering capabilities and industrial clusters contributed to the competitiveness of these nations. Drawing lessons from these experiences, the paper outlines strategic directions for the Indian shipbuilding industry, emphasising the need for stronger supplier ecosystems, technology partnerships, integrated project management and institutional collaboration. Building such a sustainable marine equipment ecosystem will be critical for India's emergence as a globally competitive shipbuilding nation.

The shipbuilding industry is not merely a ship construction business but a comprehensive industrial ecosystem in which design, equipment manufacturing, production, quality management, logistics and financing are organically interconnected. The competitiveness achieved by Korea and China in the global shipbuilding market has been strongly supported by the systematic development of their marine equipment industries. This paper examines the development pathways of the Korean and Chinese marine equipment sectors and presents implications for the future growth of the Indian shipbuilding industry.

> *Shipbuilding success depends on strong industrial ecosystems*

Keywords: Shipbuilding ecosystem; marine equipment industry; shipyard–supplier collaboration; localisation; maritime industrial policy; shipbuilding clusters; engineering capability development; supply chain integration; Indian shipbuilding industry; maritime manufacturing.

Introduction

The shipbuilding industry is far more than the construction of ships; it represents a highly integrated industrial ecosystem that connects design, equipment manufacturing, engineering integration, logistics, quality assurance and project management. The competitiveness of major shipbuilding nations is closely tied to the strength of their marine equipment supply chains and the depth of their engineering capabilities.

Over the past five decades, South Korea and China have emerged as dominant players in global shipbuilding. Their success has not been driven solely by large shipyards but by the systematic development of marine equipment industries, supported by strong policy frameworks, industrial clustering and close collaboration between shipyards and suppliers. Through progressive localisation, technological learning and engineering capability building, these countries developed comprehensive maritime industrial ecosystems capable of delivering complex vessels efficiently and competitively.

For India, which possesses a strong maritime heritage and growing ambitions in shipbuilding under initiatives such as "Make in India" and maritime infrastructure expansion, understanding the development models of Korea and China provides valuable strategic insights. Strengthening domestic marine equipment manufacturing, fostering collaborative innovation between shipyards and suppliers and building advanced engineering capabilities will be essential for India to enhance its competitiveness in the global shipbuilding market.

Historical backdrop:

1. Development of the Korean Shipbuilding Equipment Industry

Korea's shipbuilding industry began to grow rapidly in the 1970s under government-led heavy and chemical industry development policies. In the early stage, most core marine equipment was imported from Japan and Europe, resulting in strong dependence on overseas makers.

As the industry matured, localisation was gradually promoted. Major shipbuilders such as Hyundai Heavy Industries, Samsung Heavy Industries and Daewoo Shipbuilding & Marine Engineering established long-term partnerships with suppliers and developed structured systems for quality control and joint development.

In the early stage, Korean companies learned from Japanese makers through licensing, technical support and supply relationships. However, the real driving force behind localisation was strong shipyard demand for cost reduction, delivery flexibility and practical problem solving. Through repeated project experience, Korean companies gradually accumulated practical engineering capabilities across pumps, valves, electrical systems and automation equipment, eventually establishing their own technological capabilities.

2. Practical Growth Mechanisms of Korean Equipment Companies

Within the Korean marine equipment industry, it is widely recognised that engineers with shipyard experience played an important role in industrial development. Based on practical knowledge gained in design, production, procurement and quality management, many identified equipment suitable for localisation and commercialised them successfully. Items such as panels, gangways and purifiers are often cited as examples that grew under this path.

Another growth route involved companies that initially operated as agents or supply partners of overseas makers. These firms accumulated technical and quality management know-how and gradually evolved into manufacturers.

In addition, collaborative development driven by shipyard requirements played a significant role. Shipyards provided operational requirements based on real vessel conditions, while equipment makers developed and improved products accordingly. HVAC systems and butterfly valves represent typical examples of such collaboration.

DongHwa Entec Case

The growth of DongHwa Entec demonstrates the Korean-style equipment development structure. Under domestic shipyard localisation policies, the company entered the market through joint development and real vessel application experience. Korean shipyards emphasised stable supply chains and overall industrial competitiveness rather than exclusive ownership of specific technologies, which helped equipment makers secure references quickly and expand their markets.

DongHwa Entec strategically shifted from general heat exchangers toward specialised LNG-related equipment, moving from simple manufacturing competition to engineering, performance and reliability-based competition. At the same time, its business approach expanded from shipyard-centered sales toward shipowner-focused marketing, increasing market adoption.

A representative example is the HP Vaporizer. During early LNG regasification vessel construction, imported equipment was applied. Later, domestic development was achieved through national R&D projects and replacement demand triggered by tube damage issues around 2012 provided an opportunity for market entry. Continuous performance improvements based on operational experience have allowed the company to strengthen its market position. This case illustrates the Korean growth mechanism of "field problem solving → improved design → reference expansion."

> *Localisation built Korea's globally competitive equipment industry*

Shipyard Collaboration-Based Technology Development: PANASIA OCCS Case

Another characteristic of the Korean marine equipment industry is that technology accumulates through collaboration with shipyards during real vessel applications. This structure is also visible in recent decarbonisation technologies.

PANASIA, a company that has developed environmental compliance equipment such as scrubbers, SCR systems and BWTS, developed an Onboard Carbon Capture System (OCCS) in response to tightening IMO greenhouse gas regulations. In collaboration with Samsung Heavy Industries, PANASIA developed an OCCS applicable to LNG-fueled vessels and obtained Approval in Principle (AiP) from Korean Register (KR).

The OCCS consists of absorption, regeneration, liquefaction and storage processes, with PANASIA responsible for the absorption, regeneration and storage sections. The main development challenge was not chemical processing itself but integration within shipboard conditions, including space constraints, load variation, vibration and inclination and class certification requirements. This demonstrates that the competitiveness of the Korean equipment industry lies not only in equipment performance but in system engineering capability under actual operating conditions.

> ***Shipyard–supplier collaboration drives real maritime innovation***

3. China's Growth Strategy in Marine Equipment

China actively attracted global marine equipment makers by leveraging its large domestic market. Many global suppliers established local production facilities and joint ventures to directly support Chinese shipyards.

The primary purpose of these investments was market access and localised manufacturing rather than direct technology transfer. However, through participation in global supply chains and exposure to international quality standards and project execution practices, Chinese local companies gradually strengthened their manufacturing and project execution capabilities.

Initially focused on low-cost mass production, Chinese suppliers have expanded into higher value-added areas such as propulsion systems, automation and LNG-related equipment. The combination of large domestic demand, industrial clustering and strong government policy support forms the key strength of the Chinese model.

> *India's opportunity lies in building a marine ecosystem*

4. Common Success Factors of the Korean and Chinese Models

The following common elements can be identified:

1. Long-term national policy recognising shipbuilding as a strategic industry
2. Industrial ecosystem centered around large shipyards
3. Technology internalisation including design, testing and certification
4. Continuous development of skilled manpower

These elements together created stable industrial structures.

5. Implications for the Indian Shipbuilding Industry

India possesses strong human resources, a growing maritime logistics market and high development potential under the "Make in India" initiative. However, linkage between shipyards and equipment suppliers remains at an early stage.

Key strategies include:

1. Development of marine equipment clusters
2. Establishment of long-term cooperation models between shipyards and suppliers
3. Expansion of testing, certification and research infrastructure
4. Strategic partnerships with global makers
5. Development of expertise in design, quality and project management

A strategy combining localisation of global suppliers with strengthening domestic engineering capability can accelerate ecosystem growth.

6. Integrated Management for Faster Turnaround and Successful Delivery

Successful shipbuilding projects require integrated management across the entire lifecycle, including design, procurement, production, commissioning and delivery. Korean and Chinese shipyards use digital design platforms, project management systems and integrated supply chains to control schedule and quality simultaneously. Equipment suppliers also maintain real-time information sharing systems with shipyards.

India should likewise adopt phased integrated management systems to minimise schedule delays and quality risks.

The experiences of Korea and China demonstrate that successful shipbuilding industries are built not only on large shipyards but on strong supporting ecosystems of marine equipment manufacturers, engineering expertise and coordinated industrial policies. Korea's development model emphasised shipyard-driven localisation and practical engineering problem-solving, while China expanded its capabilities through large domestic demand, industrial clustering and participation in global supply chains.

Both approaches highlight the importance of long-term policy commitment, technology internalisation, skilled manpower development and strong collaboration between shipyards and suppliers. These factors collectively enabled the creation of stable and globally competitive maritime industrial ecosystems.

For India, the path forward lies in strengthening linkages between shipyards, equipment suppliers, research institutions and policymakers. Developing marine equipment clusters, enhancing testing and certification infrastructure and building expertise in design, engineering and project management will be essential steps. With coordinated efforts across government, industry and academia, India has the potential to develop a robust shipbuilding ecosystem and emerge as a major global maritime manufacturing hub in the decades ahead.

7. Conclusion

The development experiences of Korea and China provide important implications for the Indian shipbuilding industry. Korea advanced through shipyard-driven localisation and accumulation of field-based engineering experience, while China strengthened industrial capabilities through localised production expansion and participation in global supply chains.

As illustrated by DongHwa Entec and PANASIA, the core of the Korean model lies in collaborative problem solving between shipyards and equipment suppliers during real vessel applications. The true source of competitiveness is not short-term cost competition but long-term ecosystem building and accumulation of engineering capabilities.

If governments, shipyards, equipment suppliers and educational institutions share a common vision and cooperate effectively, India has strong potential to emerge as a major global shipbuilding nation. Building a sustainable marine equipment ecosystem will be the key foundation of its future competitiveness.

About the Author

Dae-Yeon Mun is the Founder and Managing Director of NVO Engineering. With over 30 years of experience in shipbuilding and offshore projects, he previously held senior roles at Samsung Heavy Industries and Dubai Drydocks, specialising in FPSO, FSO, LNGC and offshore project management.

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DATA - THE NEW OIL - Transforming Vessel Performance Through AI and Machine Learning

Venkat Krishna Soundarraja

Abstract:

This article examines the transformative role of **data analytics and artificial intelligence/machine learning (AI–ML)** in optimising vessel operations within the maritime industry. Traditional fuel consumption estimation methods rely heavily on manual compilation of speed–fuel matrices derived from logbooks and noon reports, a process that is labour-intensive and often limited in accuracy. The paper proposes a transition toward **data-driven decision-making frameworks** that utilise high-frequency sensor data and structured operational datasets generated onboard modern vessels.

Using machine learning techniques such as **multiple linear regression, decision trees and clustering algorithms**, predictive models can estimate fuel consumption with significantly improved accuracy by incorporating operational variables including vessel draft, engine load, weather conditions and speed parameters. The study also evaluates the comparative advantages of **high-frequency sensor data versus conventional low-frequency noon report data**, while addressing key challenges related to data quality, sensor calibration and data governance.

A central theme of the article is the emerging role of **seafarers transitioning ashore**, who can leverage maritime domain expertise alongside data science skills to develop effective predictive analytics systems. The study concludes that structured maritime datasets analysed through AI–ML can substantially improve operational efficiency, reduce fuel costs, support decarbonisation initiatives and accelerate the industry's progress toward **net-zero emissions**, positioning data as a strategic resource in the future of maritime operations.

Keywords: Data analytics, artificial intelligence, machine learning, fuel consumption optimisation, vessel operations, predictive modeling, maritime industry, voyage optimisation, high-frequency data, noon reports, operational efficiency, decarbonisation, emissions reduction, decision trees, regression analysis, sensor data, performance benchmarking, hull fouling, maritime domain expertise, net-zero emissions.

Introduction:

Predicting future events based on historical data has always been a subject of great interest. By analysing past trends and patterns, we gain valuable insights into how things may unfold in the future.

While there's no guarantee that history will repeat itself, we still rely on these projections to make informed business decisions, hoping that circumstances will align favorably.

Uncertainties are an inevitable part of this process, yet they, too, contribute to the historical data that will shape tomorrow's forecasts.

The marine industry, in particular, faces numerous unpredictable factors that significantly impact business decisions.

Weather conditions, geopolitical developments, port activities, regulatory changes, accidents, market fluctuations and more all play a role, none of which can be precisely timed or predicted.

> *Data transforms ship operations into predictive intelligence*

Vessel operations are heavily influenced by commercial considerations, with a constant focus on optimising fuel consumption and speed to enhance profitability and reduce costs.

In this context, "What-if" scenarios serve as crucial tools for evaluating key variables.

Current Approach- Random sampling:

Those familiar with the process know the painstaking effort required to populate speed-fuel consumption matrices repeatedly.

These matrices help estimate fuel usage under various conditions—ballast or laden voyages, tank cleaning, cargo heating, inerting, purging, port operations, anchorage stays and more.

To derive the most accurate estimates, old logbooks, log abstracts and noon reports must be meticulously reviewed.

The resulting data is then shared with owners, charterers, managers and operators, often forming the basis for charter party agreements and operational contracts.

More often than not, the estimates prove unreliable—sometimes veering so far from actual performance that the exercise devolves into a copy-paste routine with little operational relevance.

Illustration: Cumbersome manual estimations

Data-Driven Decision making with AI-ML:

With the wealth of historical data available today and advancements in "AI and machine learning (ML)", we can now generate far more accurate estimates and actionable insights.

Instead of relying solely on manual data compilation, we can leverage high-frequency sensor data or structured noon reports to run dynamic "What-if" scenarios. Key variables such as:

- Draft
- Engine load
- Depth under keel
- Weather conditions (wind speed/direction, wave height, swell characteristics)
- Shaft power & RPM
- Speed over ground vs. speed through water
- Current speed & direction

These data points can be analysed to predict fuel consumption based on their correlations.

By applying machine learning models—such as multiple linear regression, decision trees and clustering techniques—we can derive highly reliable estimates that adapt to real-world conditions. These models not only enhance accuracy but also identify hidden patterns that traditional methods might miss, leading to better decision-making in voyage optimisation, cost reduction and emissions control.

This data-driven approach minimises guesswork, improves efficiency and provides a competitive edge in vessel operations. Refer **Figure.1** for 'What-If' variables used in analysis.

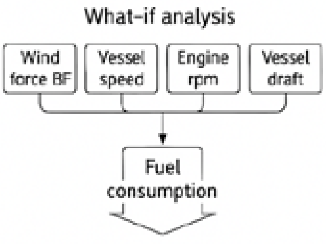


Figure. 1. What-if analysis

Benchmarking Operational Performance:

Operational data can be compared against shop test or sea trial results to assess conformance and identify deviations.

This analysis helps evaluate real-world performance against baseline expectations, enabling timely adjustments and optimising efficiency.

However, it is important to recognise that sea trials and shop tests provide limited reference points. Conducted under controlled, fixed conditions, these results are inherently restrictive.

In contrast, AI-ML models leverage a "living baseline" derived from high-frequency historical data, allowing for benchmarking across the full spectrum of real-world variables such as varying drafts, aging hulls and fluctuating weather patterns, that static sea trials simply cannot account for.

Leveraging Historical Data for Smarter Baseline Modeling:

Applying pattern recognition techniques to historical operational data enables the creation of more accurate and realistic performance baselines.

This data-driven approach moves beyond theoretical assumptions, providing actionable benchmarks that reflect real-world conditions and variability.

Fuel Consumption Optimisation for Vessels using AI-ML:

As shown in **Figure. 2,** by analysing historical data, accurate fuel consumption estimates can be derived for different operating conditions, including speed, draft, RPM and weather. The predictive analytics solution enables precise fuel consumption modeling across all operational parameters - speed, draft, RPM and weather conditions.

This powerful capability provides both shipboard teams and commercial operators with:

- Decision-Ready Intelligence - Forecast fuel needs for any voyage scenario with unprecedented accuracy.
- Operational Transparency - Visualise how each variable impacts consumption in real-world conditions.
- Strategic Advantage - Base critical decisions on data-driven projections rather than estimates.
- Cost Control - Identify and execute the most fuel-efficient operating profiles.
- By transforming complex operational data into actionable insights, the system serves as both a navigation companion for engineers and a business intelligence tool for commercial teams - bridging the gap between ship operations and financial performance.
- The true value lies in its ability to convert theoretical models into practical, voyage-specific guidance that drives measurable efficiency gains across the fleet.

> *AI reveals hidden patterns in vessel performance*

Comparing past and present "what-if" scenarios can also help detect engine wear & tear, hull and propeller degradation due to fouling, fleet wise or sister vessel performance comparisons.

Figure.2 A typical 'What-if application' to predict fuel consumptions using historic data

These insights enable better planning, business decisions, optimised vessel operations and significant cost savings.

Practical Case Study: Detecting the Efficiency Gap

To illustrate the power of AI-ML in real-world operations, consider a vessel following its drydocking. After several initial voyages, the captured historical data once

Parameter	Post-Drydock (Baseline)	Scenario A: Minimum Variance	Scenario B: High Variance
Vessel Speed	12.0 Knots	12.0 Knots	12.0 Knots
Laden Draft	11.5 Meters	11.5 Meters	11.5 Meters
Engine RPM	80 RPM	80 RPM	80 RPM
Weather (BF)	Good (BF 3)	Good (BF 3)	Good (BF 3)
Fuel Consumption	25.0 MT/Day	25.4 MT/Day	26.5 MT/Day
Variance (%)	0.0%	+1.6%	+6.0%
Additional Daily Cost	–	$240	$900
Voyage Loss (20 Days)	–	$4,800	$18,000

Table 1. Comparing operating trends over time

> *Fuel optimisation begins with high-quality operational data*

meticulously cleaned to remove outliers and noise, is processed through various machine learning algorithms. By ensuring all key parameters are available, we minimise uncertainty and establish a credible performance baseline.

The Baseline Scenario:

- Operating Conditions**:** 12 knots speed, 11.5m laden draft, 80 engine RPM.
- Environment**:** Deep sea, Good Weather (Beaufort 3), negligible currents.
- Initial Performance**:** The model confirms a fuel consumption of **25 MT/day**.

The AI-ML Insight: Using this baseline as training data, the AI continuously evaluates future voyages. If, four months later, the vessel encounters identical operating and weather conditions but consumes **26.5 MT/day**, the system immediately flags a **6% increase** in consumption. Refer table 1. A case of minimum variance is also shown.

The Impact:

- Financial Leakage**:** This seemingly small deviation translates to an additional **$18,000** in fuel costs for a single 20-day voyage.
- Proactive Management**:** Continuous "What-if" analysis allows the Chief Engineer and commercial teams to quantify hull and propeller degradation in real-time.

The Gold Standard for Accuracy: Whether utilising high-frequency (HF) sensor data or structured noon reports (LF), the credibility of these predictions' hinges on **data quality**.

Ensuring the availability of all critical parameters is the only way to reduce the margin of error and transform raw data into a reliable navigation and business tool.

Conversely, for maintaining the same consumption, a loss of speed could be observed if the focus of analysis and quantification is for loss of speed as shown in Table 2.

High-Frequency Data vs. Noon Reports: Finding the Right Balance:

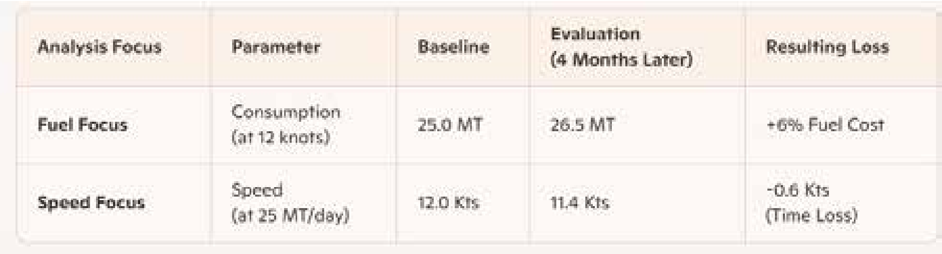
This topic remains widely debated, with strong arguments on both sides.

The answer isn't straightforward—it depends on the specific needs and expectations of the user. Refer Table 3.

Rather than dismissing either high-frequency (HF) data or noon reports (low-frequency/LF data), it's important to assess what insights each can deliver.

Too much information (TMI) can overwhelm users, leading to disengagement.

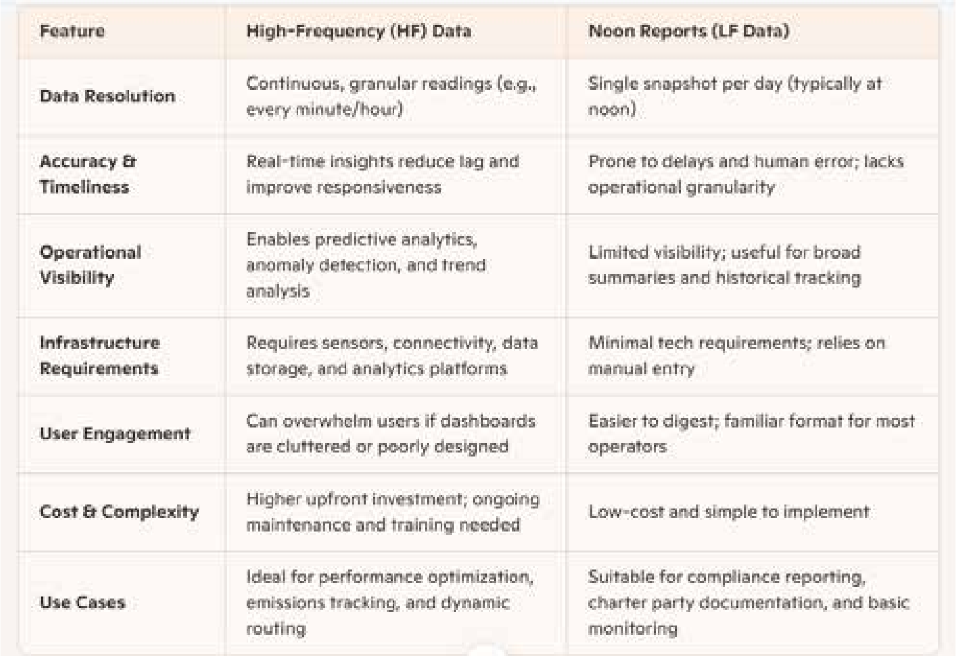
Some service providers clutter dashboards with excessive data, making it difficult to extract meaningful insights.



Analysis Focus	Parameter	Baseline	Evaluation (4 Months Later)	Resulting Loss
Fuel Focus	Consumption (at 12 knots)	25.0 MT	26.5 MT	+6% Fuel Cost
Speed Focus	Speed (at 25 MT/day)	12.0 Kts	11.4 Kts	-0.6 Kts (Time Loss)

Table 2. Focusing on fuel consumptions & speed of vessel.

Comparison Table: Merits and Demerits:



Feature	High-Frequency (HF) Data	Noon Reports (LF Data)
Data Resolution	Continuous, granular readings (e.g., every minute/hour)	Single snapshot per day (typically at noon)
Accuracy & Timeliness	Real-time insights reduce lag and improve responsiveness	Prone to delays and human error; lacks operational granularity
Operational Visibility	Enables predictive analytics, anomaly detection, and trend analysis	Limited visibility; useful for broad summaries and historical tracking
Infrastructure Requirements	Requires sensors, connectivity, data storage, and analytics platforms	Minimal tech requirements; relies on manual entry
User Engagement	Can overwhelm users if dashboards are cluttered or poorly designed	Easier to digest; familiar format for most operators
Cost & Complexity	Higher upfront investment; ongoing maintenance and training needed	Low-cost and simple to implement
Use Cases	Ideal for performance optimization, emissions tracking, and dynamic routing	Suitable for compliance reporting, charter party documentation, and basic monitoring

Table 3. Feature comparisons

> *Maritime engineers must become data-driven decision makers*

Ultimately, both HF and LF data have value—the choice depends on the client's objectives and their willingness to invest in the necessary infrastructure.

Challenges and Considerations:

- Data Quality: Reliable mathematical models depend on high-quality data.
- Sensor Accuracy: Regular calibration of key instruments is essential to ensure precise measurements.
- Data Acquisition Issues: Faulty installations, network disruptions and scaling errors can introduce inaccuracies, affecting computations and modeling.
- Data Cleaning: Inefficient handling of outliers and noise can undermine the credibility of models.
- Domain Expertise: Understanding the relevant variables is crucial for effective modeling.

Elevating the Human Element: Human in the loop

Will AI replace humans? The transition from traditional logbooks to AI-driven operations is often met with the fear of automation replacing human expertise. However, in the maritime context, AI-ML is not a replacement for the **Engineer**; it is an evolution of the engine room team.

Think of AI as a **"Digital Assistant Engineer"** working 24/7 in the background. While the human Engineer manages physical maintenance and daily operations, the AI handles the "digital drudgery".

- **Monotonous Data Crunching**: Instead of a human spending hour manually reviewing old log abstracts and noon reports to populate speed-fuel matrices, the AI processes thousands of data points from high-frequency sensors in seconds.
- **Predictive Diagnostics**: The system identifies subtle deviations in machinery health or hull efficiency that might be invisible to the naked eye, acting as a navigation companion for the engineering team.
- **Focus on High-Level Maintenance**: By automating the "What-if" scenarios and consumption forecasts, the AI frees the human Engineer to focus on critical decision-making, complex repairs and ensuring the vessel meets stringent net-zero emission goals.

Upskilling: AI as the Modern "Screwdriver"

Just as a marine engineer must be trained to use a laser alignment tool or a hydraulic jack, AI must be viewed as a 'technical tool' that requires a specific skill set to operate effectively.

- **Mechanical vs. Digital Tools**: Working mechanically requires knowledge of physical tolerances and material science; working with AI requires "digital domain expertise", an understanding of how data translates into physical performance.
- **The Necessity of Upskilling**: For AI to be a truly effective tool, seafarers transitioning ashore must upskill in areas like **statistics, advanced excel, coding (Python, R) & data visualisation (Power BI, Tableau)**.
- **Bridging the Gap**: Relying on data scientists who lack sea-time often leads to ineffective models. **The most powerful results come from professionals who combine maritime domain knowledge with data**

science tools, ensuring the AI's "output" makes sense in a "real-world" engine room.

"As a seafarer and data science practitioner, I've seen firsthand how this dual expertise drives faster, more impactful results."

Analytics powers the next revolution in shipping efficiency

Navigating Regulatory Waters with AI-ML:

The maritime industry is currently governed by IMO's short-term measures aimed at reducing greenhouse gas emissions.

While **EEXI** is a technical "one-time" certification of a ship's design, **CII** is an ongoing operational rating that measures how efficiently a ship transports goods.

- **The CII Challenge**: A vessel is rated from **"A"** to **"E"** based on its annual carbon intensity. A ship that performs well today could slip into a **"D"** or **"E"** rating next year due to hull fouling, engine degradation, or poor voyage planning.
- **AI as a Rating Shield**: This is where data-driven "What-if" scenarios become critical. Instead of waiting for the end of the year to discover a poor rating, AI models use high-frequency or structured noon data to provide a **Real-Time CII Forecast**.
- **Precision Decarbonisation**: By analysing variables like speed, draft and weather, the ML model identifies the "Sweet Spot" the exact operating profile where fuel consumption is minimised without compromising the commercial schedule.
- **Impact on Charter Value**: A vessel maintained in the **"A"** or **"B"** category via AI-optimised operations commands higher charter rates and remains compliant with environmental standards, potentially unlocking financial benefits like carbon credit trading. Ships operating efficiently can lower their carbon allowances, reduce costs or even profit from trading excess allowances. Compliance with stricter EU fuel standards reduces penalties and enhances market competitiveness.

How AI Directly Improves the CII Rating:

The formula for CII is essentially the ratio of CO2 emitted to the "work" done in transportation (capacity x distance). Since CO2 emissions are directly proportional to fuel consumption, AI improves the rating by:

1. **Optimising the "What-if" of Voyage Planning**: Calculating the most fuel-efficient route and speed based on predicted weather and currents to minimise the "Numerator" (Total Fuel Burned).
2. **Early Fouling Detection**: As seen in our case study, a 6% increase in fuel due to hull fouling doesn't just cost $18,000; it can push a vessel from a **"C"** to a **"D"** rating. AI detects this trend early, allowing for a mid-cycle hull cleaning that restores the rating.
3. **Engine Performance Benchmarking**: Comparing real-world data against shop tests ensures the engine is operating at peak thermal efficiency, reducing unnecessary emissions.

For a commercial operator, data is no longer just for the technical department. **It is the difference between a vessel being a "prime asset" or a "stranded asset" in a net-zero world.**

Conclusion:

A well-maintained operational database analysed using **AI and machine learning** effectively becomes the *digital twin* of a vessel's physical performance. This approach moves maritime operations beyond the limitations of manual noon reports toward a system of **continuous, data-driven insight**. By identifying patterns in fuel consumption and predicting issues related to machinery health, hull fouling and propeller efficiency, AI-driven analytics converts raw data into actionable operational intelligence.

The benefits of this transformation are twofold.

1. **Financial resilience:** Predictive analytics minimises the "efficiency gap" caused by unnoticed degradation and suboptimal operating conditions, enabling operators to reduce fuel costs and improve voyage profitability.
2. **Environmental leadership:** Optimised fuel consumption directly reduces carbon emissions, helping vessels maintain strong **CII ratings** and comply with **EEXI and future decarbonisation regulations**. As regulatory frameworks tighten, efficient vessels may

also gain access to **carbon credit markets and green financing opportunities**.

This transformation is creating a new professional role—the **Maritime Data Practitioner**—who combines maritime domain expertise with data science skills to translate operational data into strategic insights.

*If **data is the new oil**, then **analytics is the new combustion engine**. Those who master this capability will not only improve operational efficiency but also guide the maritime industry toward a more sustainable and data-driven future.*

About the Author

Venkat Krishna Soundarraja, Fellow of IME(I), blends 30 years of marine engineering and data science. Former Chief Engineer turned Chief Data Officer (Volteo Maritime Pte. Ltd.), he drives digital transformation and sustainability in maritime operations. As educator, mentor and researcher, he bridges theory with practice, translating complex data into clear insights while inspiring future engineers through teaching, writing and innovation.

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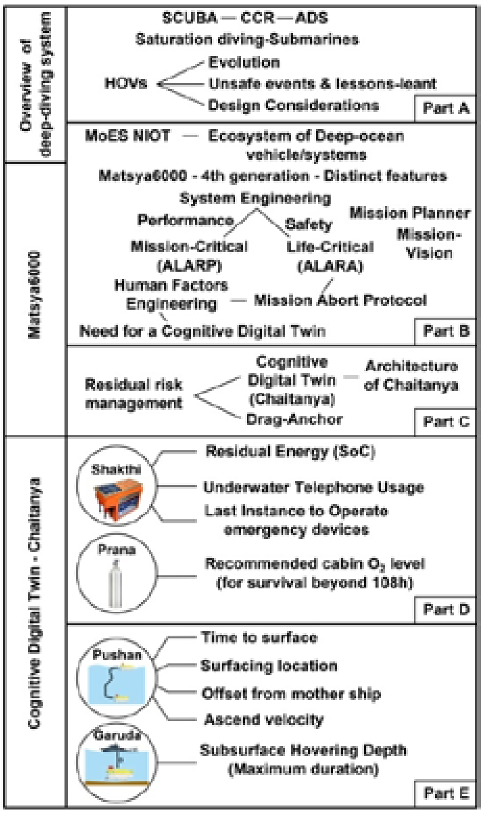
Cognitive Digital Twin "Chaitanya" for India's Deep-Ocean Human Submersible Matsya6000-Part A

N.Vedachalam, D. Sathianarayanan, S Ramesh, R. Balaji

Introduction

Safety is the key requirement for human scientific submersibles operating in challenging deep-ocean environments. Even-though adequate hardware and software redundancies are built-in for mission-critical systems, and standards for human-rating are followed to ensure the on-demand reliability of life-critical systems in Matsya6000, unforeseen emergency situations could result in cognitive incapacitation of the crew, leading to human errors. This five-part article reports the development of first-of-its-kind AI-powered Situation-aware Cognitive Digital Twin (CDT) "Chaitanya" that co-exists with Matsya6000. It comprises of 14 complex coupled-models involving interactions between engineering systems, crew physiologies, human cabin microclimate and ocean environment. Chaitanya updated with essential sensory information in real-time, simulates 15 hard-to-predict scenarios "ahead-of-time" supporting Matsya crew by redefining protocols that are optimal for their survival during the emergency period. This (first) part describes the evolution of deep-diving systems, unsafe events and lessons-learnt, and MoES-NIOT's deep-ocean submersibles ecosystem.

> *AI-powered digital twin enhances deep-ocean mission safety*



Evolution of deep-ocean diving systems

Despite the fact that the ocean covers ~70% of Earth's surface and plays a critical role in supporting life on our

> *Matsya6000 integrates engineering, human and ocean systems*

planet, from the air we breathe and the food we eat to weather and climate patterns, our understanding of the ocean remains limited. Rigorous ocean observations and documentation of biological, chemical, physical and geological aspects allow us, collectively, to protect ocean health, sustainably manage our marine resources, better understand our changing environment, and enhance appreciation of the importance of the ocean in our everyday lives. There are multiple technological challenges in exploring the deep-oceans characterised by high ambient pressure, low temperature, absolute darkness and salinity that prevent access to global positioning systems and radio signals. These hostile environmental conditions make deep-ocean human missions equally or even more complex than space missions. The challenges involved are evident from the fact that only a few have descended to the deepest part of the oceans (~11km deep Mariana Trench) compared to twelve people who have landed on the moon. The evolution of the ocean diving systems over the past eight decades is summarised in **Figure.1.**

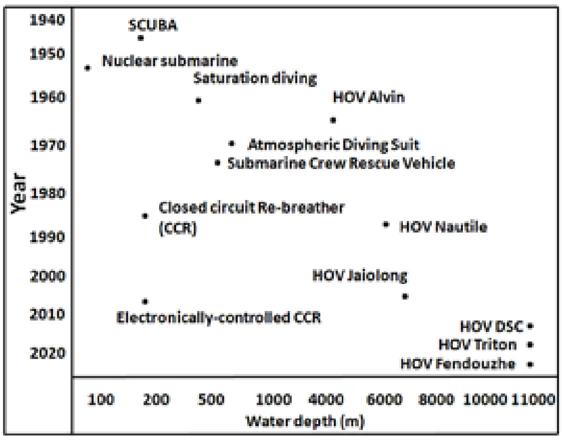


Figure.1. Evolution of deep-ocean diving systems

SCUBA, CCR and ADS

The beginning of the technical diving using *Self-Contained Underwater Breathing Apparatus* (SCUBA) in mid-1940s changed the way the diving operations that were performed by hard-hat divers using surface-supplied air with decompression status monitored by surface tenders. SCUBA diving (up to 300m water depth) involves divers suiting-up topside and descending to depth, breathing gas mixture from compressed air tanks, and then returning to the surface, themselves responsible for their own decompression status under-water. The decompression sickness (DCS) during rapid ascent is overcome by having divers breathe specialised gas mixtures (such as heliox and trimix) at various depths. Since 1985, Closed-Circuit Re-breathers (CCR) enabled deeper dives by recycling the diver's exhaled breath, removing $CO_2$and replenishing O_2 by monitoring of actual partial pressures with time. Their closed-loop design enhance dive times, efficient gas use and bubble-free operations **(Figure.2).**

Figure.2. Diver with CCR at 163m water depth

Electronically-controlled CCR introduced in 2009were based on modern computing devices worn on the wrist by the diver, programmed with decompression model-driven algorithms, derived from decompression tables. A decompression model is a mathematical representation of the kinetics of inert gas exchange in body tissues with rules to preclude ascents that might result in unsafe bubble formation. The one person atmospheric diving suit (ADS) developed in 1974 was matured with elaborate pressure joints that allow articulation enabled diving up to 700m water depths. As the ADS internal pressure is 1-atm, the occupant does not need to decompress. ADS permit less-skilled swimmers to execute deeper dives, albeit at the expense of dexterity.

Saturation diving

Saturation diving is a specialised underwater technique where divers live and work for weeks in a pressurised environment, usually up to 500m.Saturation refers to the diver's body tissues being saturated with the maximum amount of dissolved gasses possible at that depth. Divers enter the chambers, which are then gradually brought to the pressure they will experience at the working depth. Subsystems of a ship-deployable saturation diving system include diving bell, deck decompression chamber (DDC), launching and retrieval system and the hyperbaric rescue unit. When the DDC is on the surface ship, the divers transfer to a diving bell through a mating hatch in DDC. The diving bell is lowered to the dive site and the divers exit the diving bell to work. Once the divers have finished their shift, they re-enter the bell, hoisted back to the surface, and the next shift begins. From the operational perspective, the depth at which the diver's tissues become saturated (storage depth) and the vertical range over which the diver can move (excursion depths) are important.

Figure.3. Diving bell launched using ship LARS

The diving bell is fed through a large umbilical that supplies breathing gas, power, communications and hot water **(Figure.3).** The bell is also fitted with exterior-mounted breathing gas cylinders in the event of contingency. The hot water from the boilers on-board the ship is pumped down to the bell through the umbilical for protecting the divers from cold ambience. Upon completion of the underwater operations, the diving team is decompressed (in the DDC) gradually back to atmospheric pressure by the slow venting of the system pressure at an average of 1.8 bar/day, depending on the depth, length of time at that depth and the composition of the breathing gas. Thus the saturation process involves only one ascent, thereby mitigating the time-consuming and staged decompression associated with traditional diving.

Submarines

During World War II submarine technologies advanced significantly. In 1941, Japan utilised the 'midget subs' for a coordinated attack on Pearl Harbor in the Pacific Ocean, where the United States had been operating their submarines. The Cold War (1945-91) dictated much of the advancements in subsea warfare capabilities, as well as submarine safety. The study of submarine accidents during 1946-2005 has shown that the number of these incidents over the period has declined roughly 3-fold. With the first nuclear-powered submarine commissioned in 1954, in year 2000, 47 nations were operating >700 submarines, in which 300 were nuclear-powered.The standardisation of the submarine design with double hull, shock and collision withstand capabilities, and the definition of Safety Operational Envelope (SOE)/Manoeuvring Limitation Diagram (MLD) significantly improved submarine safety. As on date, 42 countries have submarines as a part of their naval fleet. The submarine count by North Korea, the United States, China, Russia, Japan, South Korea and Iran are 71, 67, 59, 49, 22, 19, and 17, respectively. Russia's Typhoon submarine is world's largest, 170m long, 48000t displacement, crew capacity of 167 with endurance of 4 months. Its twin-hull design enables it to carry 20 ballistic missiles, each with multiple nuclear warheads. Recent submarine stealth capabilities include streamlined hull shapes, sonar-absorbent hull coatings, quiet propulsion systems to minimise noise, advanced sensors for *acoustic superiority*, and reducing the submarine's *magnetic wake*.

Deep-ocean Human-Occupied Vehicles (HOV)

While the operational depth of the conventional submarines are limited to 400m water depths, Human Occupied Vehicles (HOVs) have the advantages of taking scientists to deep-ocean for carrying out high-resolution bathymetry, geological surveys, search activities, salvage operations, biological sampling, habitat analysis and carry out in-situ experiments. Scientists can continuously obtain real-time and in-situ data, design experiments and perform fine operations based on actual dynamics in real-time compared to other remotely-operated (ROVs) and unmanned robotic vehicles (AUVs) and systems **(Table.1).** The spatiotemporal limitations of underwater and surface platforms are summarised in **Figure. 4.**

Feature	**ROV**	**AUV**	**HOV**
Endurance	Unlimited	Limited	12h
Spatial capability	Limited	>10s of kms	~10s kms
Connectivity	Tethered	Untethered	Untethered
Intervention capability	Limited	Maturing	Well-proven

Table.1. Comparative capabilities of underwater robotic vehicles

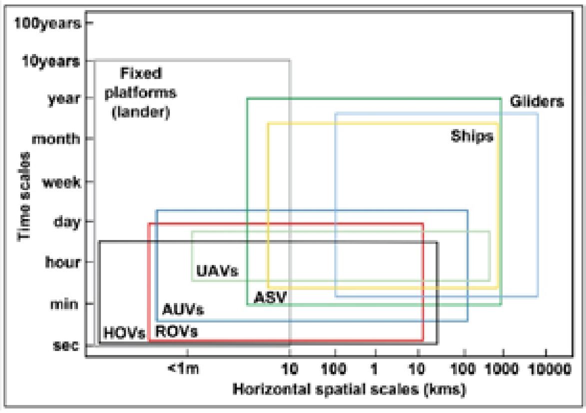


Figure.4. Spatiotemporal limits - Surface & undersea platforms

The first human dive in the deep-ocean took place in 1930when William Beebe and Otis Barton descended to a depth of 245m in a bathysphere (and then to 923m in 1934) near Bermuda. The bathysphere comprised of a pressure-resistant cast steel sphere housing humans with view ports, and equipped with life-support system, basic instrumentation and communication systems **(Figure.5).** It was suspended from the ship using a steel cable and underwater positioning of the bathysphere was achieved by adjusting the cable length and by re-positioning the surface mother ship (MOSHIP). Subsequently there have been hundreds of HOVs built that have turned out to be important stepping stones for next generation HOV. In 1960, as a significant milestone, Jacques Piccard and Don Walsh descended to10.9kmdown in the Swiss-designed, Italian-built bathyscaphe Trieste **(Figure.5).** Reaching the bottom of the Challenger Deep, the lowest point of the Mariana Trench in the Pacific Ocean, they were the first people to achieve full-ocean depth.

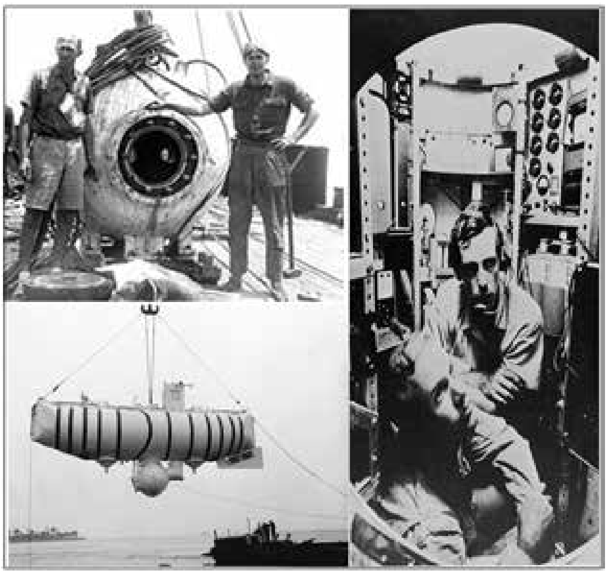


Figure.5. View of first generation HOVs

Further technical developments greatly expanded the operating range and improved the operational efficiency of the HOVs used in scientific research. After the 1stgeneration HOV Alvin, the 2nd generation HOV that were centered on the development of a lighter pressure-resistant hull for the crew, improved power supply for propulsion, and establishment of reliable systems are shown in **Table.2** and **Figure.6.** These HOV are certified for human occupancy by agencies forming part International Association of Classification Society (IACS) including the American Bureau of Shipping (ABS), Germanischer Lloyd, Det Norske Veritas (DNV), and operational guidance were given by International Marine Contractors Association (IMCA).

> ***Deep-ocean exploration demands space-level engineering reliability***

Figure.6. Deep-ocean HOVs across the world till-date

Year built	HOV	Country	Depth rating
1964	Alvin	USA	4500m
1985	Nautile	France	6500m
1990	Shinkai	Japan	6500m
	MIR	Russia	6000m
2002	RUS	Russia	6000m
2009	CONSUL	Russia	6000m
	Jiaolong	China	7000m
2012	Deep Sea Challenger	Australia	11000m
2019	Triton	USA	10925m
2020	Fendouzhe	China	10909m
2021	New Alvin	USA	6500m
2025	Matsya (being built)	India	6000m

Table.2. Evolution of HOVs post-1960

HOVs were instrumental in understanding the hydrothermal vent ecosystems that are deemed to have a fossil history that extends to the first direct evidence of the life on Earth. Once mapped by AUVs, instrumented ROVs and HOVs are used for in-situ studies. HOV such as DSV Alvin, Shinkai, MIR 1&2, Nautilus, Jaiolong were deployed to collect vent fluids, sediment, and rock samples in various hydrothermal vent fields **(Figure.7).** DSV Alvin studied the propagation activities of mussels by transplant experiments in the hydrothermal areas. Shinkai studied animal behavior and population relationships near hydrothermal vents. Deep-water ROV such as ROPOS II, Jason, Victor 6000 were used for acquired quantitative samples of faunal assemblages to estimate total biomass of a sulphides edifice, spatial and temporal patterns of supply at hydrothermal vents, video recording and photographs of macroscopic observations.

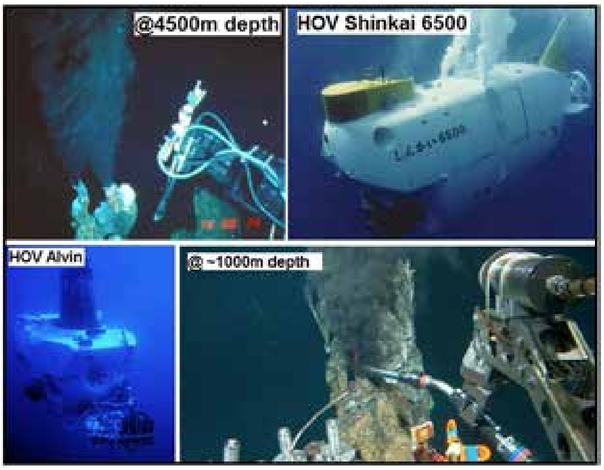


Figure.7. HOVs deployed in hydrothermal vent sampling

Hadal-depth HOVs

Following the historic descent of Jacques Piccard and Don Walsh, no HOV dives occurred over the next 50 years, and exploration was based on the descents of the remotely operated vehicles, ROV Kaiko in the 1990s and early 2000s and the hybrid ROV (HROV) Nereus in 2009. These unmanned robotic expeditions offered new insight into some of the specific organisms that live at the bottom of the Challenger Deep. Inspired by the discoveries, post-2008, significant interest was shown in the development of 3rd generation hadal-depth HOVs. There are 37 known hadal trenches in the global ocean, the 9 deepest are located along the western arc of the Pacific Ocean. They are the least explored habitat but one of the last frontiers on our planet. In map **(Figure.8),** white color shows areas with water depth > 6000m. Dark red color highlights areas with water depths >9000 m in hadal trenches, which are exclusively located in the Pacific Ocean. Values in small boxes show the maximum depth, the total area, the age of the subduction lithosphere, and the total flux of particulate organic carbon in each hadal trench. Yellow, blue, green, and red dots represent four different clusters of hadal trenches, which are grouped on how geographically distant each hadal area is from all other hadal areas **(Figure.8).**

Figure.8.Hadal trenches over the world's ocean

> *Chaitanya predicts emergencies before they occur*

Figure.9. Landers used by Triton (L) and DSC (right)

The *Deep Sea Challenger (DSC)* and *Fendouche* hadal-depth HOVs recorded depths of 11000 and 10800m respectively, in 2009 and 2012. The Five Deeps Expedition by *Triton* submersible was the first to reach the deepest point in each of the Earth's five oceans including the Puerto Rico Trench (8376m) in the Atlantic, South Sandwich Trench (7434m) in the Southern Ocean/Antarctica, Java Trench (7192m) in the Indian Ocean, Challenger Deep (10925m) in the Pacific (which is the deepest place in the planet), and Molloy Deep (5550m) in the Arctic. The expedition covered 87000 km in 10 months. As a tool for geographic exploration, the *Limiting Factor* is one of the most uniquely-capable, piloted vehicles in seafaring history **(Figure.9).**

Unsafe events and lessons learnt to improve safety

Hitherto, deep-ocean HOVs have encountered few accidents. These events have given significant inputs in evolving guidelines for safety-centered design and operations. Alvin was the first generation deep-water HOV built by Woods Hole Oceanographic Institution (WHOI) of the United States in 1964. Between 1965 and 1968, Alvin logged ~300 dives, which included finding the lost H-bomb in deep-water off-Spain, the discovery of the hydrothermal vent environment at the Galapagos Rift in 1977 and filming the Titanic in 1986 along with ROV Jason. In 1968, during a retrieval operation by vessel Lulu, handling cables got snapped and water entered the personnel sphere through the open hatch and Alvin plunged to the sea bottom at 1515m water depth. It was later salvaged in 1969 **(Figure.10)** and since then Alvin has been in operation (with a retrofit) having completed >5000 dives.

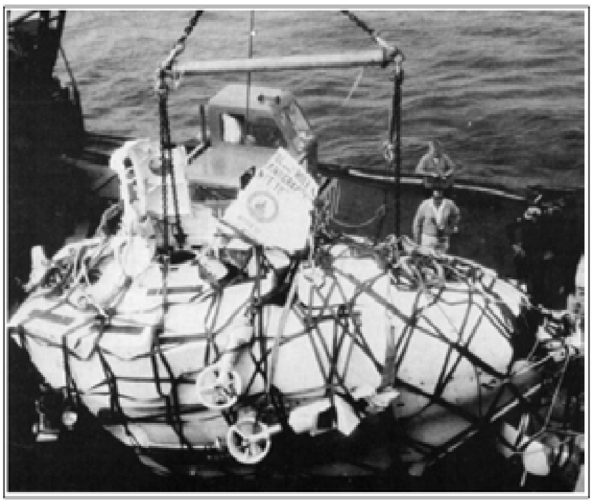


Figure.10. Alvin recovered after 1 year since it is lost in 1968

During 1973, the 76h multinational effort in the successful rescue of the 2-crewed (Roger Mallinson and *Roger Chapman*) deep-ocean submersible *Pisces III* trapped on the seabed and lying upside down (due to flooding of its compartments) at a depth of 480 m, 240 km off-Ireland **(Figure.11a)** in the Celtic Sea is the deepest successful submarine rescue in history. At the time of accident, *Pisces III*(which was laying a transatlantic telephone cable)had 64h of O_2 storage left. The synergised effort that involved Controlled Underwater Recovery Vehicle (*CURV-III*), *Pisces II & V* submersibles **(Figure.11b)** and multiple ships explained by Chapman in his book titled *No Time on Our Side* **(Figure.11c)** can be appreciated from the fact that only 12 minutes of O_2 was remaining when *Pisces III* was rescued to the sea surface **(Figure.11d).** This was possible as they decided to allow the CO_2in the air to build up beyond the normal 40 min to conserve O_2, which resulted in lethargy and drowsiness for both of them.

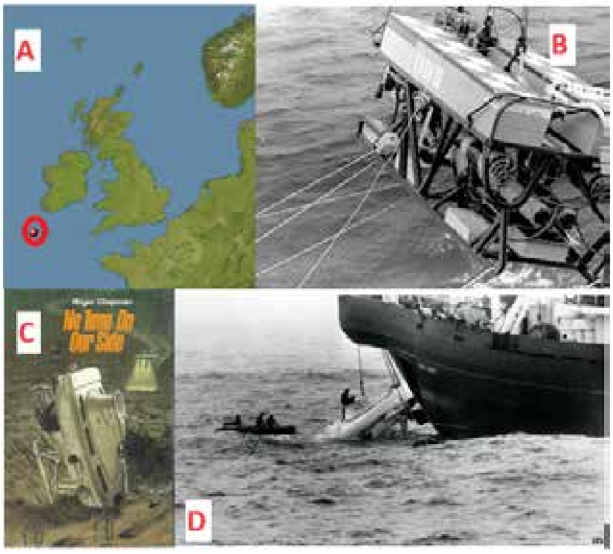


Figure.11. Rescue of *Pisces III* submersible during 1973

During 2023, *Titan*, a deep-ocean submersible **(Figure.12b)** operated by Ocean Gate, imploded during an expedition (with 5 occupants) to view the wreck of the Titanic in the North Atlantic Ocean off the coast of Newfoundland, Canada **(Figure.12a).** After the submersible had been missing for 4 days, ROV Odysseus 6000 **(Figure.12c)** from Pelagic Research Services (with Vessel Horizon Arctic) discovered a debris field containing parts of Titan, about 500m from the bow of the Titanic, recovered the debris and returned to St.John's harbor **(Figure.12d).**The entire pressure hull consisted of two titanium (Ti) hemispheres with matching Ti interface rings bonded to the 142 cm internal diameter, 2.4mlong carbon fiber-wound cylinder. Investigations revealed that failure of the carbon-fiber hull was the most likely cause of implosion, given that no large pieces of carbon fiber are known to have been recovered. The incident which spread shock waves in the deep-ocean HOV sector showed the importance of certification and the need for tighten regulatory frameworks.

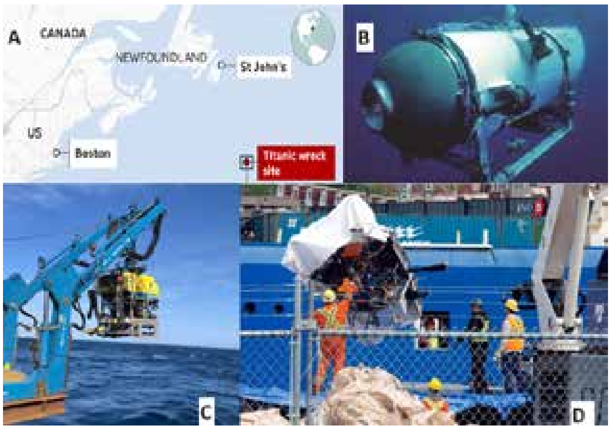


Figure.12. Salvage of Titan submersible during 2023

MoES-NIOT deep-ocean submersibles ecosystem

Ministry of Earth Sciences (MoES), under the Government of India, through well-integrated multi-disciplinary programs on earth systems (including lithosphere, atmosphere, biosphere and hydrosphere) is providing services for weather, climate, ocean and coastal state, hydrology, seismology, and natural hazard; as well as to explore and harness marine living and non-living resources in a sustainable manner and to explore the three poles of the planet (Arctic, Antarctic & Himalayas). The programs include INR ~5000Cr PRITHIVI scheme, INR ~4000Cr Deep Ocean Mission and INR 2000Cr Mission Mausam under the Monsoon Mission.

MoES organizations include the National Institute of Ocean Technology (NIOT) Chennai, National Centre for Polar & Ocean Research (NCPOR) Goa, Indian National Centre for Ocean Information Services (INCOIS) Hyderabad, National Center for Coastal Research (NCCR) Chennai, and Centre for Marine Living Resources & Ecology (CMLRE) Kochi under the *Ocean Science & Technology sector*; the India Meteorological Department (IMD), National Centre for Medium Range Weather Forecasting (NCMRWF), Indian Institute of Tropical Meteorology (IITM) Pune under the A*tmospheric sciences sector*; and

> *India advances indigenous human deep-sea exploration technologies*

the National Centre for Earth Science Studies (NCESS), Trivandrum and Earthquake Risk Evaluation Centre (EREC) under the S*eismology sector*. Multiple high-performance computing (HPC) facilities of MoES include Arka and Arunika (22 Petaflops) helps to improve weather and climate services.

Over the past 25 years, NIOT under the mandate of MoES is carrying out various technology programs in blue economy with persistent innovation to achieve integrated ecological, economic and social well-being. The activities of NIOT include development of eco-friendly technologies for exploring and harvesting deep-ocean minerals, unconventional hydrocarbons, harnessing renewable energy, desalination from seawater and bio-prospecting; and to monitor the health of the ocean environment and coastal ecosystems including coastline protection, cyclone and tsunami early warning systems, coral habitat observations, sustainable fishing and the Polar Ocean monitoring. MoES-NIOT's present deep-ocean submersible ecosystem include 6000m depth-rated ROV-ROSUB6000, 500m depth-rated Polar/Shallow water ROV (PROV), 3000m depth-rated Autonomous Coring System (ACS) capable of taking cores up to 100m below the sea floor **(Figure.13).** The ecosystem also includes a Kongsberg-make 6000m depth-rated Autonomous Underwater Vehicle (OMe6000).

ROSUB6000 has carried out >44 dives in water depths up to 5289m in poly-metallic nodule, gas hydrate and hydrothermal sulphides sites in the Bay of Bengal and Indian Ocean. For the benefit of the scientific community, deep-ocean explorations were webcast from ROV through satellite telemetry. ACS that has proved its capability (in 30 deployments) by collecting cores at 2960m water depths is a valuable and cost-effective tool for ground-truth validation and spatial quantification of marine gas hydrates in India. PROV has been deployed in 40 locations for bio-diversity studies, search operations and in the New Indian Barrier ice-shelf in Eastern Antarctica. AUV OMe6000 has carried out ~10 scientific surveys in depths up to 5270m in poly-metallic nodule, gas hydrate and hydrothermal sulphides sites in the Bay of Bengal and Indian Ocean. Through a well-planned search mission, OMe6000 was able to map the debris of a lost Indian defense aircraft in an area of 16 km^2 at ~3400m water depths in the Bay of Bengal.

Deep Sea Technologies team of NIOT, based on the experiences gained over more than 2 decades in the design, development and operations of these unmanned deep-ocean submersibles and systems, under the deep-ocean mission, is now indigenously developing a 6000m depth-rated battery-powered human scientific submersible Samudrayaan-Matsya6000 **(Figure.13).**

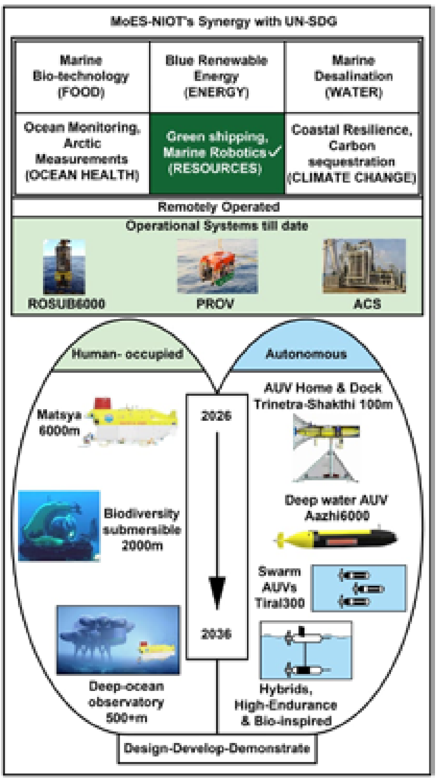


Figure.13. NIOT present deep-ocean submersible ecosystem

NIOT's Vision-2047, aligning with the United Nations Ocean Decade Sustainable Development Goals

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(UN-SDG), aims to design, develop, demonstrate and deliver technologies for exploration and harvesting of deep-ocean and coastal resources to meet the future food, energy, water, ocean health and climate-change requirements through sustainable solutions thus enhancing the contribution of blue economy to India's GDP and to ensure sustainability of the ecosystem surrounding the subcontinent.

The strategic development plans in the marine robotics sector of Deep Sea Technologies team of NIOT for the next ten years include indigenous development of a range of human-occupied and autonomous vehicles/systems **(Figure.13).** Human-occupied systems include Matsya6000 and scaling-up its capability to hadal depths, submersible for bio-diversity studies and the deep-ocean observatory to facilitate long-term human presence for research (like International Space Stations/ISS) featuring reliable life-support systems, transparent feed-through homing and docking (H&D) of deep-ocean submersibles enabling transfer of humans and resident underwater vehicles as station range-extenders. Autonomous systems include Trinetra-Shakthi100AUV with H&D capabilities, deep-water AUV Aazhi6000, swarm AUV Tiral500 for increased spatial surveys, long-endurance, hybrid and bio-inspired autonomous underwater vehicles.

In the next issue...

System engineering design of HOVs and safety-centered design of life-critical systems of Matsya6000 are discussed.

Abbreviations

ABS	American Bureau of Shipping
ADS	Atmospheric Diving Suit
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
APoS	Acoustic Base Line Positioning Systems
AUV	Autonomous Underwater Vehicles
BF	Body frame
CB	Centre of buoyancy
CCR	Closed Circuit Re-breather
CDT	Cognitive Digital Twin
CG	centre of gravity
CO2	Carbon Dioxide
DCS	Decompression Sickness
DDC	Deck Decompression Chamber
DNV	Det Norske Veritas
DoF	Degrees of freedom
DR	Dead Reckoning

DSC	Deep Sea Challenger
DT	Digital Twin
DVL	Doppler Velocity Log
FIDES	Failure-In-Time Determination for Electronic Systems
FOG	Fibre Optic Gyro
GPS	Global Positioning System
HOV	Human-Occupied Vehicles
HROV	Hybrid ROV
IACS	International Association of Classification Society
IMCA	International Marine Contractors Association
INS	Inertial Navigation Systems
LARS	Launching and Retrieval System
LBL	Long Base Line
MoES-NIOT	Ministry of Earth Sciences-National Institute of Ocean Technology
MOSHIP	Mother Ship
O2	Oxygen
OOR	out-of-roundness
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RLG	Ring Laser Gyro
ROVs	Remotely-Operated Vehicles
SCUBA	Self-Contained Underwater Breathing Apparatus
SOE	Safety Operational Envelope
SSBL	Short base line
UAT	Underwater Acoustic Telephone
USBL	Ultra-short baseline
WHOI	Woods Hole Oceanographic Institution

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Navigating the Future Ocean: Law, Science and Robotics in the Transformation of Shipping and Ports

Future mariners must master law, science, technology

R. Venkatesan, Abhay Singh Thakur

Abstract

The maritime industry, responsible for transporting more than 80 percent of global trade, is undergoing rapid transformation driven by climate change, decarbonisation policies, digitalisation and advances in marine robotics and autonomous technologies. For India—a maritime nation with a rich seafaring heritage and ports handling nearly 95 percent of its merchandise trade—these developments present both significant challenges and strategic opportunities.

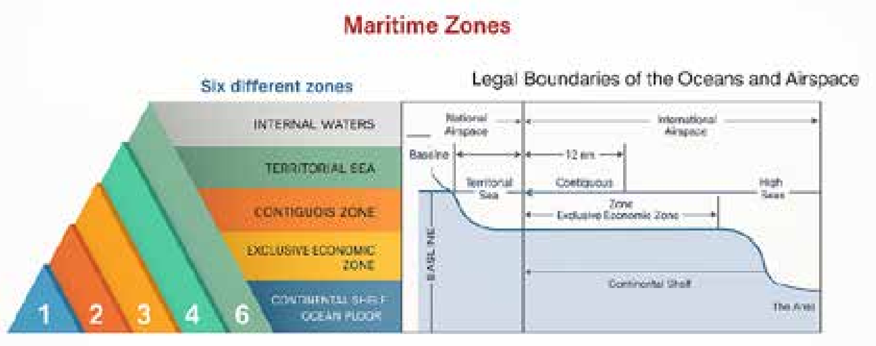
This article examines the evolving role of maritime professionals, including officers and engineers at sea, port managers, policymakers and maritime executives ashore, who must increasingly operate at the intersection of maritime law, oceanographic science and emerging technologies. Using the Northern Indian Ocean as a case study, the paper explores how legal frameworks, environmental change and technological innovation intersect in modern shipping operations. It identifies gaps in maritime governance and workforce preparedness, emphasising the need for interdisciplinary education and integrated skill development.

The study concludes that combining maritime law, ocean science, digital technologies and robotics will be essential for ensuring safe navigation, regulatory compliance, climate resilience and sustainable maritime growth in the twenty-first century.

Keywords: Maritime law, UNCLOS, Blue Economy, maritime governance, oceanography, marine robotics, maritime autonomous surface ships (MASS), climate change, decarbonisation, Indian Ocean, maritime education, port resilience, digital shipping, ocean observation, maritime policy.

Introduction

India's maritime heritage extends back more than four thousand years and reflects a long tradition of seafaring, shipbuilding and oceanic trade. Archaeological discoveries at Lothal in Gujarat have revealed one of the earliest known dockyards in the world. This ancient port, equipped with tidal gates, mooring stones and drainage channels, demonstrates that maritime engineering and trade were central to the Indus Valley Civilization. These findings highlight the historical importance of maritime commerce



and technological innovation in India's civilisational development.

In the contemporary era, India continues to reinforce this maritime identity through initiatives such as the National Maritime Heritage Complex at Lothal, India Maritime Week and policy platforms designed to promote maritime cooperation and technological innovation. These initiatives aim to highlight India's historical contributions to maritime development while positioning the country as a leading maritime power in the twenty-first century.

India's maritime frontier extends across more than 11,000 kilometres of coastline, including the Andaman and Nicobar and Lakshadweep island chains. These coastal regions support ports, fisheries, offshore energy production and vital shipping routes connecting Asia, Europe and Africa. National programmes such as Sagarmala, the Deep Ocean Mission and Blue Economy initiatives aim to integrate port development, maritime logistics, ocean science and sustainable economic growth.

However, the maritime sector itself is undergoing rapid transformation. Climate change, environmental regulations, digitalisation and autonomous technologies are reshaping maritime operations. These developments require maritime professionals to possess broader competencies that combine traditional maritime skills with knowledge of law, environmental science and advanced technologies.

Building Skills for the New Maritime Era

Shipping remains the backbone of global commerce, transporting more than four-fifths of traded goods worldwide. In India, maritime transport carries approximately 95 percent of merchandise trade by volume, making the maritime sector essential to national economic development and global connectivity.

Despite its importance, the maritime sector faces a range of emerging challenges. Rising sea levels, warming ocean temperatures, intensifying cyclones and stricter environmental regulations are altering operational conditions for ships and ports. These changes require maritime professionals to develop new interdisciplinary capabilities.

The United Nations Convention on the Law of the Sea (UNCLOS) provides the primary legal framework governing maritime rights and responsibilities. Adopted in 1982 and entering into force in 1994, UNCLOS has been ratified by more than 170 states and establishes fundamental principles governing ocean use.

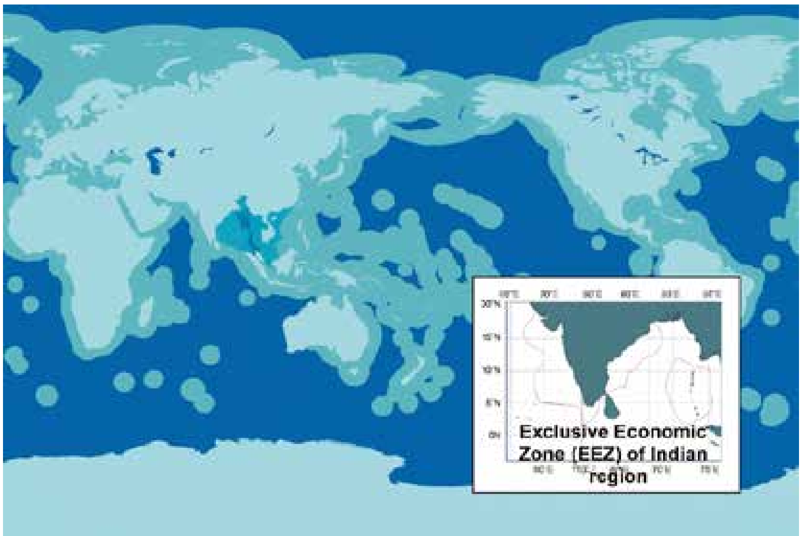
UNCLOS created several key institutions including the International Tribunal for the Law of the Sea, which provides dispute resolution mechanisms for maritime conflicts and the International Seabed Authority, which regulates exploration and exploitation of mineral resources in the international seabed area beyond national jurisdiction.

In addition to UNCLOS, the International Maritime Organization has developed core conventions governing maritime safety and environmental protection. These include the International Convention for the Safety of Life at Sea, the International Convention for the Prevention of Pollution from Ships, the Standards of Training, Certification and Watchkeeping Convention and the Maritime Labour Convention.

Together these frameworks form the backbone of global maritime governance. However, navigating this regulatory environment requires more than procedural knowledge. Maritime professionals must understand how legal frameworks interact with operational realities at sea and in ports.

The Legal Backbone of Shipping

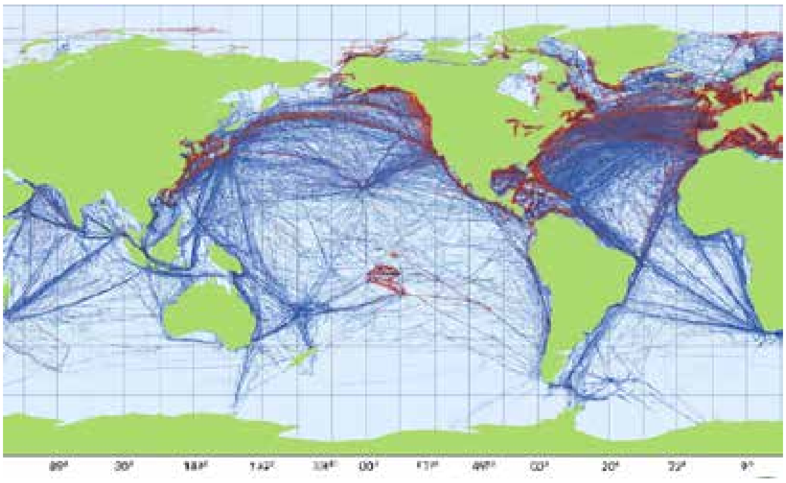
Modern shipping operations involve vessels crossing multiple maritime jurisdictions during a single voyage. UNCLOS defines the structure of these maritime zones and clarifies the rights and responsibilities of coastal and flag states.



Exclusive Economic Zone (EEZ) of the Global and India

> *Ocean governance shapes tomorrow's shipping operations*

> *Climate change is redefining maritime infrastructure resilience*



Coverage of the ocean vessels participating in the Global Ocean data collection programme of UNESCO IOC & WMO. The UN has given a call to support global ocean observing through shipping

Territorial seas extend up to twelve nautical miles from the coastline and are subject to the full sovereignty of the coastal state. The contiguous zone extends up to twenty-four nautical miles and allows coastal states to enforce customs, immigration, fiscal and sanitary regulations.

The Exclusive Economic Zone extends up to two hundred nautical miles and grants coastal states sovereign rights over marine resources including fisheries, seabed minerals and renewable energy production.

Beyond these zones lie the high seas, which remain open to all states for navigation and economic activities under international law.

India exercises sovereign rights over an Exclusive Economic Zone covering approximately 2.3 million square kilometres. The Andaman and Nicobar Islands contribute nearly one-third of this maritime area, making them strategically significant for maritime security and resource management.

A major development in ocean governance is the Biodiversity Beyond National Jurisdiction agreement adopted in 2023. This treaty focuses on conserving marine biodiversity in areas beyond national jurisdiction through measures such as marine protected areas, environmental impact assessments and equitable benefit sharing of marine genetic resources.

Although the BBNJ agreement does not directly regulate shipping, it reinforces environmental responsibilities under UNCLOS and contributes to a more integrated ocean governance framework.

The Ocean as a Shared Operating Space

The ocean covers more than seventy percent of the Earth's surface and plays a central role in regulating global climate systems. For maritime professionals, understanding ocean dynamics is essential for navigation safety, operational efficiency and environmental protection.

Scientific organisations such as UNESCO's Intergovernmental Oceanographic Commission coordinate the Global Ocean Observing System, which collects real-time oceanographic data through satellites, buoys, research vessels and autonomous monitoring platforms.

Commercial ships also contribute valuable meteorological observations through voluntary programmes known as Ships of Opportunity. These observations help fill gaps in satellite monitoring and improve weather forecasting.

The Northern Indian Ocean, which includes the Arabian Sea and the Bay of Bengal, is particularly important for global shipping and regional climate systems.

The Arabian Sea experiences seasonal upwelling and higher salinity levels, influencing ocean circulation and marine productivity. In contrast, the Bay of Bengal exhibits strong stratification and plays a major role in the formation of tropical cyclones.

Monsoon-driven currents such as the East India Coastal Current influence vessel routing and fuel efficiency. Extreme weather events including tropical cyclones and long-period ocean swells pose hazards to maritime operations and coastal communities.

Climate Change and Maritime Infrastructure

Climate change is reshaping marine environments and creating new risks for shipping and port operations. Rising sea temperatures, melting polar ice and ocean acidification are altering marine ecosystems and weather patterns.

Sea level rise threatens port infrastructure and coastal communities. Storm surges and stronger cyclones can damage breakwaters, quays and port facilities.

Changes in monsoon patterns also increase uncertainty in voyage planning and navigation safety. Shipping companies must increasingly rely on advanced forecasting systems and real-time ocean monitoring.

Northern Indian Ocean—Monsoon Currents and Major Shipping Routes with autonomous ocean observation tools (Arabian Sea vs. Bay of Bengal)

> *Robotics and AI are transforming ocean exploration*

India's Sagarmala programme aims to modernise port infrastructure and logistics networks. Future port designs must incorporate climate-resilient features such as elevated quays, improved drainage systems and cyclone-resistant structures.

Shipping contributes approximately three percent of global greenhouse gas emissions. In response, the International Maritime Organization has adopted regulations aimed at reducing carbon intensity and promoting alternative fuels such as hydrogen, ammonia and advanced biofuels.

India's renewable energy potential positions the country to become a regional hub for green maritime fuels and sustainable shipping technologies.

Digitalisation and Marine Robotics

Digital technologies are transforming maritime operations. Modern vessels are equipped with sensors that continuously monitor engine performance, fuel consumption, weather conditions and navigational parameters.

These systems enable predictive maintenance, weather-optimised routing and real-time fleet monitoring. By analysing operational data, shipping companies can improve efficiency and reduce fuel consumption.

However, digitalisation also introduces cybersecurity risks. Protecting navigation systems, communication networks and operational data is becoming increasingly important. Marine robotics is another rapidly evolving field. Maritime Autonomous Surface Ships and uncrewed underwater vehicles rely on artificial intelligence, satellite communications and advanced sensors to operate with minimal human intervention.

The International Maritime Organization is currently developing regulatory frameworks for autonomous shipping through the Maritime Autonomous Surface Ships Code.

These technologies promise improved efficiency and safety but will also transform maritime employment patterns, creating new roles in robotics management, remote vessel operations and maritime data analytics.

Skills and Responsibilities for Modern Mariners

The transformation of the maritime industry requires a new generation of maritime professionals equipped with interdisciplinary skills.

Deck officers must combine traditional navigation skills with knowledge of environmental regulations, meteorology and oceanographic data interpretation.

Marine engineers must maintain propulsion systems that comply with emissions regulations while managing advanced monitoring systems and alternative fuel technologies.

Shore-based managers must understand legal frameworks, climate risks and sustainability policies when making strategic decisions regarding fleet renewal and port infrastructure investments.

Arctic Shipping Routes in Summer—The Northern Sea Route (along Russia's Siberian coast) and Northwest Passage (through the Canadian Arctic Archipelago) are becoming operationally viable as sea ice retreats, with critical environmental implications for pristine Arctic ecosystems and indigenous communities

Maritime Education and Workforce Development

India is strengthening maritime education through collaborations between the Directorate General of Shipping, the Indian Maritime University and leading research institutions.

Innovation initiatives encourage research in green propulsion technologies, digital navigation systems and maritime data analytics.

Simulation-based training environments now integrate digital twins, automated navigation systems and weather routing technologies.

Continuous professional development will be essential as maritime technology and regulatory frameworks evolve.

Conclusion

The maritime industry is entering a transformative era in which traditional seamanship intersects with international law, ocean science and advanced technology.

Global frameworks such as UNCLOS and IMO conventions increasingly shape maritime operations, while climate change and digitalisation redefine shipping practices.

For India, these developments present both challenges and opportunities. By integrating scientific research, technological innovation and interdisciplinary education, India can strengthen its leadership in global maritime affairs.

The maritime professionals of the future must be capable of navigating not only the oceans but also the complex intersection of law, science and technology.

Such integration will be essential for building a resilient, sustainable and competitive maritime economy in the decades ahead.

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India s Arctic Observatory (IndARC) being deployed from the Norwegian Research vessel at Svalbard, Norway

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Vibrations that Speak: Using Vibration and Condition Monitoring Data in Post-Accident Analysis

Gajanan Karanjikar

Abstract

Modern vessels generate large volumes of machinery condition data through vibration monitoring, torque measurement systems and integrated condition monitoring platforms. Despite the availability of such information, machinery failures still occur where early warning signals were present but not effectively interpreted or acted upon.

This paper examines the role of vibration and condition monitoring (CM) data in post-accident analysis of marine machinery failures. Using examples such as shaft-line misalignment, bearing degradation, resonance effects and progressive vibration growth, the article demonstrates how historical vibration trends can reveal developing defects long before catastrophic failure occurs. The discussion also considers the regulatory context including SOLAS, the ISM Code, IMO casualty investigation requirements and classification society expectations.

By treating vibration data as forensic evidence rather than merely operational information, marine engineers and investigators can better understand failure mechanisms and identify missed opportunities for preventive action. The paper highlights how effective interpretation of vibration data strengthens accident investigations, improves maintenance decision-making and reinforces the importance of condition monitoring as a critical component of modern ship safety management.

Keywords: Vibration monitoring; condition monitoring; marine accident investigation; shaft alignment; bearing failure; resonance; machinery diagnostics; propulsion system reliability; SOLAS; ISM Code.

Introduction

Modern ships are increasingly equipped with sophisticated monitoring systems capable of collecting large volumes of operational data. Condition monitoring platforms measure vibration levels, bearing condition indicators, torsional vibration, shaft torque and structural responses in real time. In theory, such information should enable early detection of machinery defects and prevent catastrophic failures.

In practice, however, accidents involving propulsion failures, bearing damage, crankshaft incidents and auxiliary machinery breakdowns continue to occur. Investigations frequently reveal that warning signs were present in historical monitoring data but were not recognised, interpreted correctly, or acted upon in a timely manner. The result is that what appears to be a sudden failure is often the final stage of a long developing mechanical problem.

> *Steel speaks first — vibration tells the story*

Vibration analysis and condition monitoring provide valuable tools for understanding the health of rotating machinery. When properly interpreted, vibration signatures can reveal developing faults such as shaft misalignment, imbalance, looseness, resonance conditions and bearing damage. Over time these indicators create a historical record of machinery behaviour that becomes highly valuable in post-accident analysis.

In recent years, accident investigators, classification societies, insurers and regulators have increasingly recognised the importance of condition monitoring data when assessing machinery failures. Historical vibration records can help determine whether a failure was sudden and unforeseeable or the result of a progressive defect that should have been detected earlier. Such distinctions are critical when evaluating seaworthiness, maintenance practices and compliance with safety management requirements.

This article explores how vibration and condition monitoring (CM) data can be used in **post-accident analysis**, with particular focus on shaft vibration, bearing condition, misalignment, resonance and data-driven failure diagnosis. It also touches on the regulatory framework (SOLAS, ISM Code, IMO casualty investigation standards and class rules) and the legal and financial consequences for owners when evidence shows that warning signs were present but not acted upon.

By understanding how machinery "speaks" through vibration trends and spectral patterns, marine engineers and investigators can transform condition monitoring systems from passive data collectors into powerful tools for improving safety, reliability and accident analysis.

Modern ships are full of data, but very often the most important signals were "speaking" long before an accident and nobody was listening. Vibration trends, bearing condition indicators and shaft-line data can provide powerful evidence of machinery health, both before and after a casualty. When things go wrong - a main bearing failure, stern tube damage, crankcase explosion, loss of propulsion - this data becomes a forensic resource in the hands of the marine engineer and accident investigator.

1. When steel starts talking

Ships do not fail in silence. Long before a stern tube overheats, a crankpin wipes, or a foundation cracks, the steel has usually been "talking" in the language of vibration.

On a modern bulk carrier or tanker, the main propulsion train and auxiliaries routinely generate vibration data:

- **Online CM systems** tracking velocity, acceleration, bearing envelope values and spectral signatures.
- **Shaft torque and power systems** record torsional vibration and irregularities in loading.
- **Hull and superstructure sensors** fitted for comfort or structural monitoring, which incidentally capture machinery effects.

When a serious incident occurs - for example, a main bearing failure leading to loss of propulsion and tow into harbour - vibration history often holds the key to understanding whether this was a sudden, unforeseeable event or the outcome of a progressive defect that could (and should) have been detected earlier.

> *Most machinery failures whisper before they scream*

In an era where loss of propulsion and blackouts are treated with increasing seriousness - especially in confined U.S. and European waters - the question is no longer just "what broke?" but "what was the machinery trying to tell us beforehand and what did we do with that information?"

2. What vibration and CM can tell us

Vibration and condition monitoring are not magic; they are pattern-recognition tools grounded in simple physics.

At a high level, they help answer four questions:

1. **Is the machinery running smoothly?** - overall vibration levels and trend plots.
2. **What kind of mechanical problem is developing?** - spectral analysis (1× rpm, 2×, gearmesh, blade passing, etc.).
3. **Where is the defect located?** - comparison across sensors and directions (horizontal, vertical, axial).
4. **How urgent is the situation?** - rate of change and proximity to alarm limits.

In the context of accident investigation, the focus is on **changes over time**, not isolated readings:

- Slowly rising 1× and 2× shaft vibration, pointing towards growing misalignment or bent shaft.
- Increasing high-frequency bearing envelope values, indicating early rolling-element damage.
- Peaks at or near a structural natural frequency, signalling dangerous resonance.

When we overlay this with event timelines - dry dockings, grounding, propeller damage, fuel changes, unusual manoeuvres - we begin to build a coherent picture of cause and effect.

3. Shaft vibration and misalignment - the long lead-in to failure

Main shaft lines are particularly revealing. A typical installation may have:

- Sensors on the **thrust bearing**, intermediate bearings and stern tube.
- Optional shaft-line torsional and bending measurement.

- Sometimes, accelerometers are on the hull close to the bearings.

After a casualty such as a **stern tube bearing wipe**, intermediate bearing damage, or coupling failure, the investigator should:

- Obtain **historical vibration trends** - at least several months before the incident.
- Examine **1× rpm components** (fundamental rotational frequency) for signs of increasing amplitude.
- Check for **2× and higher harmonics**, which may indicate misalignment, ovality, or looseness.
- Identify any correlation between increasing vibration and key events: contact, heavy weather, grounding, propeller blade repair, etc.

It is common to find that, following an incident such as a light grounding or a propeller strike, vibration levels increase but remain below alarm thresholds. Without proper analysis, this becomes the “new normal”. Over time, elevated vibration accelerates bearing wear, causes local heating and deforms lubrication films - until the point where the bearing fails dramatically, often in restricted waters.

In such cases, condition monitoring data can demonstrate that:

- The defect was **progressive and detectable**.
- Opportunities existed to investigate and correct alignment or propeller condition.
- Failure to act may constitute a breach of the company’s duty to maintain the ship in a seaworthy condition.

4. Bearings that complain before they collapse

Rolling element bearings in generators, pumps and shaft-line support systems are classic candidates for CM. Techniques such as **envelope detection**, **spike energy monitoring and high-frequency resonance analysis** are widely used.

Post-incident, the investigator should look for:

- Rising trends in bearing condition indicators (gE, BCU, or manufacturer-specific metrics).
- Emergence of characteristic defect frequencies - ball pass frequency outer race (BPFO), inner race (BPFI), ball spin, cage frequencies - in spectra.
- Evidence that alarms were triggered, acknowledged and perhaps suppressed, without corrective work.

For example, a generator bearing failure that allows fragments to enter the stator, causing a short circuit and subsequent blackout, may appear at first to be a sudden malfunction. Vibration history may show months of **increasing bearing energy values** and repeated alarms that were treated as background noise.

From a legal standpoint, this shifts the narrative from “unexpected electrical failure” to “mechanical defect that was signalled but not addressed”, with clear implications for how regulators, insurers and courts view the owner’s due diligence.

5. Resonance - when the ship and machinery sing the same note

Resonance is responsible for many puzzling accidents:

- Cracked foundations on auxiliary engines.
- Fatigue failure of pipe supports and small-bore branches, leading to oil leaks and fires.
- Excessive vibration of deck structures in certain speed ranges.

In a resonance scenario, the excitation frequency (often 1×, 2× rpm, propeller blade passing, or a gearmesh frequency) coincides with a natural frequency of part of the structure. The result is disproportionately high amplitudes.

In post-accident analysis, vibration data can reveal:

- Strong peaks at specific frequencies that grow dramatically within a narrow speed band.
- Phase relationships and mode shapes (from multi-point measurements) showing how a foundation or girder is flexing.

If the failure occurred at a well-known excitation frequency within the normal operating range, questions arise about whether **modal analysis, sea trials and class approvals** adequately considered resonance during design and commissioning - or whether later modifications (added piping, stiffeners removed, new equipment) inadvertently created a problem.

6. Data-driven diagnosis - turning CM into evidence

For vibration and CM data to be useful in accident investigation, they must be:

- **Available** - recorded, stored and retrievable even after the incident.
- **Time-synchronised** - aligned with engine logs, VDR data, alarm logs and human recollections.
- **Interpretable** - collected according to a consistent measurement strategy (same points, same speeds, similar loads).

Once this is in place, a systematic approach might be:

Ignored vibration trends often precede catastrophic failure

> *Condition monitoring turns data into forensic evidence*

1. Construct a **timeline** of the incident, including any preceding warning signs (noise, heat, smell, previous alarms).
2. Extract vibration and condition data for **"before", "during" and "after"** the critical events.
3. Analyse overall levels and spectra, focusing on changes rather than absolute values.
4. Compare damaged and undamaged similar components (e.g., a failed bearing versus a healthy one on another unit).
5. Map findings against physical evidence (fracture surfaces, wear patterns) and witness statements.

This is where vibration truly "speaks": it either corroborates or challenges hypotheses about what failed first and why. It may show, for example, that what appeared to be a sudden crankpin failure was preceded by weeks of abnormal 2× frequency growth consistent with misalignment, followed by rising bearing energy just before the event.

7. Codes, conventions and the regulatory context

International instruments do not yet mandate specific vibration analysis methods, but they do create the **expectation of systematic monitoring and response**, especially for critical machinery.

Key elements include:

- **SOLAS Chapter II-1** - requires that machinery installations provide adequate reliability and safety. For main propulsion, this implies that known threats such as misalignment and bearing stress are proactively managed and abnormal behaviour is investigated.
- **SOLAS Chapter IX (ISM Code)** - obliges companies to establish procedures for maintenance of the ship and equipment, identify critical systems and analyse non-conformities, accidents and hazardous occurrences. Vibration and CM data form part of the evidence base for these analyses.
- The **IMO Casualty Investigation Code** - sets standards for safety investigations, emphasising systematic collection of technical evidence and identification of underlying causes, not just immediate failures. CM data is a prime example of such technical evidence.
- **Classification society rules** - increasingly reference condition-based maintenance and may accept CM-supported intervals for certain surveys, while expecting owners who use CM to respond promptly to warning trends. Some societies also provide guidance on acceptable vibration levels for habitability and machinery.
- Relevant **ISO standards** (e.g., ISO 10816 / 20816 series for vibration evaluation, ISO 17359 for condition monitoring) - not mandatory in themselves, but widely recognised benchmarks for interpreting vibration severity and designing CM programmes.

When an incident occurs, flag States, class and insurers will look at how the owner's Safety Management System handled earlier abnormal vibrations. Were they logged, analysed and acted upon, or were limits treated as advisory and routinely exceeded without consequence?

8. Legal and financial consequences - when ignored signals cost real money

The financial impact of vibration-related failures can be substantial:

- **Direct repair costs** - bearings, crankshafts, stern tubes, foundations, pipework and associated labour and yard time.
- **Off-hire and lost earnings** - tugs, deviations, waiting for dry-dock slots, extended stays in repair yards.
- **Third-party damage and consequential losses** - if the failure leads to grounding, collision, fire, or oil release.
- **Survey and investigation costs** - class, flag, consultants and expert witnesses.
- **Longer-term costs** - increased insurance premiums, reputational damage with charterers and terminals and closer regulatory scrutiny.

From a legal perspective, vibration and CM data can be a double-edged sword. On the one hand, it can show that an owner had an effective monitoring programme, detected problems early and took reasonable steps, thereby strengthening a defence that the ship was **seaworthy and maintained with due diligence**. On the other hand, it may reveal a pattern of **ignored alarms, repeated limit exceedances and minimal follow-up**, supporting allegations that the owner or manager failed to properly maintain the vessel.

In disputes over charterparty performance, hull and machinery insurance, P&I claims, or limitation of liability, such evidence can be decisive. Judges and arbitrators respond well to **clear, time-based plots and transparent analysis**, as opposed to vague statements about "normal vibration".

9. Lessons for owners and engineers

The core message is simple: **if you collect vibration and condition data, you must take it seriously**. It is not just a box-ticking exercise or a way to extend overhaul intervals.

> ***The accident began long before the breakdown***

It is a form of continuous survey - a way for the ship to tell you how it feels.

For owners and marine engineers, key practical points are:

- Design CM systems and routines with **investigation in mind**: good sensor locations, consistent measurement practices and secure data storage.
- Integrate CM results into the **planned maintenance system** and ISM processes, so that abnormal trends trigger investigations, not just alarm acknowledgements.
- Train engineers to understand basic vibration patterns and when to escalate concerns.
- After any significant contact, grounding, heavy weather event, or propeller repair, use vibration data as part of the **post-event assessment**.
- In the aftermath of an accident, bring CM data into the centre of the investigation, not as an afterthought.

Conclusion

Vibration really does speak. The question for the marine industry is whether we will allow it to be just background noise, or whether we will listen carefully enough to prevent the next "sudden" failure before it makes the headlines.

Modern ships generate enormous quantities of machinery condition data, yet this information only becomes valuable when it is interpreted and acted upon effectively. Vibration and condition monitoring systems provide continuous insight into the mechanical health of propulsion and auxiliary equipment. When failures occur, historical vibration records often reveal that the machinery had been signalling distress long before the incident took place.

Post-accident analysis increasingly relies on such data to reconstruct the sequence of events leading to a casualty. Rising vibration trends, changes in spectral patterns, bearing condition indicators and resonance signatures can all provide evidence of developing mechanical defects. When correlated with operational events such as groundings, propeller damage, heavy weather exposure, or maintenance activities, these indicators help investigators distinguish between sudden failures and progressive deterioration.

The regulatory framework surrounding maritime safety—including SOLAS, the ISM Code and IMO casualty investigation standards—does not mandate specific vibration analysis methods. However, these instruments establish clear expectations that ship operators will maintain machinery in a reliable condition and investigate abnormal behaviour. When condition monitoring systems identify warning signs, failure to respond appropriately may have significant operational, legal and financial consequences.

For shipowners and marine engineers, the lesson is clear. Condition monitoring must be integrated into the broader safety management system rather than treated as a routine data-collection exercise. Abnormal vibration trends should trigger investigation, engineering assessment and corrective action where necessary. Engineers must be trained not only to collect data but also to understand its implications for machinery health.

Ultimately, vibration monitoring gives machinery a voice. It allows steel structures, rotating shafts and bearings to communicate early warnings of developing problems. The challenge for the maritime industry is not the availability of data, but the willingness to listen carefully and respond before those signals culminate in failure. When used effectively, vibration and condition monitoring can transform accident investigations, strengthen preventive maintenance and contribute significantly to safer and more reliable ship operations.

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Dual-Fuel Gas-Burning Diesel Engines for Marine Propulsion

Part 3: Medium-Speed Dual-Fuel Engines, Fuel Systems, Control and Safety Architecture

Kaushik K Seal, Saptarshi Basu

Abstract

Medium-speed dual-fuel (DF) engines have become one of the most important propulsion technologies for modern vessels operating under increasingly strict environmental regulations. These engines enable ships to operate on either natural gas or conventional liquid fuels while maintaining performance characteristics comparable to conventional diesel engines. This article examines the architecture, performance characteristics, fuel systems and safety strategies of contemporary medium-speed four-stroke dual-fuel engines used in marine propulsion and power generation applications.

Representative engines examined include the MAN 51/60DF and L32/44DF series, the Wärtsilä 46DF platform and the Hyundai HiMSEN H22CDF and H27DF engines. These engines typically operate at rotational speeds between 500 and 1,000 rpm and use low-pressure gas admission combined with micro-pilot diesel ignition to initiate combustion in a lean premixed gas-air mixture. Modern designs have largely replaced earlier pre-combustion chamber concepts with direct in-cylinder pilot injection, resulting in improved efficiency, reduced methane slip and better combustion stability.

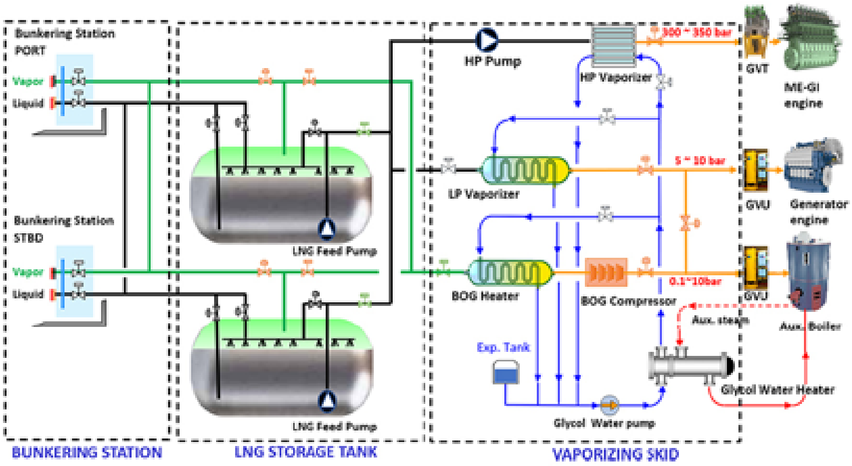
The paper reviews key technical subsystems including gas admission architecture, common-rail pilot injection systems, fuel ratio control algorithms, combustion monitoring systems and integrated safety frameworks. Particular attention is given to the control strategies used to detect and mitigate abnormal combustion phenomena such as pre-ignition, excessive pressure rise rates and heavy running conditions.

Performance data indicate that modern medium-speed dual-fuel engines can achieve thermal efficiencies of 44–48% while producing identical power output in both gas and diesel modes. When operating on natural gas, these engines typically comply with IMO Tier III nitrogen oxide limits without requiring selective catalytic reduction systems. Sulfur oxides and particulate matter emissions are nearly eliminated in gas mode due to the sulfur-free nature of natural gas fuel.

Integrated safety architectures—including double-walled ventilated gas piping, gas detection networks, independent safety PLC systems, nitrogen purging arrangements and automated fuel changeover systems—provide multiple layers of protection against gas leakage or combustion instability.

With thousands of engines now operating globally in cruise ships, ferries, offshore vessels and diesel-electric propulsion plants, medium-speed dual-fuel engines have reached technological maturity. Their ability to combine operational flexibility, environmental compliance and high efficiency makes them a key propulsion solution during the maritime sector's transition toward lower-carbon fuels.

Keywords: Medium-speed dual-fuel engine, marine propulsion, lean-burn combustion, low-pressure gas admission, micro-pilot ignition, Wärtsilä 46DF, MAN 51/60DF, Hyundai HiMSEN H27DF, Fuel Ratio Control (FRC), methane slip, Tier III NOx, gas valve unit (GVU), marine LNG propulsion, combustion monitoring systems, safety shutdown hierarchy.



FGSS system

> *Dual-fuel engines bridge today's fuels and tomorrow's energy*

1. Introduction

The maritime industry is undergoing a major technological transition driven by environmental regulation, fuel cost considerations and global decarbonisation goals. Regulations under MARPOL Annex VI require substantial reductions in nitrogen oxide emissions, sulfur oxides, particulate matter and greenhouse gas emissions from ships. In response to these regulatory pressures, dual-fuel engine technology has emerged as a practical and commercially viable propulsion solution.

Marine dual-fuel engines are capable of operating on both gaseous fuels—typically natural gas in the form of liquefied natural gas (LNG)—and conventional liquid fuels such as marine gas oil or heavy fuel oil. This capability provides operators with operational flexibility while enabling significant reductions in pollutant emissions during gas-mode operation.

Medium-speed four-stroke dual-fuel engines represent a particularly important segment of the marine propulsion market. These engines are widely used in cruise ships, ferries, offshore support vessels, tugs and diesel-electric propulsion plants where rapid load response and flexible power generation are essential.

Modern medium-speed dual-fuel engines typically operate between 500 and 1,000 rpm and are configured with between six and eighteen cylinders. The engines use turbocharging and charge-air cooling systems to achieve high power density and thermal efficiency.

One of the defining features of modern dual-fuel engines is their use of lean-burn gas combustion. In gas mode, natural gas is mixed with air before entering the cylinder, creating a homogeneous air-fuel mixture. Because methane has a high auto-ignition temperature, combustion cannot occur through compression alone. Instead, ignition is initiated by injecting a small quantity of diesel fuel—referred to as pilot fuel—directly into the cylinder.

Earlier generations of dual-fuel engines used pre-combustion chambers to ignite the gas mixture. In this configuration, pilot fuel was injected into a small pre-chamber where combustion began before propagating into the main combustion chamber. Although effective, this approach introduced additional heat losses and mechanical complexity.

Modern engines have largely replaced pre-chamber ignition with direct in-cylinder pilot injection. This design simplifies the combustion chamber, improves combustion efficiency and allows higher peak cylinder pressures to be achieved.

Representative examples of modern medium-speed dual-fuel engines include:

- MAN Energy Solutions 51/60DF
- Wärtsilä 46DF
- Hyundai HiMSEN H22CDF and H27DF

These engines employ similar combustion principles but differ in their specific fuel system architectures, control strategies and mechanical configurations.

2. Combustion System Architecture

2.1 Lean-Burn Gas Combustion

In gas mode operation, dual-fuel engines follow a thermodynamic cycle similar to the Otto cycle rather than the conventional diesel cycle.

During the intake stroke, natural gas is admitted into the intake air stream through electronically controlled gas admission valves. The gas mixes with air in the intake manifold or intake ports to form a homogeneous lean mixture.

The mixture is then compressed during the compression stroke. Because methane has a relatively high auto-ignition temperature, the mixture does not ignite under compression alone. Instead, ignition is initiated by injecting a small quantity of diesel pilot fuel directly into the combustion chamber.

The pilot injection typically represents between one and five percent of the total fuel energy input. Once the pilot fuel ignites, a flame kernel forms and propagates through the lean gas-air mixture, completing the combustion process.

Lean-burn combustion offers several important advantages:

- Reduced peak flame temperature
- Lower nitrogen oxide formation
- Improved thermal efficiency
- Stable combustion over a wide load range

Typical operating lambda values for gas mode range between 1.4 and 1.8, meaning the engine operates with significant excess air.

2.2 Combustion Chamber Design

Modern dual-fuel engines use combustion chambers optimised for lean-burn operation.

Typical design parameters include:

Compression ratio: 13.5–14.0

Swirl ratio: 1.5–2.5

Squish clearance: approximately 1 mm

The piston crown geometry is designed to promote turbulence and efficient mixing within the combustion chamber. Two-piece piston designs are commonly used, consisting of a forged steel crown and a cast-iron skirt.

Additional design features include flame rings and anti-polishing rings that protect the cylinder liner and reduce wear.

Valve arrangements typically include two intake valves and two exhaust valves, along with one or more gas admission valves integrated into the cylinder head.

3. Gas Fuel Supply and Admission Systems

3.1 Low-Pressure Gas Admission

Most medium-speed dual-fuel engines use low-pressure gas admission systems.

In these systems, gas is supplied to the engine at pressures typically between 4 and 16 bar. The gas is injected into the intake air stream through electronically controlled gas admission valves.

The low-pressure concept offers several advantages:

- Reduced infrastructure complexity
- Lower system cost
- Improved safety due to lower gas pressure
- Reduced risk of gas leakage

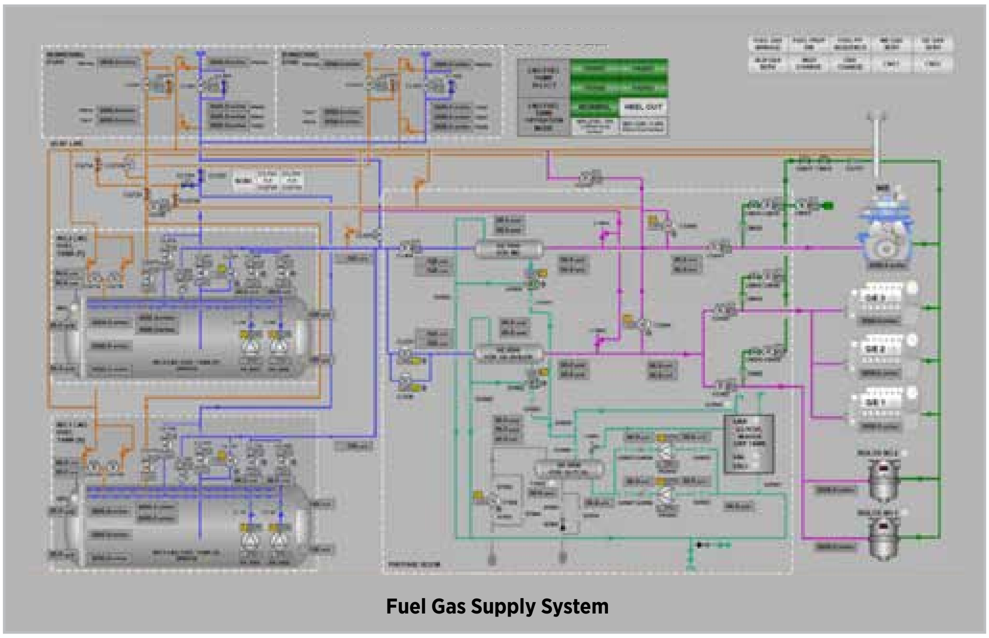
The gas supply system typically includes filters, pressure regulators, flow meters and a gas valve unit that isolates the gas supply during emergency conditions.

3.2 Pilot Fuel Injection System

Modern dual-fuel engines use common-rail pilot fuel injection systems.

Pilot fuel injection pressures typically range between 900 and 1,300 bar. Electronic control allows precise adjustment of injection timing and quantity for each cylinder.

> “
> *Lean-burn combustion meets Tier III without SCR*
> ”



Fuel Gas Supply System

Cylinder pressure sensors and knock detection systems provide feedback to the engine control system, allowing real-time optimisation of combustion.

This closed-loop control architecture improves combustion stability and reduces the risk of knocking or misfiring.

4. Engine Control and Combustion Monitoring

4.1 Distributed Engine Control Systems

Modern dual-fuel engines employ distributed digital control systems consisting of several hierarchical levels.

The central engine controller manages overall engine speed, load control, fuel mode selection and alarm handling.

Cylinder control units are installed at each cylinder and manage gas admission timing, pilot fuel injection and combustion monitoring.

Independent safety controllers operate separately from the main engine control system and monitor critical safety parameters such as gas leakage and ventilation failure.

4.2 Fuel Ratio Control

Fuel Ratio Control (FRC) is a key feature of lean-burn dual-fuel engines. The system maintains stable combustion by controlling the air-fuel equivalence ratio.

Lambda is calculated using measurements of scavenge air flow, gas flow rate and pilot fuel injection quantity.

If the mixture becomes too rich, the system reduces gas admission duration or increases air supply.

If the mixture becomes too lean, the system increases gas admission or adjusts pilot fuel injection.

These adjustments maintain combustion stability while ensuring optimal efficiency and low emissions.

4.3 Abnormal Combustion Detection

Dual-fuel engines continuously monitor combustion parameters to detect abnormal conditions.

Pre-ignition is detected by analysing cylinder pressure signals during the compression phase. If pre-ignition occurs, corrective actions may include increasing pilot fuel injection, retarding gas admission timing, or switching the affected cylinder to diesel mode.

The control system also monitors the rate of pressure rise during combustion. Excessive pressure rise may indicate knocking or overly rapid combustion.

If pressure rise limits are exceeded, the system increases pilot fuel injection and adjusts combustion timing to moderate the combustion process.

5. Safety Architecture and Protection Systems

Safety is a critical aspect of dual-fuel engine design because natural gas is flammable and must be handled with strict control measures.

Modern dual-fuel engines incorporate several layers of safety protection.

5.1 Gas Detection and Ventilation

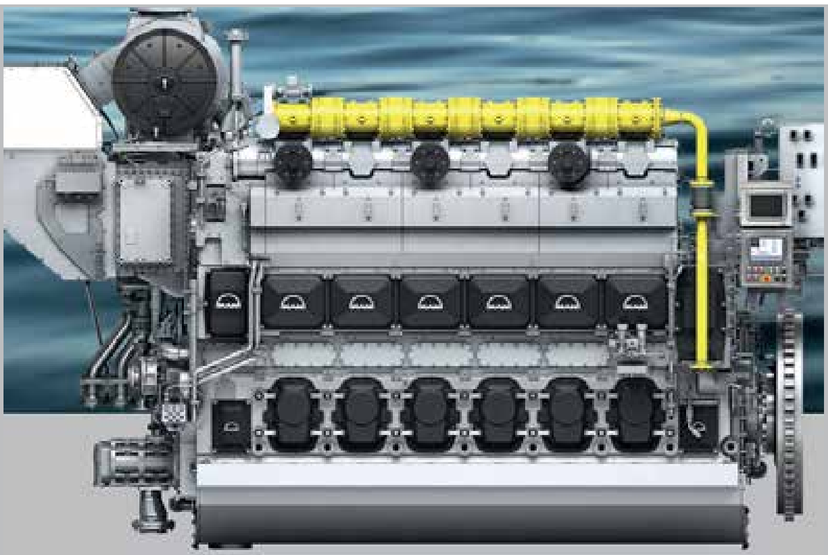
Gas detection sensors are installed at multiple locations throughout the engine room and gas handling equipment.

If hydrocarbon gas is detected above predefined thresholds, alarms are generated and gas supply systems may be automatically isolated.

Ventilation systems ensure that gas cannot accumulate within enclosed spaces.

5.2 Nitrogen Purging Systems

Nitrogen purging systems are used to remove residual gas from pipelines and fuel system components.

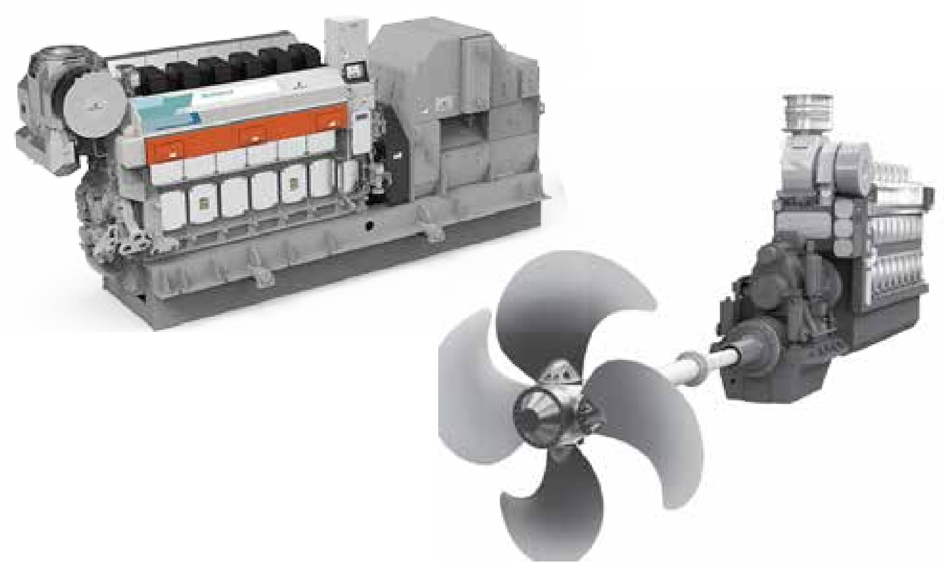


Stroke engines from MAN B&W

> ***Micro-pilot ignition stabilises lean gas combustion***

> *Advanced controls prevent knock, misfire and pre-ignition*

Stroke engines from Wartsila



Purging cycles typically involve pressurising the system with nitrogen, venting the gas-nitrogen mixture and repeating the process until hydrocarbon concentration falls below safe limits.

5.3 Safety Shutdown Hierarchy

Dual-fuel engines employ a multi-level safety shutdown hierarchy.

Level 1 – Alarm

Minor deviations generate operator alarms without interrupting engine operation.

Level 2 – Gas Standby

The system prepares for possible gas shutdown while maintaining readiness for diesel operation.

Level 3 – Gas Stop

Gas supply is isolated and the engine switches automatically to diesel operation.

Level 4 – Emergency Gas Shutdown

Severe hazards such as gas leakage trigger immediate isolation and depressurisation.

Level 5 – Engine Shutdown

Critical engine protection events lead to complete engine shutdown.

6. Performance Characteristics

Modern medium-speed dual-fuel engines demonstrate performance comparable to conventional diesel engines.

Typical characteristics include:

Power output: identical in gas and diesel modes

Thermal efficiency: 44–48% in gas mode

Specific energy consumption: 7,700–8,200 kJ/kWh

Emission performance is significantly improved when operating on natural gas.

- Sulfur oxides are nearly eliminated because natural gas contains negligible sulfur.
- Particulate matter emissions are reduced by more than 90%.
- Nitrogen oxide emissions are typically below 2 g/kWh, allowing compliance with IMO Tier III limits without exhaust after-treatment systems.
- Carbon dioxide emissions are reduced by approximately 20–25% due to the lower carbon content of methane.

Conclusions

Medium-speed four-stroke dual-fuel engines represent a mature and highly capable propulsion technology for modern ships.

The transition from pre-chamber ignition to direct in-cylinder pilot injection has significantly improved combustion efficiency, reliability and emissions performance. Combined with low-pressure gas admission systems and advanced electronic control architectures, these engines deliver high efficiency and operational flexibility.

The ability to switch seamlessly between natural gas and conventional liquid fuels provides ship operators with important operational resilience. At the same time, gas-mode operation offers major environmental advantages including reduced nitrogen oxide emissions, negligible sulfur emissions and lower carbon dioxide output.

Integrated safety systems—including gas detection networks, double-walled piping, nitrogen purging systems and multi-level shutdown hierarchies—ensure that gas fuel can be handled safely in marine environments.

With widespread deployment across cruise ships, ferries, offshore vessels and LNG carriers, medium-speed dual-fuel engines have become a central component of the maritime sector's energy transition. Future developments are expected to include further reductions in methane slip, integration with hybrid propulsion systems and adaptation for alternative fuels such as bio-LNG, ammonia and synthetic methane.

These advancements will allow dual-fuel engines to remain an important propulsion technology as the maritime industry moves toward low-carbon and eventually zero-carbon shipping.

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