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TRANSFORMING SHIPPING THROUGH Technology and Sustainability

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Editorial

"It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change." — *Charles Darwin*

Maritime Resilience in an Uncertain World

The events of 2026 have reaffirmed that the sea remains both the lifeline of global commerce and a stage for geopolitical uncertainty. The recent conflict involving the United States and Iran, together with renewed tensions in the Strait of Hormuz, once again exposed the vulnerability of global supply chains. Merchant ships, ports, insurers, energy cargoes and, above all, seafarers found themselves at the centre of crises beyond their control. The disruption of a single strategic waterway demonstrated how regional instability can rapidly affect freight markets, energy security and international trade.

Alongside these challenges, shipping continues to undergo a profound technological and environmental transformation. The adoption of the non-mandatory International Code for Maritime Autonomous Surface Ships (MASS Code) at MSC 111 marks a significant step towards autonomous and remotely operated vessels, allowing valuable operational experience before mandatory implementation later this decade.

MEPC 84 further reinforced that maritime decarbonisation is an irreversible global priority. India's Carbon Credit Trading Scheme (CCTS), expected to become operational later this year, represents an important milestone in developing a domestic compliance carbon market aligned with the Paris Agreement. Continued progress in greenhouse gas reduction, alternative fuels, energy efficiency and environmental protection will increasingly shape the competitiveness of the maritime sector.

Technology, however, must always serve people. Artificial intelligence should remain transparent, explainable and human-centric, while autonomous shipping must preserve clear human accountability. Cybersecurity, robust regulations, resilient infrastructure and comprehensive training will be essential to safely navigate the transition to low- and zero-carbon shipping.

This edition of *Marine Engineers Review* reflects these priorities through articles on advanced turbocharging, cognitive digital twins, AI-assisted decision-making, sustainable ship recycling and electromagnetic propulsion. As maritime engineering embraces innovation, our success will ultimately depend on balancing technology with safety, sustainability, ethics, accountability and international collaboration.

The August 2026 issue highlights maritime innovation, sustainability, and engineering excellence shaping the future of global shipping.

We begin with a look at a century of marine turbocharger evolution. Kaushal Patel traces its contribution to engine efficiency, emissions compliance and sustainable propulsion.

This is followed with responsible ship recycling, where GMS Leadership examines the fourth pillar of sustainable shipping through ESG, the circular economy, the Hong Kong Convention and Extended Producer Responsibility.

Venkat Krishna explores Artificial Intelligence at sea, emphasising how AI can complement rather than replace seafarers by combining data-driven insights with human judgement and governance.

We then examine the potential of Magnetohydrodynamic (MHD) and Electrohydrodynamic (EHD) propulsion for quieter, more sustainable marine operations, alongside the technical challenges facing wider adoption.

Safety takes centre stage as Capt. Gajanan presents forensic engineering approaches to gasket and flange failures, highlighting how root-cause analysis can strengthen engineering practices and prevent recurrence.

The issue also features Chaitanya, an AI-powered Cognitive Digital Twin developed by NIOT for the Matsya6000 submersible, supporting predictive decision-making and crew safety in deep-ocean missions.

This issue also brings highlights from three IRS–CEMS technology conclaves covering AI, XR, advanced engineering, innovation and skill development, aligned with India's Maritime Amrit Kaal Vision 2047.

We hope this issue informs, inspires, and stimulates thoughtful discussion as the maritime industry navigates an era of rapid technological change and sustainable transformation.

Happy reading!

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From Power Boosters to Emissions Busters: The Evolution of The Modern Marine Turbocharger

Kaushal Patel

Abstract

Marine turbocharging has undergone a remarkable transformation over the past century, evolving from a technology primarily intended to increase engine power into a critical enabler of fuel efficiency, emissions compliance and operational flexibility. Beginning with Alfred Büchi's pioneering concept and the commercialization of the first heavy-duty marine turbocharger by Brown Boveri & Co. (BBC) in 1924, successive innovations have continuously addressed the changing priorities of the shipping industry. Initially driven by the demand for higher propulsion power, turbocharger development later focused on minimizing fuel consumption following global oil crises and, more recently, on meeting increasingly stringent environmental regulations under IMO MARPOL Annex VI, EEXI, CII and FuelEU Maritime.

This article traces the technological evolution from the early VTR series to modern Accelleron platforms, highlighting advancements such as higher-pressure ratios, wider compressor maps, sequential turbocharging, Engine Part-Load Optimization (EPLO), two-stage turbocharging and digital condition monitoring. It also examines how modern turbochargers support emerging combustion technologies including Miller timing, Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR) and future alternative fuels. The paper demonstrates that turbochargers have become integral components of the decarbonisation pathway, enabling marine engines to achieve improved efficiency, lower emissions, enhanced operational flexibility and reduced lifecycle maintenance costs. As shipping transitions toward carbon-neutral operations, turbocharger technology will remain one of the industry's most important enablers of sustainable propulsion.

Keywords: Marine Turbocharging; Accelleron; Turbocharger Evolution; Two-Stroke Marine Engines; Four-Stroke Marine Engines; Miller Timing; Exhaust Gas Recirculation (EGR); Selective Catalytic Reduction (SCR); IMO MARPOL Annex VI; NOx Emissions; Energy Efficiency Existing Ship Index (EEXI); Carbon Intensity Indicator (CII); FuelEU Maritime; Sequential Turbocharging; Engine Part-Load Optimization (EPLO); Compressor Map Matching; Decarbonisation; Alternative Marine Fuels; Digital Condition Monitoring; Marine Propulsion.

Introduction

Since the beginning of the twentieth century, turbocharging has fundamentally transformed marine diesel engine technology by recovering waste exhaust energy to improve engine performance and efficiency. What began as an innovative method to increase engine power has gradually evolved into one of the most critical technologies supporting modern maritime decarbonisation. The commercialisation of the first heavy-duty exhaust gas turbocharger by Brown Boveri & Co. (BBC) in 1924 marked the beginning of a technological journey that has continuously adapted to the changing operational, economic and environmental priorities of the global shipping industry.

During the early decades of marine diesel engine development, turbochargers primarily enabled higher engine outputs by increasing the amount of combustion air supplied to the cylinders. This significantly improved power density and eliminated the need for mechanically driven scavenging pumps, thereby revolutionising large two-stroke propulsion engines. As fuel prices escalated during the oil crises of the 1970s and subsequent periods of high bunker costs, industry priorities shifted from maximising engine power to optimising fuel consumption. Turbocharger manufacturers responded with improved compressor efficiencies, innovative cartridge-based designs and enhanced serviceability that substantially reduced operating costs.

The twenty-first century introduced a new challenge: environmental sustainability. Successive IMO emission regulations, particularly MARPOL Annex VI Tier I, II and III requirements, together with EEXI, CII and regional regulations such as FuelEU Maritime, have significantly altered engine design philosophies. Modern turbochargers now play an essential role in enabling advanced combustion technologies including Miller timing, Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR) and sequential turbocharging while maintaining high efficiency across an increasingly wide operating range. These developments have made turbochargers indispensable components in reducing both fuel consumption and greenhouse gas emissions.

This article reviews the technological evolution of marine turbochargers from their origins to the latest high-efficiency platforms. It discusses the engineering innovations that have enabled higher pressure ratios, improved compressor map flexibility, optimised part-load operation, digital condition monitoring and compatibility with future low- and zero-carbon fuels. The paper illustrates how the modern marine turbocharger has evolved from a simple power-boosting device into a sophisticated system that supports reliability, efficiency, emissions reduction and the long-term decarbonisation objectives of global shipping.

When the first commercially manufactured turbocharger was developed by Accelleron's predecessor Brown Boveri & Co (BBC) in 1924, the technology began a journey that has kept pace with industrial demands for power and efficiency for more than a century so far. Originally designed to facilitate increased engine power output, today's turbochargers must now support a wide spectrum of needs, from reducing maintenance demand to helping cut air pollutants to handling emerging fuels.

No industry better reflects this development path than the global maritime market, where the shifting priorities of ship operators have continuously redefined what they need from their turbochargers – first through fierce competition, then a relentless focus on fuel costs and later through emissions compliance and energy efficiency demands.

Ahead of its time

The idea of turbocharging arrived before the materials that could make it a reality. In 1905, Swiss engineer Alfred Büchi patented a compound engine in which an exhaust-driven turbine and a compressor shared a common shaft. This turbine-compressor combination recovered energy from the exhaust stream, forcing more air into the cylinders to produce more power.

BBC's engineers cracked the metallurgy problem in June 1924 with the VT402, the world's first heavy-duty exhaust-gas turbocharger. Marine application followed almost immediately on the German liners *Preussen* and *Hansestadt Danzig*, each with a pair of ten-cylinder four-stroke engines carrying BBC turbochargers. The addition of turbocharging increased each ship's engine output from around 1,750bhp to 2,500bhp – a transformative power boost for shipowners competing on deadweight and speed.

By the mid-1950s the turbocharger had become and remains, standard equipment on every marine engine built. The enabler was BBC's groundbreaking VTR series of turbochargers, reaching a compression ratio of 2:1 and turbocharger efficiency of 56% overall – enough to turbocharge the big two-stroke engines that still relied on engine-driven scavenging pumps.

Removing those pumps – and enabling ever more powerful engine designs – required further advances in both turbocharger technologies and compression capability. Across the next two decades, boost pressure climbed from about 1.35 bar to as much as 6.5, multiplying an engine's base power output by several times.

Focus on efficiency

If the first half century of marine turbocharging was about increasing engine power, the second was about reducing the cost of producing it. The oil shocks of

the 1970s and the surging fuel prices after 2008 made bunker fuel the dominant cost for ship operators. For turbochargers, that changed the game; power still mattered, but the number of grams of fuel needed to generate every kilowatt-hour was even more important.

The response of ABB Turbo Systems – formed after Swedish company Asea merged with BBC to become ABB in 1988 - was to develop the TPL series. Launched in 1996, it abandoned the VTR series' water-cooled gas-side casings with heat shielding intermediate walls, keeping gas temperature higher and delivering more power to the compressor. As a result, turbocharger efficiency climbed from the 50–55% of 1950s BBC units to around 74.7% for ABB units in 1989. For ship operators, each percentage point gain equated to lower fuel spend.

The second idea behind TPL was architectural. Every TPL was built around a central cartridge carrying the rotor between flange-connected casings. That meant the whole machine could be dismantled with the exhaust pipes left in place - a serviceability advantage that offered dramatic operating cost reductions for operators already battling higher fuel costs. And, as it would turn out, a fundamental design shift that paved the way for the operational and fuel flexibility demanded of today's turbochargers.

Enter the emissions era

The focus on fuel efficiency laid the foundation for turbocharging's role in the decarbonisation drive that characterises modern shipping. But other emissions regulations, coming a decade before EU and IMO greenhouse gas and energy intensity regulations, would shift the turbocharger beyond its role as a power and efficiency device.

When IMO MARPOL Annex VI NOx limits came into force – Tier I for ships built from 2000, tighter Tier II limits from 2011 and even lower limits under Tier III in designated areas from 2016 – turbochargers needed to accommodate new engine design and operational realities.

On the engine design side, a focus on NOx emissions meant finding ways to reduce high combustion temperatures that increase the formation of nitrogen oxides. The most widely adopted strategy involved limiting the amount of air coming into the cylinder – either through Miller timing on four-stroke engines, or by varying the timing of exhaust valve opening on two-stroke engines. Both require turbochargers with higher compression ratios.

In the case of four-stroke engines using extreme Miller timings, the required compression ratios exceeded those achievable by a single turbocharger, leading to the development of two-stage turbocharging - combining a large low-pressure turbocharger in series with a smaller high-pressure one in order to reach the pressure ratios that strong Miller timing needs.

Accelleron's Power2 system, for example, was introduced in 2010 and remains a key technology for four-stroke marine engines that need to operate within tight NOx thresholds. It lifts turbocharging efficiency to above 75%, supporting a pressure ratio of up to 12:1 and potentially saving more than 10g/kWh on fuel consumption.

Axial vs radial: two concepts, one job

In every marine turbocharger the compressor is a centrifugal, or radial, machine. Air enters along the shaft and is flung outwards through a diffuser to build pressure. That part has barely changed in a century. The design that matters sits on the turbine side; it is governed almost entirely by exhaust volume flow (depending largely on the size and power of the engine).

In a radial-inflow turbine, the exhaust gas enters radially to the shaft - striking the turbine and then turning ninety degrees before exiting along the shaft. Compact and able to deliver a high-pressure ratio per stage at modest flow, it suits smaller, faster engines. In Accelleron's range, radial turbochargers include the A100-M and A100-H for medium- and high-speed four-stroke and gas engines – the latest A200-H reaching pressure ratios up to 6.5:1 – together with the compact MXP units for small-bore auxiliaries.

An axial turbine, by contrast, passes exhaust gas straight through the blading, parallel to the shaft. It excels at very high-volume flow with high efficiency at large size, so it dominates the big, slow two-strokes and the largest four-strokes. This is Accelleron's axial line: the A100-L and A200-L and now the ACCX300-L, covering two-stroke bores from roughly 30 to 95 cm.

Supporting effective after-treatment

New auxiliary machinery introduced to meet NOx requirements – specifically exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) - also affected turbocharger development.

EGR recirculates cooled exhaust to dilute the air charge and lower flame temperature. But on a two-stroke engine, where the scavenge pressure exceeds the exhaust pressure, gas must be actively pumped back. This is often achieved with an electrically driven blower, bringing an energy cost that again needs to be offset by more efficient turbochargers and different turbocharging strategies.

For SCR, the turbocharger's position defines the system. As the optimal position for a good catalytic reaction is directly in the stream of the hot exhaust, on two-stroke engines the SCR reactor most often sits in a high-pressure position before the turbocharger to achieve optimal exhaust temperature for a catalytic reaction. This location for the SCR results in a drop in pressure of air reaching the turbocharger and an increase of back-pressure between the exhaust receiver and the cylinder. This means that the piston must work harder to generate the same power, while a reduced scavenging margin decreases the efficiency of the engine. The fuel consumption penalty is exacerbated at low loads, when exhaust temperature falls below the point that ignites a catalytic reaction. In these cases, a cylinder bypass must feed warm scavenge air to the turbine inlet.

The answer, in all cases, is more boost from the turbocharger – achieved through increased efficiency and by rematching the turbine blade area for the lower intake pressure. Facing those emerging operational and design changes, the successor to the TPL turbocharger series had a clear brief. The A100-L was launched in 2011, as the first IMO NOx limits came into force. It pushed single-stage turbocharging pressure ratios to 5:1 at around 75% efficiency, with exceptionally wide compressor maps – giving engines the extra margin needed for Miller timing, EGR and SCR.

The wide compressor maps of the A100-L and A200-L (launched in 2013, three years ahead of IMO's Tier II NOx requirements) also supported the de-rating of engines that had become more popular under slow steaming – and that would become more important still under incoming IMO regulations on energy efficiency. As the focus shifted further from power to efficiency, ship operators needed a flexible turbocharger that was not only efficient at high engine loads but that could be rematched to part-load requirements.

Optimising part-load performance

Meeting both the increased efficiency requirement of NOx compliance and the part-load operation of slow steaming placed unprecedented demand on modern turbochargers. One strategy to achieve this was via sequential turbocharging with a turbocharger cut-out. Parallel turbochargers allow one unit to be bypassed or cut-out, delivering efficient turbocharging at low engine loads. In the case of a simple turbocharger cut-out, this is a permanent change, used when load demand is always low. In cases where flexibility is required in order to switch between low and high load demands, an automated cut-out/cut-in system is required, such as Accelleron's FiTS2 sequential turbocharging concept. This combines variably specified turbochargers and wide compressor maps with automated cut-out at low and part loads, letting an engine adapt quickly when a vessel's engine load changes.

Part-load optimisation is particularly in demand today, driven by IMO's Carbon Intensity Indicator (CII) and Energy Efficiency Index for Existing Ship (EEXI), alongside increasing carbon costs under FuelEU Maritime and other incoming regulations. The simple compliance solution for CII and EEXI, to limit engine power, leaves engines operating far from their optimal efficiency unless engine and turbocharger tunings are also adapted. In these cases, less power generation cuts absolute fuel consumption but increases the cost of each unit of power the operator produces.

FiTS2 is one strategy that can support this. Another, for vessels facing a permanent change in operating profile and without turbocharger cut-out capability, is Accelleron's Engine Part-Load Optimization (EPLO) service. This upgrade adapts to the specific case and can include re-matching or cutting out turbochargers as well as adjusting the engine's fuelling, injection and exhaust valve timing. The result is that engine and turbocharger are more efficient at the new lower load.

On Hapag-Lloyd's 14,000-TEU sister ships *Basle Express* and *Essen Express*, EPLO with a fixed cut-out on one turbocharger returned fuel savings above 10 g/kWh (equating to about 5% in the relevant load ranges) with commissioning completed just four weeks after the order. The upgrade program with Hapag-Lloyd has since been extended across the rest of the vessel class, joining more than a hundred vessels to date that have been contracted for an EPLO upgrade.

From compressor map to engine map

A compressor map is a turbocharger's performance fingerprint. It plots pressure ratio against air flow, overlaid with islands of constant efficiency and lines of constant rotor speed. Two limits bound it: the surge line on the left, where flow becomes unstable and the choke line on the right, where no more air will pass. The usable area between them is what engineers mean by a map's "width".

An engine has its own operating line – the sequence of flow-and-boost points it demands as load and speed change, from idle to full power. Matching is the work of laying that operating line onto the compressor map so that it runs through the high-efficiency islands while keeping a safe margin from both surge and choke across the whole range.

This is why map width has become so valuable. A narrow map can be tuned to sit efficiently at a single design point, usually full load, but drifts towards surge or poor efficiency as the engine is de-rated or slowed. A wide map – the hallmark of the A100-L, A200-L and ACCX300-L – keeps the turbocharger efficient as the operating line moves, which is what makes slow steaming, Miller timing, EGR back-pressure and turbocharger cut-out workable without surging.

Re-matching – changing the turbine area or nozzle rings, trimming the compressor, or cutting out a unit – shifts the engine's operating line back into the best part of the map when its duty changes for good. That is the mechanism behind both FiTS2 and EPLO.

Advancing into the unknown

The call for flexibility in modern turbochargers - to accommodate low-load optimisation for slow steaming and engine power limitation alongside increased high-load efficiency for NOx compliance measures – is answered by the wide maps and high-pressure ratios of the A100-L and A200-L. Looking to the future, those demands will only grow. Energy efficiency requirements will continue to increase, whether through IMO regulations or further regional intervention. And operational efficiency will likely become an even higher priority for ship operators working to stretch constrained profit margins amidst increasing fuel prices and evolving trade constraints.

It was with these challenges in mind that the latest generation of turbochargers for two-stroke marine engines was conceived. The ACCX300-L inherits the advantages of the A100/200-L series and pushes them further. Specific volume flow is raised by more than 20% compared to the A200-L, while the compressor map is pushed to above 5:1 - with high efficiency held across the load profile.

Aside from the increased power density, the platform's modular concept also has a significant impact on both serviceability and installation flexibility. Common components and standardised interfaces used across the fewest possible frame variants reduces supply chain complexity, increases spare part availability and gives flexibility in both design and installation configuration. That flexibility, combined with even higher power density, enable the TWIN concept, whereby just two frame sizes can serve high engine powers with smaller, lighter units - and more freedom in how they are arranged on the engine.

The new platform is also built around an exchangeable cartridge carrying all the rotating parts, which can be removed from the cold side and replaced from a pool of new or refurbished units in an estimated twelve hours during an ordinary port call. Combined with a digital-ready design that enables condition monitoring and easy troubleshooting, those features translate to a notable reduction in maintenance and service requirements for cash-constrained operators.

The wheel turns again

A century on, the machine that Büchi sketched and BBC made real is doing a job its inventors would barely recognise. It began as a way to turn wasted exhaust energy into power. It became an instrument of fuel economy when bunker prices came to dominate ship operators' costs. And it is now an essential emissions component – enabling both NOx compliance and energy efficient operation at low loads. The line of turbocharger innovators from BBC through to Accelleron have been present at every turn.

The next turn of the wheel will include further decarbonisation - including the fuels that will deliver it – and a continued focus on simplifying operations for

ship companies and crews under pressure. With the latest technologies, upgrades and services already designed with these challenges in mind – aligned to ever-expanding digital capabilities for optimising performance and maintenance – ship operators will continue to rely on the essential and evolving role of the marine turbocharger.

Conclusion

The evolution of marine turbocharging mirrors the broader transformation of the maritime industry itself. Over the past century, turbochargers have progressed from simple exhaust energy recovery devices designed to increase engine power into highly engineered systems that are central to modern marine propulsion, fuel efficiency, emissions compliance and operational optimisation. Successive technological advancements have enabled higher pressure ratios, wider compressor operating ranges, improved serviceability and greater flexibility under varying engine loads, allowing ship operators to meet increasingly demanding economic and environmental objectives.

Modern turbochargers have become indispensable enablers of advanced combustion strategies such as Miller timing, Exhaust Gas Recirculation, Selective Catalytic Reduction, sequential turbocharging and engine derating for slow steaming. Furthermore, digital monitoring capabilities, modular cartridge designs and part-load optimisation services significantly reduce maintenance requirements while improving engine availability and lifecycle performance. These innovations have ensured that turbochargers remain compatible with evolving regulatory frameworks including IMO MARPOL Annex VI, EEXI, CII and regional decarbonisation initiatives.

Looking ahead, the transition toward low-carbon and zero-carbon fuels—including methanol, ammonia, hydrogen and other alternative energy carriers—will require even greater adaptability from turbocharging systems. Future developments will focus not only on higher efficiency and lower emissions but also on intelligent diagnostics, predictive maintenance, operational flexibility and seamless integration with increasingly digitalised engine management systems. As shipping continues its journey toward net-zero emissions, the marine turbocharger will remain a cornerstone technology, transforming exhaust energy into cleaner, more efficient and more sustainable propulsion while supporting the industry's long-term environmental and commercial objectives.

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SUSTAINABLE SHIP & OFFSHORE RECYCLING - The Fourth Pillar of Shipping

How Responsible Ship Recycling Anchors the ESG Agenda and Closes the Circular-Economy Loop

Anand Hiremath
Kiran Thorat
Nayeem Noor

Abstract

Shipping's sustainability discourse has long orbited three pillars — shipbuilding, operation and maintenance & repair — while its end-of-life stage remained an externality. We argue that ship recycling is the industry's indispensable fourth pillar: the point at which a vessel's embodied steel re-enters the economy and where the environmental, social and governance (ESG) commitments made across a ship's operating life are ultimately tested. Drawing on 2025 UNCTAD data confirming India as the world's largest ship recycling nation, the entry into force of the Hong Kong Convention and the disclosed ESG positions of blue-chip tonnage providers, we show that responsible recycling is simultaneously the purest expression of the circular economy in heavy industry and a decisive test of shipowner ESG credibility. We conclude that only an inclusive model grounded in Extended Producer Responsibility (EPR) can align the incentives of owners, cash buyers, recyclers and financiers.

1. Introduction: Naming the Fourth Pillar

Every ship is built to be recycled. A merchant vessel is engineered for a working life of roughly two to three decades, after which the same physical asset that carried global trade becomes a dense, mobile reserve of high-grade steel and reusable equipment. Yet in the architecture of maritime sustainability, the end-of-life stage has habitually been treated as a footnote — an inconvenient postscript to the celebrated stories of newbuilding, operation and repair. This framing is no longer tenable. As the global fleet ages and decarbonisation accelerates fleet renewal, the volume, visibility and value at stake in dismantling ships have grown to the point where recycling must be recognised as a **fourth pillar of shipping**, structurally equal to the three that precede it.

The reason is not merely rhetorical. Over 95% of a vessel's lifecycle carbon is emitted during operation, but as ships shift to zero- and low-carbon fuels, the embodied emissions of steel — in construction and in recycling — will command a far larger share of the lifecycle footprint. Ship recycling is where that embodied value is either recovered or squandered. It is also where the human-rights, occupational-safety and environmental commitments an owner makes in glossy ESG reports meet their most searching test: the beach, the yard and the workers who cut the steel. The fourth pillar, in other words, is where ESG stops being a disclosure and becomes a practice.

2. India: The World's Largest Ship Recycling Nation

The centre of gravity of this fourth pillar sits in South Asia and, as of 2025, unambiguously in India. According to the United Nations Conference on Trade and Development (UNCTAD), India's share of global ship recycling rose to **35.4% in 2025, up from 30.1% in 2024**, while the volume recycled climbed nearly 60% — from 1.86 million to 2.99 million gross tons in a single year. With this, India became the world's number-one ship recycling nation, achieving a headline target of the Maritime India Vision 2030 five years ahead of schedule.

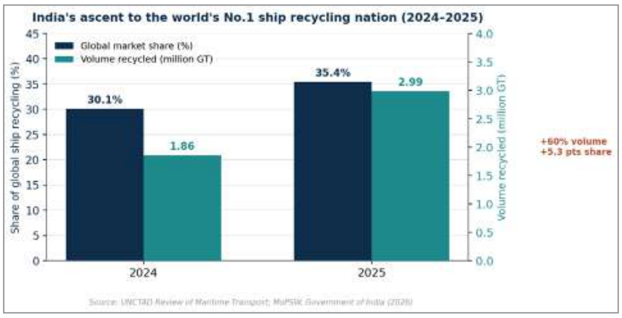

Figure 1. India's market share and recycled volume, 2024 vs 2025 (UNCTAD; MoPSW).

This leadership is anchored by the Alang–Sosiya cluster in Gujarat, widely regarded as the single largest ship recycling location on earth and underpinned by regulatory reform. The Recycling of Ships Act, 2019 aligned India's framework with the Hong Kong Convention; India ratified the Convention the same year; and the government has since layered on financial support, a Ship-breaking Credit Note Scheme worth 40% of scrap value and a master plan to nearly double capacity to roughly 9 million light displacement tons through the expansion of Alang. With the Baltic and International Maritime Council (BIMCO) projecting that more than 16,000 vessels will be recycled globally over the next decade, India is structurally positioned to handle 500–600 large vessels a year. The strategic question is no longer whether India leads, but whether that leadership is exercised responsibly — and made visible to the stakeholders who now demand it.

3. The Purest Circular Economy in Heavy Industry

If the circular economy has a flagship in heavy industry, it is ship recycling. A modern circular-economy framework distinguishes value-retention options in a hierarchy - reduce, reuse, refurbish, recycle - and a well-run recycling yard operates across all four simultaneously. Steel constitutes 75–85% of a vessel by mass; machinery, navigation and safety equipment, furniture, cabling and non-ferrous metals make up most of the remainder. In a competent yard, more than 98% of that mass is returned to productive use rather than landfilled.

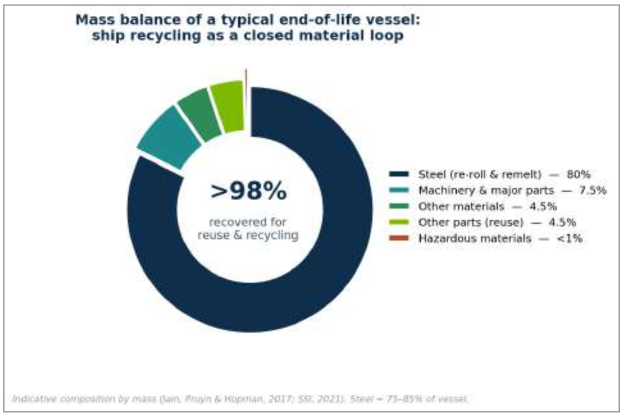

Figure 2. Indicative mass balance of an end-of-life vessel — a near-closed material loop.

The environmental case is compelling and quantifiable. Steel is infinitely recyclable without loss of properties and it is the most recycled material in the world: the World Steel Association reports that around 680 million tonnes of steel scrap were recycled in 2021, avoiding over one billion tonnes of CO_2 that virgin production would have emitted. Recycling steel typically requires up to three-quarters less energy and emits some 70% less carbon than the primary blast-furnace route, saving roughly 1.5 tonnes of CO_2 per tonne of scrap. The Indian sub-continent's distinctive contribution sharpens this further: rather than re-melting all scrap, Indian yards refurbish and re-roll a large share of a ship's steel plate directly into construction bars, a route that never reaches the melting point and can cut emissions still further.

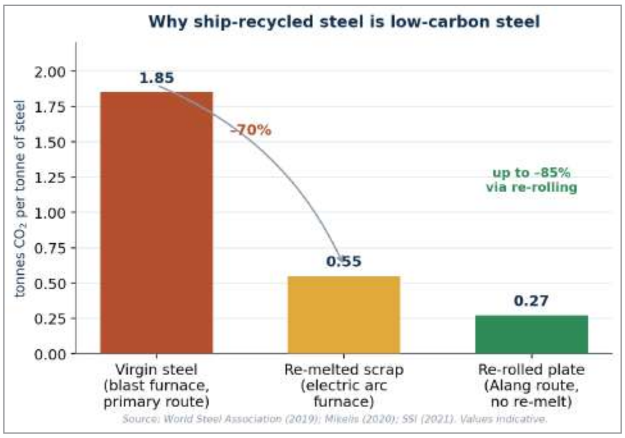

Figure 3. Carbon intensity by steel route — ship-recycled steel is, by construction, low-carbon steel.

This is the introspective heart of the matter. The maritime industry spends heavily to shave marginal percentages off operational emissions, yet the end-of-life stage quietly delivers one of the largest, most certain carbon savings available anywhere in its value chain. Every tonne of ship steel re-rolled in Alang is a tonne of iron ore not mined, coking coal not burned and blast-furnace CO_2 not emitted. Ship recycling does not merely dispose of a

vessel; it displaces primary production. Recognising and monetising that displacement, through certified emission reductions and green-steel accounting, is among the most underexploited opportunities in industrial decarbonisation.

4. Responsible Recycling Upholds Shipowner ESG

For a tonnage provider, ESG credibility is a chain no stronger than its final link. A company can decarbonise its fleet, publish a human-rights policy and win sustainability awards and still see all of it unravel in a single headline if one of its retired vessels is beached and cut by unprotected workers on a contaminated shoreline. This is why the most sophisticated blue-chip owners now treat end-of-life management as a board-level ESG matter rather than a disposal transaction.

One of the Leading Ship Owners offers the clearest disclosure example. Every vessel is recycled under their **Ship Recycling Standard,** built on a strict interpretation of the Hong Kong Convention and going beyond it on anti-corruption, labour and human rights. They demonstrated at the Indian yard in Alang that commercially viable, responsible recycling on the sub-continent is achievable and it continues to fund a mobile health unit that delivered around 15,000 out-patient services to the Alang community in 2024. Crucially, The Ship Owner publicly frames the coming wave of large "post-Panamax" vessels as a capacity challenge that can only be solved through global consensus on approving more yards to Hong Kong Convention standards, an explicit call to grow, not restrict, responsible capacity.

> Responsible ship recycling is not a cost centre to be minimised; it is the final proof of an owner's ESG commitments and the moment at which a vessel's embodied value is either recovered or lost.

This Ship Owner is not alone. Another Leading Ship Owner has committed to sell only to yards meeting strict environmental standards; Wallenius Wilhelmsen recycles at pre-vetted craned and landing facilities with on-site supervisors empowered to stop work on safety grounds; and cash buyers such as GMS, the world's largest buyer of ships and offshore assets for recycling, have institutionalised these expectations through the Sustainable Ship & Offshore Recycling Program (SSORP), investing directly in yard upgrades and worker training to Hong Kong Convention-compliant practice. The entry into force of the Convention on **26 June 2025** converts these voluntary standards into a binding global baseline: 24 States Parties, covering 57% of world tonnage and all four major recycling nations, now require authorised facilities, ship-specific recycling plans and a certified Inventory of Hazardous Materials for vessels of 500 GT and above.

The social dimension, the "S" that is hardest to audit remotely, is where the fourth pillar most directly upholds ESG. A vessel recycled responsibly generates thousands of direct and downstream livelihoods, from cutters and crane operators to re-rolling mills, foundries, refurbishers and, notably, women workers segregating recovered electronics in Bhavnagar's downstream markets. Table 1 summarises how each ESG dimension maps onto responsible recycling practice.

ESG dimension	How responsible ship recycling delivers it
Environmental	Displaces virgin steel (−1.5 t CO_2/t); >98% material recovery; controlled handling of asbestos, PCBs, ODS and oily wastes; no intertidal contamination in compliant yards.
Social	Safe, trained workforce with PPE; occupational health infrastructure; large direct and downstream employment; community health and skilling investment.
Governance	Hong Kong Convention authorisation, IHM certification and ship-specific recycling plans; transparent, auditable chain of custody; anti-corruption and traceable payments.

Table 1. Mapping the ESG framework onto responsible ship recycling practice.

5. The Marine Engineer's Role in the Fourth Pillar

Marine engineers have a direct role in making ship recycling safer, cleaner and more valuable. Long before a vessel reaches the recycling yard, engineering records influence the quality of the Inventory of Hazardous Materials, the accuracy of machinery and equipment identification, the safe isolation of systems and the management of residues in tanks, pipelines, boilers, purifiers, incinerators, refrigeration systems and engine-room auxiliaries.

A well-prepared vessel is safer to recycle. Clear drawings, updated machinery records, accurate bunker and sludge information, refrigerant records, asbestos

awareness, PCB identification and proper documentation of modifications all reduce uncertainty at the yard. They also support better planning of cutting sequences, lifting operations, confined-space entry, waste segregation and hot-work controls.

For marine engineers, responsible recycling should therefore be seen as the final engineering handover of the vessel. The same discipline that governs safe operation at sea must continue into safe dismantling ashore. In this sense, the fourth pillar is not separate from engineering practice; it is the final chapter of it.

6. From ESG Commitment to Field Execution

Responsible recycling is not achieved by selecting a compliant yard alone. It is achieved through disciplined execution: a verified Inventory of Hazardous Materials, a ship-specific recycling plan, trained workers, controlled cutting sequences, safe-for-hot-work preparation, downstream waste traceability and regular reporting from the yard floor. This is where the role of an experienced cash buyer and recycling monitor becomes central.

For GMS, the responsible-recycling conversation has moved beyond price discovery. The cash buyer is no longer only a commercial bridge between owner and yard; it is also a risk manager, documentation coordinator, ESG enabler and custodian of end-of-life accountability. Through SSORP, the recycling process can be monitored from the owner's decision to recycle through to completion, with emphasis on HKC-aligned documentation, worker safety, environmental controls, progress reporting and measurable carbon outcomes.

This practical layer matters because ESG failure rarely occurs in the boardroom. It occurs when procedures are

not translated into work permits, gas-free certificates, lifting plans, waste manifests, training records and daily supervision. The future of responsible recycling will therefore be decided not only by regulation, but by whether the industry can make good practice repeatable at yard level.

What Responsible Recycling Looks Like in Practice

GMS's Sustainable Ship and Offshore Recycling Program demonstrates how responsible recycling can be operationalised. Publicly disclosed SSORP impact indicators include more than 125 vessels supervised, more than 100 IHM surveys, over 10,000 workers trained, more than 700 safety awareness sessions, 281+ HKC data points and more than 1 million tonnes of CO_2-equivalent emissions saved. The program also measures the carbon footprint of each recycled vessel and states that these calculations are verified by a class society.

These figures are important because they move the discussion from aspiration to evidence. The industry does not need to choose between commercial recycling and responsible recycling; it needs systems that make responsible recycling measurable, auditable and repeatable.

7. Transparency as the Market-Driven Mechanism

Regulation sets the floor; transparency raises the ceiling. The **Ship Recycling Transparency Initiative (SRTI)**, launched in 2018 and now hosted by the Smart Freight Centre, is the pivotal market-driven instrument here. Through a voluntary disclosure questionnaire, shipowners publish their recycling policies, practices and progress on a common platform, allowing cargo owners, financiers, insurers and NGOs to reward responsible behaviour and expose laggards. From eleven founding signatories, the community has grown to around 31 signatories, including 14 disclosing shipowners operating more than 3,600 vessels.

The SRTI's theory of change is elegantly simple: disclosure creates accountability, accountability informs decisions across the value chain and market pressure drives standards upward faster than regulation alone. For an owner, becoming a signatory is itself an ESG signal; for a financier applying the Poseidon Principles or ESG screens, SRTI data is decision-grade evidence. Transparency thus converts responsible recycling from a private virtue into a competitive advantage, precisely the mechanism the industry needs while regulatory capacity in recycling nations continues to mature.

8. Toward Extended Producer Responsibility

The remaining structural flaw is that the actor best placed to design a ship for safe, high-value recycling and the actor that profits most from its operating life,

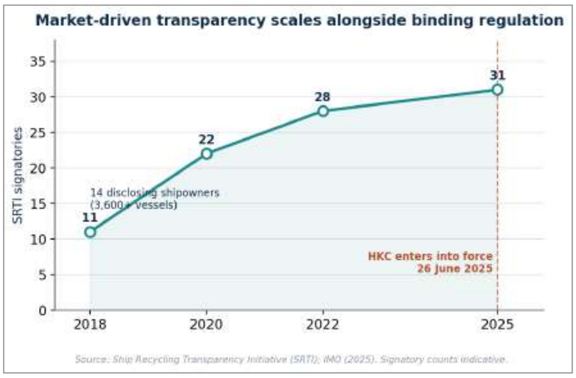

Figure 4. Voluntary transparency (SRTI) scaling alongside the binding Hong Kong Convention.

is too often disconnected from its end-of-life outcome. Once a vessel is sold, frequently through intermediaries and flags of convenience, the original owner's influence and accountability can evaporate. The circular economy in other sectors has answered this through **Extended Producer Responsibility (EPR)**: the principle that producers retain responsibility for their products across the full lifecycle, including end-of-life.

Applied to shipping, EPR reframes the fourth pillar as a shared, inclusive obligation rather than a transaction to be offloaded. In practice, it means several things at once: designing ships for disassembly and material recovery from the drawing board; maintaining a living Inventory of Hazardous Materials from build to beach; embedding responsible-recycling clauses with real financial teeth in sale contracts and recognising cash buyers, whom the Hong Kong Convention treats as owners, as accountable custodians of the standard rather than mere price-arbitrageurs. It also means the producer and financier co-investing in the yard and worker upgrades that make responsible recycling viable, closing the loop between those who create the asset and those who dismantle it.

An inclusive, Extended-Producer-Responsibility model is the only way to align the incentives of owners, cash buyers, recyclers and financiers around a single outcome: safe, green, high-value recycling as the default, not the exception.

9. Conclusion

Ship recycling has quietly become one of the most consequential arenas in maritime sustainability. It is where the largest single carbon saving in the ship lifecycle is realised, where an owner's ESG promises are ultimately honoured or exposed and where the circular economy operates at an industrial scale with a material-recovery rate few sectors can match. India's rise to global leadership, the Hong Kong Convention's entry into force and the maturing transparency architecture of the SRTI together mark an inflexion point: the fourth pillar is no longer optional or invisible.

The task ahead is to make responsible recycling the norm rather than the differentiator. That requires holding regulation and transparency in tension, the Convention as the enforceable floor, the SRTI and ESG disclosure as the aspirational ceiling and binding them with an inclusive Extended Producer Responsibility that reconnects the shipowner to the beach. If shipping treats its final pillar with the seriousness it affords its first three, it will not only close its own material loop; it will offer heavy industry a working template for the circular, low-carbon economy that lies ahead.

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Navigating the Digital Horizon: Why Marine Intuition Cannot Be Replaced by Artificial Intelligence?

A Critical Examination of Human-AI Collaboration in Maritime Operations

Venkat Krishna Soundarraja

Abstract:

The rapid integration of Artificial Intelligence (AI) into maritime operations has sparked considerable debate about the future role of experienced seafarers. While AI demonstrably excels at real-time data processing, predictive maintenance, fatigue mitigation through 24/7 monitoring and early hazard detection, it fundamentally cannot replicate the holistic, multi-sensory intuition forged through decades of seafaring experience. This article critically examines the boundaries of AI capability in the maritime domain, arguing that the "gut feeling" of a veteran mariner — encompassing tacit knowledge of crew dynamics, nuanced physical cues and ethical crisis judgement — remains irreplaceable in high-stakes, ambiguous and unprecedented scenarios. Industry data reveals a significant trust paradox: while 82% of maritime professionals acknowledge AI's operational benefits, adoption remains shallow due to human, cultural and governance barriers rather than technical ones. The article concludes that the optimal maritime future lies not in replacement but in purposeful Human-AI collaboration — a model where AI serves as co-pilot and force multiplier and where Subject Matter Experts (SMEs) are empowered as co-creators of digital solutions.

Introduction:

Can AI match Marine intuition in comparison to a vastly experienced seafarer & his myriad experiences at sea? The answer is '**No**'. AI cannot fully match the marine intuition of a vastly experienced seafarer. It excels in data processing but lacks holistic judgement from decades of seafaring experiences, particularly in novel, high-stakes or ambiguous situations.

While AI excels at processing vast datasets for route optimisation & detecting objects beyond human visibility, it lacks the ability to sense that something 'feels wrong' or to make complex ethical decisions.

Instead of a replacement, the industry must view AI as a co-captain or force multiplier that complements human experience.

Why experienced seafarers retain the edge?

1. **Handling ambiguity & novelty**: Experienced seafarers (subject matter experts) can adapt to unprecedented situations-such as sudden weather shifts or complex emergency maneuvers-where historical data might not exist.

   Moreover, many issues resolved onboard are never documented, neither the root cause nor the solution is recorded.

   Without such data, AI systems lack the training context to provide effective recommendations. In these

scenarios, the AI can only speculate, which rarely leads to concrete or actionable solutions.

2. **'Feeling' the ship**: human intuition often senses through nuanced physical cues (vibration, sound, smell, atmospheric changes etc.) that sensors may not capture or correctly interpret.

3. **Situational context**: A seafarer understands the 'human element', including crew exhaustion, the subtle communication of a foreign-language crew or navigating in a way that prioritises safety over raw efficiency.

4. **Ethical & Crisis judgement**:

   In situations where human lives are at stake, AI struggles to make ethical choices or handle unexpected threats like piracy or drone warfare.

Where does AI outperform humans?

1. **Data analysis & speed**:

   AI can analyse massive amounts of data in real-time, including engine performance, weather conditions & navigation data, which is difficult for humans to do constantly.

2. **Fatigue reduction & monitoring**;

   AI systems can provide 24/7 monitoring, reducing the risk of errors caused by human fatigue or stress.

3. **Early detection**:

   Certain technologies & systems already developed can detect smaller hazards(buoys, containers, small boats etc.,) in low visibility better than human eyes.

4. **Predictive maintenance**:

   AI can detect when machinery is nearing failure by tracking trends & patterns in sensor data, preventing breakdowns before they occur.

Key limitations of AI at sea:

1. **Cybersecurity risks**: As AI navigation increases, so does the risk of being hacked or having signals spoofed.

2. **'Tail effects'**: AI struggles with low probability, high impact '**black swan**' events not in its training data.

   Black swan events are rare unpredictable events that lie outside normal expectations, like COVID-19, geo-political events (Russian-Ukraine war, US, Israel-Iran war etc.) AI predictions collapse because the event is unprecedented.

3. **Data reliability**: AI depends on quality data, if sensors are damaged or data is inconsistent, AI driven decisions can be unsafe.

4. **Black box models**: Models (often deep learning systems) whose internal decision-making process is opaque or hard to interpret. We see the inputs and outputs, but the reasoning in between is hidden in layers of complex parameters.

5. **Interpretability matters**: In high-stakes domains (finance, healthcare, maritime safety), we need models that explain themselves, especially when data goes "off script."

6. **Human oversight**: Black box models can't be left alone during crisis. Humans must step in with intuition, scenario planning and domain expertise.

7. **Regulatory and legal gaps**: International maritime law (IMO conventions, SOLAS, COLREGs) hasn't fully caught up with autonomous AI decision-making. Liability in case of accidents remains unclear — is it the shipowner, the AI vendor, or the crew?

8. **Crew acceptance and trust**: Even if technically sound, AI systems face resistance from seafarers who may distrust opaque algorithms. Human factors — training, confidence and cultural attitudes — can limit adoption.

9. **Connectivity dependence**: AI systems often rely on satellite links for real-time data. In remote oceans, connectivity can be intermittent, degrading AI's ability to update or coordinate with shore-based systems.

10. **Energy and resource constraints**: Advanced AI systems require significant computational power, which can strain shipboard energy systems. Maritime environments often prioritise fuel efficiency and safety over heavy computing loads, making deployment tricky.

Summary:

Feature	Veteran seafarer	Maritime-AI
Data Input	Multi-sensory (smell, touch, sound etc.)	Data-driven (Sensors, telemetry)
Reasoning, Trust basis	Tacit knowledge & experience, gut feeling. Proven track record & physical understanding of the machinery.	Statistical probability or correlation, requires an explainable AI to be trusted in safety critical roles.
Crisis response	Intuitive & adaptive	Rules based & Algorithmic
Reliability	Susceptible to fatigue/stress	Consistent 24/7 monitoring
Context	Understands the 'Ship's Soul'	Understands the 'Ship's Data'
Explainability	**High:** you can walk a junior engineer through your logic & physical 'why' or explain to the vessel superintendent how you solved a particular problem?	**Low:** Deep learning models often provide a result **without** a human readable 'audit trail'.
Error handling	If you make a mistake, you can usually trace the lapse in judgement or the false sensory input.	If the AI 'hallucinates' or fails, the root cause is often buried in layers of neural networks.
Adaptability	You can adapt your model of the ship instantly if a new never before seen refit occurs.	The AI must be 'retrained' on new data or it will continue using an outdated '**black box model**'.

Beyond the hype: What the maritime industry really thinks of AI?

Despite widespread enthusiasm for AI's potential, most maritime companies are **stuck in the early stages of AI adoption, unable to scale beyond small experiments.**

Research has revealed that a sector that is curious and cautiously optimistic, but still uncertain about how to move from experimentation to meaningful adoption.

82% of professionals believe AI can improve operational efficiency and reduce manual workloads. 81% have already launched pilots or small-scale projects. Yet despite this enthusiasm, adoption remains shallow with only 11% having formal policies to scale.

Just 23% are training staff to build confidence and trust in using AI as part of their daily work.

Maritime, traditionally slow to adopt new technology, is compressing typical 10–15-year adoption cycles into just 2-3 years for AI. What we see emerging is a trust paradox where the benefits and potential of AI are broadly recognised, but that same potential is causing hesitation. **The real barriers are not technical. They are human.**

Two-thirds of respondents fear overreliance on AI could weaken human oversight. Crucially, 37% have personally witnessed AI failures, yet remain optimistic, suggesting an industry learning from mistakes rather than abandoning AI entirely.

Many are skeptical of vendor promises and overhype.

69% are concerned about poor business outcomes if AI solutions miss critical red flags in contracts or voyage planning, while nearly a quarter express concerns about vendor claims outpacing real-world results. To realise AI's value at scale, maritime leaders must shift their approach. Adoption is no longer just a technical issue. It is a challenge of governance, culture and communication. Success will depend on transparent implementation, strong leadership, & tools designed specifically for the realities of maritime operations.

Maritime leaders want to act but often feel uncertain about where to begin or how to scale?

Senior executives and C-Suite leaders, in particular, express a genuine interest in AI, **but there remains a significant gap between this enthusiasm and organisational readiness for implementation**. The conversation frequently skews towards binary thinking: risk or opportunity, transformation or disruption.

There is a significant disconnect between the development, deployment and actual use of AI on ships, fueling mistrust. **"Salespeople sell a dream... and then time-stressed seafarers are left trying to unbox and make it work."**

What's holding people back?

Emotional blockers:

Despite widespread optimism, there are signs that maritime stakeholders remain concerned about AI's growing capabilities.

While many can acknowledge the benefits of new technology, emotional responses can still lead to resistance, **particularly when that technology feels unfamiliar, intrusive, or threatening.**

People train their AI models but they don't train their people.

If the crew and the office do not understand the AI outputs, it could lead to misuse, which creates mistrust. **We need to first train our people and our minds.**

To adopt AI successfully, individuals as well as organisations need a pilot mindset, not just letting tech happen to them, but actively steering its use towards real outcomes.

Tech Entrepreneurs in Maritime AI:

Many of the "AI for shipping" ventures are spearheaded by Tech entrepreneurs who recognise the vast potential in digitising a traditionally conservative industry. Their enthusiasm has brought fresh ideas, investment and momentum into maritime digitalisation.

At the same time, these initiatives often originate outside the lived experience of seafaring, operations management, or regulatory compliance. While this outsider perspective can spark innovation, it also highlights the importance of securing counsel from subject matter experts (SMEs) within the industry. Collaboration between entrepreneurs and seasoned maritime professionals ensures that digital solutions are not only cutting-edge but also practical, safe and compliant with international standards.

Why trust is hard to build?

1. **Surface level solutions:** Without seafaring or operational background, products can end up as dashboards or analytics that look slick but don't solve the gritty, day-to-day problems of shipboard operations, bunkering, or compliance reporting.
2. **Marketing vs Reality:** AI gets positioned as a buzzword to attract investors, but mariners and operators quickly spot when tools don't align with real workflows.
3. **Exclusion of SMEs (Subject matter experts):**

   Subject matter experts (Chief engineers, Masters, Fleet managers) are rarely embedded in design teams. Their tacit knowledge—like how checklists are actually used onboard or how dual-fuel reporting is structured—is hard to replicate without them.

Trust will only come when:

- **SMEs are co-creators:**

  Mariners need to be part of product design, not just end-users.
- **Transparency is prioritised:**

AI outputs must be explainable, not black-box predictions.

- **Incremental adoption:**

  Tools that solve one pain point well (e.g. emissions reporting) will gain traction faster than 'all-in-one' platforms. **Many marine startups overextend themselves by trying to tackle too many areas at once, diluting their expertise & struggling to establish credibility**.

  "**Without SME input, products miss the mark and fail to deliver**".

The Gray Area:

1. **SME depth vs. Tech breadth:**

   Mariners know the nuances of ballast water management, dual-fuel operations, or port compliance—**but they may not know how to structure that knowledge into a database schema or machine learning model.**

2. **Tech outsiders with jargon:**

   Non-mariners often learn a handful of shipping terms and assume they've grasped the ecosystem. They can pitch confidently to investors, **but their solutions lack the tacit knowledge that comes only from lived operations.**

Why this matters?

SMEs may dismiss digitalisation as "gimmicky," while tech founders dismiss mariners as "too traditional." Both sides underestimate the other's domain.

Without bridging this gap, AI in marine risks becoming:

- **Shallow digitisation:**

  Fancy dashboards that don't integrate with shipboard workflows.

- **Distrusted tools:**

  Mariners won't adopt systems that feel imposed by outsiders.

- **Missed opportunities:**

  Real value—like reproducible emissions reporting, predictive maintenance, or voyage optimisation—remains underdeveloped, models remain poorly conceived.

Bridging the divide:

1. **Hybrid teams:**

   Pair SMEs with data scientists in product design. The SME defines the problem; the technologist translates it into algorithms.

2. **Upskilling SMEs:**

   Even basic literacy in data structures, coding logic, or AI workflows empowers mariners to challenge and refine tech solutions.

3. **Respect for tacit knowledge:**

   AI models should be trained not just on sensor data but on SME annotations— for example, 'This vibration pattern is normal in heavy seas' or 'Slight temperature spikes in exhaust gas are typical when switching fuel grades'.

4. **Iterative co-creation:**

   Start small (e.g., automating one compliance report) and expand trust gradually. Avoid overloading yourself by trying to tackle too much at once; in other words, don't bite off more than you can chew.

How to make AI your Co-pilot?

While handing over complete control to AI feels unacceptable, risky and untrustworthy, it is entirely feasible to use AI as a co-pilot—leveraging its strengths while keeping critical decision-making firmly in human hands.

Human-AI collaboration: AI handles tedious monitoring or heavy data analysis & the human makes the informed judgement calls with a full understanding of context & consequence.

Imagine a seasoned Chief Engineer, Master, or veteran seafarer—someone with years of hard-earned experience—transitioning into a technological role. Such a leader could chart an effective roadmap for marine digitalisation, bridging tradition with innovation and inspiring fellow seafarers to embrace the future with confidence.

The outcomes of such a transition are:

1. **Technological proficiency:** SMEs achieve digital fluency, enabling them to interpret code and architect specialised marine applications. SMEs stop being passive recipients of tech and become active shapers.
2. **The Domain-Tech knowledge:** By bridging the gap between operational expertise and technology, SMEs ensure developers deliver outcomes aligned with real-world data and user needs.
3. **User-centric design:** They drive the creation of high-impact applications that solve genuine maritime challenges, fostering user trust through thoughtful design.

4. **Growth & Authority:** Through continuous learning, SMEs transition into lucrative consultancy and advisory roles within the marine and energy sectors.
5. **Thought leadership:** They translate research into practical implementation while contributing original insights via industry white papers and blogs.
6. **Mentorship:** They empower the broader maritime community by guiding fellow seafarers and strengthening the professional fraternity.

Requisites: A Professional Growth mindset

1. **Openness** to change and professional evolution.
2. **Dedication** to constant learning and staying tech informed.
3. Active **reading & writing** to improve technical literacy.
4. Immediate **application** of new skills to prevent stagnation.
5. Peer **networking** for collaborative growth.
6. Project **documentation** and progress tracking.
7. **Resilience** and a commitment to **mentoring** others.

Conclusion:

AI is a powerful tool, not a replacement for the seasoned mariner. The maritime industry stands at a critical inflection point. The technology to augment human capability is available; the challenge lies in deploying it wisely, transparently and collaboratively.

AI's capacity for data analysis, continuous monitoring and pattern recognition is genuinely transformative — but **it operates within the boundaries of its training data and algorithmic logic. It cannot sense the "soul" of a ship.** It cannot read a crew's silent exhaustion, improvise in a truly unprecedented crisis, or bear moral accountability for a life-or-death decision. These remain the sovereign domain of human expertise.

The maritime industry's trust paradox — recognising AI's potential while hesitating to commit it, is not a failure of imagination but a reflection of hard-earned operational wisdom. The industry is right to be cautious. **Premature or uncritical AI adoption in safety-critical environments carries real and serious consequences.** The solution is not to slow digitalisation but to deepen it through meaningful SME participation, transparent system design and a governance culture that keeps humans firmly in the decision-making loop.

Ultimately, the most productive and safest maritime future is one in which the veteran mariner and the AI system are genuine co-pilots. The mariner brings irreplaceable intuition, ethical judgement and contextual wisdom; the AI brings tireless vigilance, computational precision and predictive insight. Together, they are far more capable than either alone. The imperative for the maritime industry is not to choose between human and artificial intelligence, but to invest purposefully in the partnerships, training and governance frameworks that make their collaboration both effective and trustworthy. **"AI won't take your job—people who master AI will".**

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Strategic Application of MHD and EHD Drives for Military and Civilian Application

Saptarshi Basu, Bhaskar Bhandarkar, Vipul Mohan Sethi, B.K. Singh

Abstract

Magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) drives are emerging technologies with significant potential for military and specialised civilian maritime applications. By accelerating conductive fluids through electromagnetic forces, MHD propulsion eliminates conventional propellers and rotating machinery, enabling silent, vibration-free operation with reduced maintenance.

The successful demonstration of the *Yamato-1* vessel established the feasibility of MHD propulsion in seawater. Its key advantages include near-zero underwater noise, elimination of cavitation, enhanced stealth and compatibility with nuclear and renewable power sources, making it particularly attractive for submarine propulsion and covert naval operations.

Military applications include silent submarines, underwater surveillance, directed-energy weapon platforms and high-power naval systems. Civilian applications extend to efficient MHD power generation, silent research vessels, pollution control, biomedical microfluidics using EHD technology and specialised low-speed ships. These technologies also support zero-emission shipping by reducing greenhouse gas emissions and underwater noise pollution.

Major challenges remain, including lower propulsion efficiency than modern propellers, high electrical power requirements, dependence on superconducting magnets and cryogenic cooling, electrode corrosion, seawater electrolysis, electromagnetic interference and high capital costs.

Recent advances in high-temperature superconductors such as **Yttrium Barium Copper Oxide (YBCO)** and **Bismuth Strontium Calcium Copper Oxide (BSCCO)** operating at liquid nitrogen temperatures (77 K), together with neodymium-iron-boron permanent magnets, advanced corrosion-resistant materials and electrode-free induction MHD concepts, are improving system feasibility and reliability.

MHD propulsion is best suited to large submarines and specialised vessels where sufficient thruster size and power are available. Hybrid propulsion systems combining MHD thrusters for silent low-speed operation with conventional pump-jets for cruising currently offer the most practical solution.

Although widespread commercial adoption is unlikely in the near future due to cost and efficiency constraints, continued advances in superconductors, materials and power electronics are expected to make MHD propulsion an increasingly viable option for high-value naval platforms and specialised civilian vessels where stealth, reliability and environmental performance are paramount.

Keywords: Magnetohydrodynamic propulsion, Electrohydrodynamic drives, Silent propulsion, Submarine technology, Superconducting magnets, Marine propulsion systems, Military applications, Acoustic stealth, Zero-emission shipping, High-temperature superconductors, MHD power generation, Directed-energy weapons, Naval propulsion, Hybrid propulsion systems, Seawater conductivity, Cryogenic systems, Electrode erosion, Electromagnetic launcher systems, Environmental

remediation, Microfluidic systems, Yttrium Barium Copper Oxide (YBCO), Bismuth Strontium Calcium Copper Oxide BSCCO)

Introduction

Magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) drives offer unique advantages for strategic applications in both military and civilian domains, leveraging the direct manipulation of fluids using magnetic or electric fields to provide silent, efficient and versatile power and propulsion solutions.

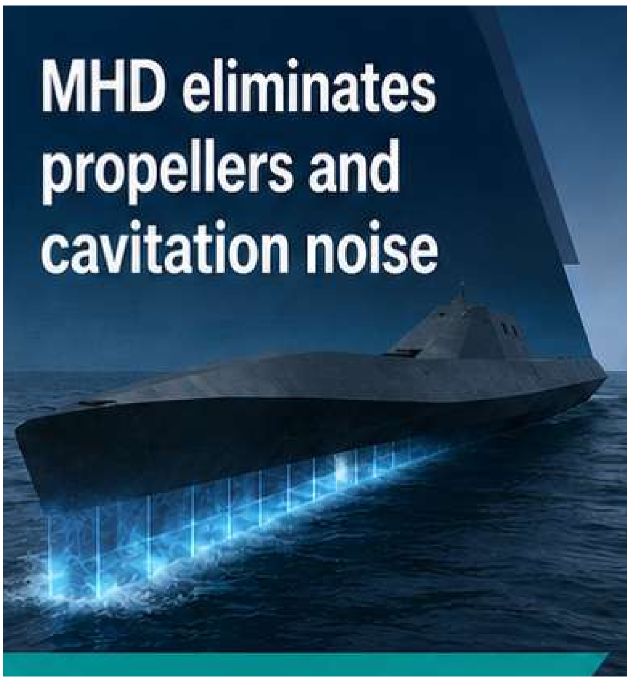
- **MHD (Magnetohydrodynamic) Drives** use magnetic and electric fields to accelerate an electrically conductive fluid (like seawater or ionised gas) to produce thrust. They are “engine-less” and mechanically silent.
- **EHD (Electrohydrodynamic) Drives / Ionic Wind Propulsion** use strong electric fields to ionize a fluid (like air) and accelerate the ions, creating thrust through collisions with neutral molecules. They are solid-state and completely silent.

While both are electric propulsion systems, their operating principles, medium requirements and current technological maturity lead to very different strategic applications.

Military Applications

MHD drives have been actively developed for advanced military systems, particularly for portable power generation and silent propulsion in naval platforms. The key strategic benefits include:

- Silent operation for underwater vehicles, such as submarines and unmanned underwater drones, enhancing stealth and reducing acoustic signature, which is crucial for surveillance and covert manoeuvres.



- Portable, high-output MHD power systems have been demonstrated for delivering rapid pulsed power needed in advanced weapon platforms, electromagnetic launchers and directed-energy weapons without reliance on conventional turbines or moving parts.
- MHD propulsion systems are being explored for hypersonic vehicles, potentially allowing for new frontiers in rapid deployment, aerial surveillance and electronic warfare, as these systems can operate at high speeds with minimal noise.
- EHD drives are integral to microfluidic systems for defence applications, such as on-chip chemical analysis, autonomous sensor networks and rapid-response medical diagnostics during field operations.

Military Applications

The strategic military value of Magnetohydrodynamic (MHD) propulsion lies primarily in enhancing naval stealth, speed and efficiency.

Ultra-Silent Submarines: MHD propulsion eliminates propellers, shafts and reduction gears, significantly reducing acoustic signatures and making submarines extremely difficult to detect by passive sonar. This offers a major advantage in surveillance, covert operations and anti-submarine warfare. Current limitations include high power demand, reliance on superconducting magnets with cryogenic cooling and lower efficiency than modern pump-jet propulsion.

High-Speed Underwater Vehicles: MHD-assisted supercavitation can create a gas bubble around an underwater vehicle, greatly reducing drag and enabling speeds exceeding 100 knots. Such technology is being explored for high-speed autonomous underwater vehicles and advanced naval weapon systems.

Hull Drag Reduction: Applying magnetic fields to seawater can modify boundary-layer characteristics, reducing hydrodynamic drag. This improves fuel efficiency, extends operational range and enhances endurance for naval vessels.

Civilian Applications

MHD and EHD technologies offer several promising civilian applications:

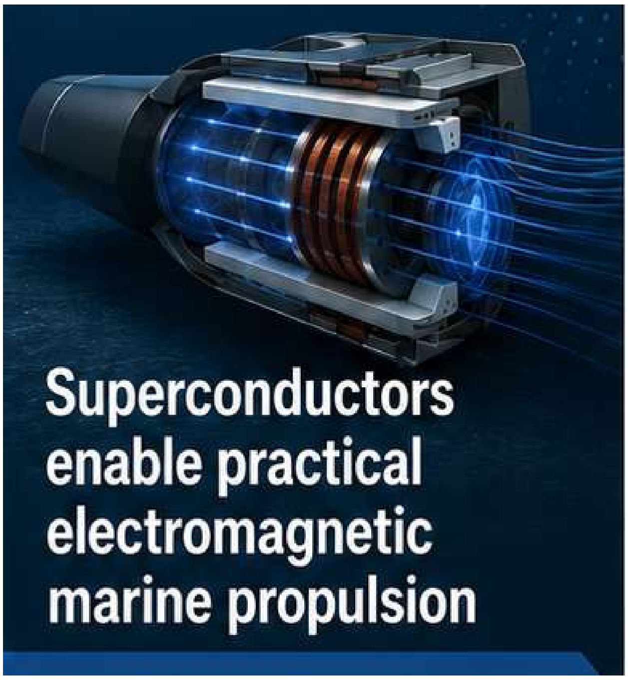
- **Power generation** through direct thermal-to-electrical energy conversion, improving plant efficiency.
- **Silent propulsion** for ferries, research vessels and underwater vehicles where low noise and zero emissions are desirable.
- **Industrial MHD pumps** for transporting corrosive fluids and molten metals without moving mechanical parts.
- **EHD systems** for biomedical devices, microfluidics, electrostatic air pollution control and precision fluid handling.

- **Environmental and industrial processes**, including gas cleaning and liquid-metal cooling in energy and metallurgical industries.

Strategic Impact

MHD and EHD drives provide quiet, low-emission and low-maintenance operation by eliminating moving parts. Their adoption could enable next-generation military platforms with superior stealth, operational flexibility and rapid power delivery, while supporting cleaner and more sustainable civilian transportation, energy generation and industrial systems.

In summary, MHD and EHD drives are strategically leveraged for silent propulsion, portable power generation, environmental control and microfluidic manipulation, with expanding roles in both defence and civilian industries as technology matures and their unique properties are harnessed for specialised applications.



Comparative Analysis & Strategic Outlook

Feature	MHD Drive	EHD Drive
Operating Medium	Electrically Conductive Fluid (Seawater, Plasma)	Dielectric Fluid (Air, Vacuum)
Key Principle	Lorentz Force	Corona Discharge / Ion Acceleration
Noise Signature	Extremely Low (No Moving Parts)	Virtually Silent (Solid-State)
Primary Military Use	Naval Stealth (Submarines)	Aerial Stealth (UAVs), Flow Control
Primary Civilian Use	Research Vessels, Industrial Pumps	Silent Drones, Electronics Cooling
Technology Readiness	Low (Lab prototypes, significant engineering challenges)	Low to Medium (Small-scale prototypes, active research)
Main Challenge	Immense Power & Efficiency (Requires Superconductors)	Low Thrust Density & High Voltage Requirements

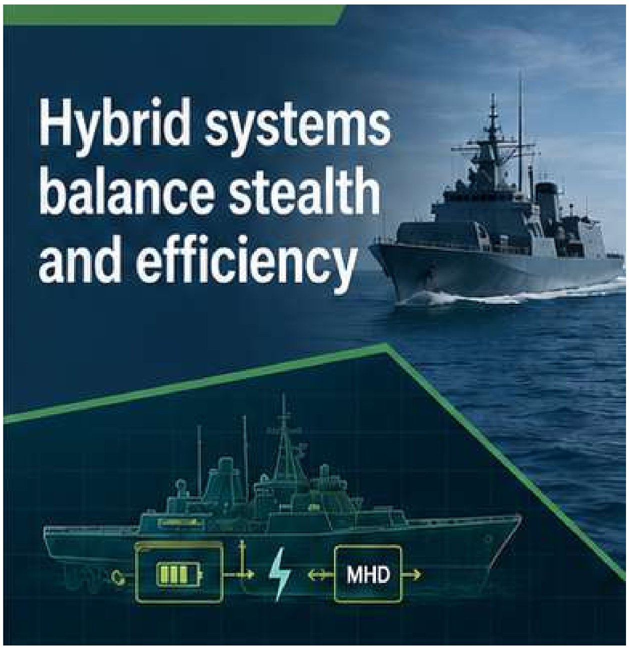
Comparative Advantages and Disadvantages

Advantages of MHD Propulsion

1. Acoustic Stealth: Absence of rotating propellers eliminates cavitation noise and mechanical vibration, potentially providing significant military submarine advantages
2. Noise Characteristics: Noiseless operation compared to conventional propellers
3. No Cavitation Limitations: Unlike propellers, MHD thrusters experience no cavitation constraints, theoretically enabling high-speed operation
4. Mechanical Simplicity: Absence of rotating machinery, transmission gears and mechanical seals
5. Flow Control Potential: Multiple thruster units enable thrust vectoring and enhanced manoeuvrability
6. Magnetic Field Confinement: Can be designed to minimise external magnetic signatures with proper shielding

Disadvantages and Challenges

1. Lower Propulsive Efficiency: Compared to optimised screw propellers with $\eta > 70\%$, MHD systems remain less efficient at practical operating points
2. Magnet System Weight and Complexity: Superconducting magnets add 15-20 tons per thruster unit; structural containment necessary for magnetic forces
3. Cryogenic Requirements: Liquid helium cooling (or liquid nitrogen for high-temperature superconductors) adds operational complexity and continuous heat loss compensation
4. Electrode Erosion: Seawater electrolysis produces hydrogen/chlorine gases; electrode material selection critical
5. Magnetic Signature: While shielding is possible, residual magnetic field may be detectable
6. High Electrical Power Requirements: Substantial power conditioning and delivery systems required (megawatt-scale generation)



7. Capital and Operating Costs: Superconductor acquisition, cryogenic systems and power conditioning represent significant initial investments

Advanced Magnet Technologies and Future Prospects

High-Temperature Superconductor Development

Recent advances in ceramic superconductors (YBCO, BSCCO) with critical temperatures to 125 K enable:

- Liquid nitrogen cooling (77 K) instead of liquid helium (4.2 K)
- Dramatically simplified refrigeration systems
- Reduced operational complexity
- Potential for field strengths exceeding current limits

However, fabrication into practical high-current conductors remains an outstanding technical challenge.

Permanent Magnet Systems

Recent research demonstrates that permanent magnets (NdFeB) can provide modest MHD propulsion (0.15-0.25 Tesla fields):

- Eliminates cryogenic complexity entirely
- Dramatically reduces weight and system cost
- Enables smaller vessel propulsion
- Trade-off: achievable fields insufficient for high-efficiency operation in large vessels

Scaling Analysis and Optimal Vessel Size

Critical Insight: MHD propulsion efficiency improves with vessel size when thruster dimensions scale appropriately. A submersible of 10-meter diameter with 2-meter ducts achieves different performance than same-sized ducts on a 100-meter submarine.

Optimal Applications:

- Large submarines (>100-meter length)
- Low-speed bulk cargo tankers
- Specialised military vessels requiring acoustic stealth
- Research platforms where silence and efficiency are balanced

Supporting Systems and Integration

Power Generation and Supply

Yamato-1 Approach:

- Land-based initial cooling of superconducting magnets
- Onboard AC generators providing electrode power supply
- Persistent current mode operation (once energised, magnets maintain field without continuous power input)

Requirements:

- Multi-megawatt power generation capacity
- High-current DC conversion systems (kiloampere-scale)
- Robust voltage regulation under dynamic load conditions

Cryogenic Systems

Liquid Helium Circulation:

- Helium liquefier on shore for initial cooldown
- Shipboard helium refrigerator reliquefies evaporated helium
- Closed-loop circulation maintaining 4.2 K temperature
- Heat leak approximately 0.5-1 W per square meter of insulation

Modern Alternative (High-Temperature Superconductors):

- Liquid nitrogen circulation systems
- Simpler insulation requirements
- Reduced cryogenic complexity
- Commercial nitrogen availability

Auxiliary Systems

Thermal Management:

- Seawater cooling loops for cryogenic heat rejection
- Refrigeration system capacity: typically, 5-10 kW for megawatt-class MHD systems

Emergency Propulsion:

- Backup diesel-electric systems for loss-of-superconductor scenarios

- Manual control systems independent of main power plant

Navigation and Control:

- Thrust vectoring through modular thruster design
- Precision speed control via electrode current regulation
- Enhanced manoeuvrability compared to conventional single-propeller vessels

Numerical Modelling and Computational Analysis

Magnetic Field Analysis

Magnetic field distribution is evaluated using the **Biot–Savart law** and **finite element analysis (FEA)** to optimise field strength and uniformity.

Key findings:

- Magnetic field non-uniformity increases toward channel edges (5–15% variation).
- NiFe magnetic shielding reduces field leakage by **20–30%**.
- Field strength increases almost linearly with superconductor current up to the critical limit.

Current Density and Hydrodynamic Analysis

Current density is obtained by solving Maxwell's equations coupled with fluid conductivity, while hydrodynamic performance is analysed using the Navier–Stokes equations with the Lorentz force.

Key findings:

- Uniform current distribution is essential for maximum thrust.
- Optimised electrode placement and multi-unit thrusters improve efficiency.
- Non-uniform current can reduce thrust by **10–25%**.
- Ship simulations show steady-state operation after approximately **40s**, with drag increasing proportionally to $\mathbf{V^2}$ and wake effects reducing net thrust.

Current Density and Electric Potential Distribution

Maxwell equation solution coupled with conductivity: $\nabla^2\psi = \nabla\cdot(\mathbf{u} \times \mathbf{B})$

Key Findings:

- Current density distribution significantly affects thrust generation
- Two-unit modules produce more uniform current distribution than single-unit configurations
- Electrode placement optimisation critical for maximising effective Lorentz force
- Non-uniform current can reduce effective thrust by 10-25%

Hydrodynamic Analysis

Navier-Stokes equation solution with incorporated Lorentz force source term: $\rho(\partial \mathbf{u}/\partial t + (\mathbf{u}\cdot\nabla)\mathbf{u}) = -\nabla p + \mu\nabla^2\mathbf{u} + (\mathbf{J} \times \mathbf{B})$

Ship Model Analysis (MHD-1):

- Initial acceleration generates significant waves and wake patterns
- Steady-state achieved after ~40 seconds
- Drag force increases with velocity: (F) Drag $\propto V^2$
- Wake effects reduce available thrust for propulsion

Challenges and Limitations

Technical Challenges

- Fabrication of high-current superconductors (>8 T).
- Reliable cryogenic cooling and thermal cycling of superconducting magnets.
- Electromagnetic interference with onboard electronic systems.
- Integration of MHD thrusters into efficient hull designs.

Operational Challenges

- High capital cost of superconducting and cryogenic systems (approximately **US$50–100 million** for military-grade installations).
- Specialised operation, maintenance and logistics requirements.
- Environmental concerns related to cryogenic heat rejection and electrode corrosion.

Performance Limitations

- Lower propulsion efficiency than modern propellers across a wide speed range.
- Poor scaling for small vessels due to limited seawater conductivity.

- Conventional propeller systems remain more economical and technologically mature for most commercial applications.

Challenges and Future Directions

Despite the successful demonstration by *Yamato-1*, several challenges impede the widespread adoption of MHD propulsion:

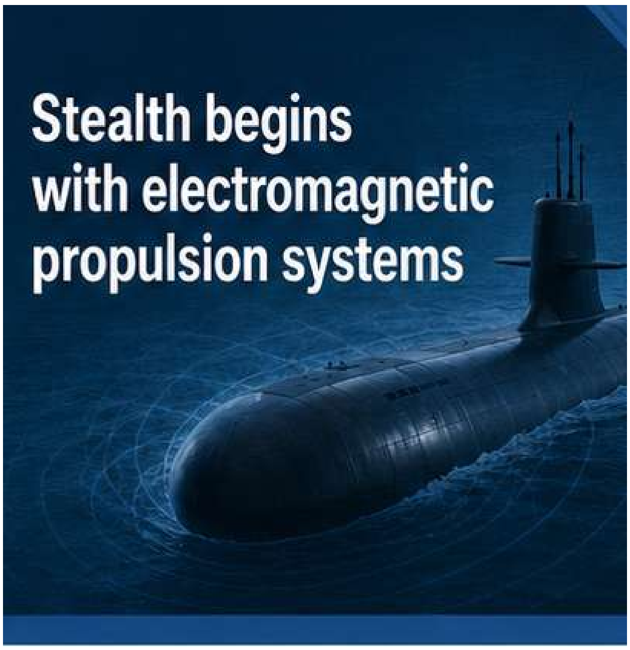
- **High Magnetic Field Requirements:** Efficient thrust generation requires intense magnetic fields (8-20 Tesla), necessitating bulky and expensive superconducting magnets and cryogenic systems.
- **Low Conductivity of Seawater:** The relatively low electrical conductivity of seawater leads to significant Ohmic losses (I^2R losses), reducing overall system efficiency.
- **System Complexity and Cost:** The integration of cryogenics, powerful magnets and large-scale DC power conversion makes the system complex and economically unviable for most commercial applications currently.
- **Onboard Support Systems:** For practical use, ships must carry their own cooling, magnetisation and demagnetisation facilities, adding to weight and complexity.

Opportunities and Constraints

Technological Opportunities

Reduced Environmental Impact

Magnetohydrodynamic (MHD) propulsion offers significant environmental advantages over conventional diesel and gas turbine propulsion. By generating thrust through electromagnetic interaction rather than combustion and rotating propellers, MHD systems can substantially reduce greenhouse gas emissions, underwater radiated noise and cavitation. These benefits support sustainable maritime operations, protect marine ecosystems and facilitate compliance with increasingly stringent environmental regulations.



Disruptive Innovation in Marine Propulsion

MHD propulsion represents a fundamental shift in ship design by eliminating moving mechanical components, resulting in lower vibration, reduced maintenance and improved reliability. Thrusters can be integrated within the hull, reducing hydrodynamic drag while enhancing stealth and overall efficiency. The technology is also well suited to clean energy sources, including modular nuclear reactors, fuel cells and renewable energy systems, making it a promising solution for future zero-emission vessels.

Research and Development Synergies

Recent advances in enabling technologies are steadily improving the practicality of MHD propulsion. High-temperature superconductors reduce cooling requirements while producing stronger magnetic fields. Improvements in lithium-sulphur and solid-state batteries increase power density and endurance, while advanced corrosion-resistant materials and protective coatings enhance durability in seawater. Together, these developments are addressing many traditional limitations and improving the long-term feasibility of MHD propulsion for both naval and specialised commercial applications.

Economic and Industrial Constraints

High Capital Investment

The widespread adoption of MHD propulsion is limited by the high cost of superconducting magnets, cryogenic cooling systems, high-capacity power supplies and corrosion-resistant components. For most commercial operators, these capital costs outweigh the expected operational benefits unless supported by technological advances or regulatory incentives.

Power Infrastructure Challenges

MHD systems require continuous megawatt-scale electrical power beyond the capability of conventional diesel plants. Suitable sources, such as nuclear reactors, large battery systems, or hybrid renewable power, present additional challenges related to cost, space, safety and regulatory approval. The lack of standardised maritime power infrastructure further limits commercial deployment.

Limited Suitability for Smaller Vessels

MHD propulsion is most effective on large vessels where sufficient space is available for superconducting magnets, power conditioning equipment and cooling systems. For small and medium-sized ships, conventional propulsion remains more practical and economical.

Material and Durability Constraints

Marine environments expose MHD components to seawater corrosion, electrochemical reactions and thermal stresses, accelerating material degradation. Electrode erosion, surface polarisation and gas bubble formation reduce conductivity and thrust efficiency, increasing maintenance requirements and lifecycle costs.

Applications and Future Outlook

Military Submarine Applications

Potential Advantages:

- Acoustic stealth critical for submarine warfare; MHD eliminates cavitation noise signature
- High-speed capability (40+ knots theoretically achievable)
- Silent operation at moderate speeds beneficial for surveillance missions
- Potential thrust-vectoring capability enhances agility

Current Status: Ongoing research reported (as of recent years) in multiple nations; U.S., Russia, China reported development programs

Specialised Civilian Applications

1. Research Submersibles: Scientific applications where silence and efficiency balanced differently than military requirements
2. Low-Speed Tankers: Bulk cargo transportation at 5-10 knots; MHD viable with moderate field strengths (2.5-4 T)
3. Deep-Ocean Mining Vehicles: Specialised operations where stealth and precise control valuable
4. Arctic Operations: Silent operation valuable in sensitive polar environments

Technology Development Path

Near-term (5-10 years):

- Continued prototype development with high-temperature superconductors
- System integration and reliability testing
- Cost reduction through manufacturing improvements

Medium-term (10-20 years):

- Operational deployment of small prototype vessels
- Demonstration of acoustic advantages in realistic naval scenarios
- Development of hybrid systems combining MHD and conventional propulsion

Long-term (20+ years):

- Possible transition to high-performance military submarines if technical challenges overcome
- Limited civilian application due to economic factors
- Specialisation in applications valuing silence and efficiency over cost

Large-Scale Naval Applications

Integration with High-Temperature Superconducting Magnets

Research on seawater pump-jets suggests **>5 T magnetic fields** over ~100 m^3 volumes are required for high-efficiency ship propulsion

This necessitates:

- Liquid helium cryogenic systems
- High-temperature superconducting coil housings
- Magnetic fringe field shielding systems for onboard electronics

Reactor and Power System Requirements

Nuclear-electric power systems are most suitable due to immense electrical demand:

Concept	Reactor Type	Propulsion Efficiency
Closed-cycle gas turbine → generator → thruster	HTGR	Moderate
Liquid metal MHD generator → electrical thruster	LMFBR	High but complex

Feasibility calculations for a 30-knot submarine required **100 MW thermal reactor power** and advanced superconducting thrusters.

Future development must focus on:

1. **Advanced Superconductors:** Developing high-temperature superconductors (HTS) that operate at more manageable temperatures, reducing cooling demands.
2. **Seawater Conductivity:** Research into methods to temporarily enhance the local conductivity of seawater within the thruster.
3. **Integrated System Design:** Designing compact, efficient and fully integrated onboard systems for magnetisation and cryogenics.
4. **Electrode-free induction MHD** to eliminate electrolysis losses
5. **High-temperature superconductors** to reduce cryogenic load
6. **Flow-stabilised seawater channel geometry** optimisation

7. **Hybrid MHD–pump jet propulsion integration** in next-generation submarines

Challenge	Impact
Electrolysis gas bubble formation	Reduces conductivity and thrust
Electrode corrosion	Shortens operational lifespan
Cryogenic magnet support	Increases mass and system complexity
Low seawater conductivity	Requires extremely high current
Hydrodynamic flow losses in duct	Reduces net thrust

Conclusion

Magnetohydrodynamic (MHD) propulsion offers a promising alternative to conventional propellers, with its greatest advantage being virtually silent operation, making it highly attractive for submarines and other specialised vessels. Electrohydrodynamic (EHD) technology similarly shows potential for silent UAVs and advanced aerodynamic control.

Although practical deployment is constrained by high power requirements, superconducting magnet systems, cryogenic complexity and efficiency losses, ongoing advances in materials science and power electronics could accelerate adoption. Near-term applications are likely to be hybrid systems, where MHD enables low-speed, stealth operations while conventional propulsion provides cruising power.

Experimental demonstrations have confirmed MHD's technical feasibility and modern superconductors have significantly improved its efficiency potential. The technology is best suited to large vessels where stealth and reliability outweigh cost considerations.

Beyond military use, MHD offers important environmental benefits, including reduced underwater noise, zero direct emissions and improved sustainability. While unlikely to replace conventional propulsion for mainstream commercial shipping, MHD is expected to become a valuable propulsion option for high-value naval, scientific and specialised maritime applications as the technology matures.

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Gaskets, Flanges and Sudden Floods:

Engineering Failures in Piping Systems and Their Forensic Examination

Marine Engineering Accident Investigation Series

Gajanan Karanjikar

Abstract

Failures of gaskets, flanges, bolts and piping joints are often regarded as routine maintenance issues, yet they remain a significant cause of flooding, machinery damage, fires, propulsion loss and costly marine casualties. This article examines how seemingly minor piping defects can escalate into major incidents and explains the engineering principles governing flange integrity, gasket selection, bolt preload, pressure testing and boundary management. Drawing upon forensic accident investigation techniques and international regulatory requirements, including SOLAS, the IMO Casualty Investigation Code, the ISM Code and IACS requirements, the article demonstrates how investigators distinguish root causes from secondary damage. It highlights the importance of systematic evidence collection, engineering analysis and organisational learning in preventing recurrence. The discussion reinforces that effective accident investigation extends beyond identifying failed components to understanding why technical vulnerabilities developed and why warning signs were overlooked.

Keywords: Marine casualty investigation; Piping failures; Flange joints; Gaskets; Bolt preload; Engine room flooding; Forensic engineering; Pressure testing; SOLAS; ISM Code; IACS; Root cause analysis; Machinery safety; Shipboard maintenance; Marine engineering.

Introduction

Marine engineering casualties frequently originate not from catastrophic structural failures but from relatively small defects within piping systems. A leaking flange, deteriorated gasket, improperly tensioned bolt, or inadequately tested repair boundary can rapidly develop into flooding, fire, pollution, or loss of propulsion. Because piping systems serve virtually every critical shipboard function, their integrity is fundamental to vessel safety and reliability.

This article explores the engineering mechanisms behind piping joint failures and explains how modern forensic investigation techniques are used to reconstruct casualty events. By integrating engineering analysis with regulatory compliance and maintenance practices, it illustrates how accident investigations convert technical failures into practical lessons for improving ship safety.

A ship does not always flood because of collision, grounding or dramatic shell damage. Sometimes the casualty begins with something much smaller and far less glamorous: a leaking flange, an overstressed gasket, an under-tensioned bolt, a poor test boundary, or a pipe spool that was never properly aligned after maintenance. Yet these modest-looking failures can escalate with alarming speed. In machinery spaces, pump rooms, ballast lines, fire mains and cargo systems, piping failures can release water, oil, steam or other fluids under pressure,

damage adjacent equipment, trigger fires, disable propulsion and in extreme cases compromise the vessel's survivability. SOLAS chapter II-1 treats machinery and electrical installations as core elements of ship safety and the wider casualty-investigation framework under the IMO Casualty Investigation Code requires systematic collection and assessment of technical evidence after such events.

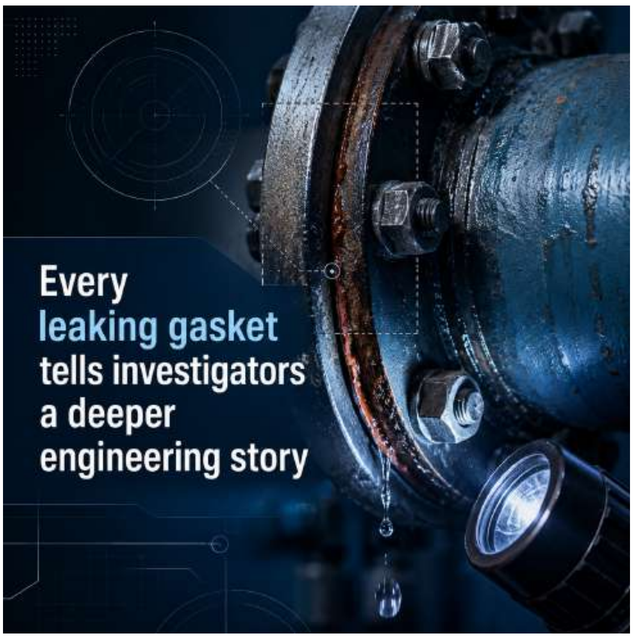
For the accident investigator, piping failures are especially revealing because they sit at the intersection of design, fabrication, installation, maintenance and operation. A fractured flange joint or blown gasket is rarely just "bad luck." It usually reflects a deeper chain: poor flange selection, uneven bolt loading, incompatible gasket material, vibration, thermal cycling, unsupported pipework, corrosion, pressure surges, or inadequate pressure testing. The real skill in forensic examination lies in distinguishing the primary defect from the violence of the aftermath. A flooded engine room may show bent pipe supports, torn insulation and displaced valves, but the first failure may have been a narrow leakage path across one gasket quadrant or a single bolt that relaxed over time and allowed the joint to lose compression.

The engineering significance of flanges and gaskets is often underestimated because they are so common. A flange joint appears simple: two mating faces, a gasket between them and a set of bolts providing the compressive load needed to create a seal. In reality, it is a carefully balanced system. The gasket must deform enough to fill surface irregularities but retain enough resilience to maintain sealing stress under pressure, temperature variation and vibration. The flange must be rigid enough to transmit load without excessive rotation. The bolts must deliver the right preload, not just "tight enough," and that preload must be distributed evenly. If any part of this balance is wrong, leakage begins. If the medium is water, the result may be flooding; if it is fuel oil or hydraulic oil, the result may be fire; if it is steam, the result may be severe personnel injury and rapid thermal damage.

In post-casualty investigation, **flange design** is often the first technical checkpoint. Were the flanges appropriate for the pressure, temperature and service fluid? Did the joint design match class-approved drawings and maker's recommendations? Was there evidence of mixed standards, such as mismatched facing types, incorrect bolt lengths, non-original washers or makeshift spacer arrangements? These questions matter because piping on ships is not a free-for-all. IACS Unified Requirements set international minimum safety requirements and the UR P series specifically addresses piping rules, including current and updated provisions for pipes and plastic piping systems. IACS has also recently issued a dedicated recommendation to improve shipbuilding quality standards for machinery piping systems in fabrication, installation, commissioning and function testing.

One of the most frequent hidden causes of joint failure is **incorrect bolt tension**. Marine engineers are well aware that bolts can loosen, but the deeper truth is that many joints fail without the bolts ever visibly "coming loose." Uneven tightening can warp the flange faces and create non-uniform gasket stress. Over-tightening can crush or extrude the gasket, damage the flange seating area, or yield the bolts so that preload is lost after a few thermal cycles. Under-tightening leaves insufficient sealing stress from the start. Add vibration, pulsating pressure, thermal expansion, pump start-stop loads or slight piping misalignment and the joint begins to breathe. That breathing may first appear as harmless sweating, then staining, then a pin-jet and eventually a full blowout when the gasket no longer has any effective compression reserve.

This is why a serious piping investigation must document bolt condition with almost forensic care. Were the bolts original and of the correct grade? Was there



evidence of necking, thread galling, corrosion wastage or mixed materials? Did the nuts bottom out before proper compression was achieved? Were witness marks present showing progressive movement? On dismantling, investigators often find telling asymmetry: one side of the gasket heavily crushed, the opposite side barely compressed and bolts with highly variable residual torque. Such patterns do not happen by chance. They usually point to poor assembly practice, hurried maintenance in service, or flange misalignment that forced the bolts to act as alignment tools instead of preload devices.

Gasket selection is another rich field of hidden error. A gasket is not just a ring of compressible material; it is a service-specific component. It must match the fluid, pressure, temperature, flange finish and expected mechanical behaviour of the joint. A material suitable for cold seawater may be entirely unsuitable for hot oil. A gasket that seals well in static conditions may fail under vibration. A soft gasket may compensate for flange imperfection but creep over time. A harder spiral-wound or metallic design may require better flange condition and more controlled bolt loading than the crew can reliably achieve during emergency repair. In casualty work, incompatible gasket substitution is a recurring theme: "similar-looking" material used because it was available onboard, or a generic spare substituted for a maker-specific item. Once investigators compare the installed gasket with the approved specification, the chain of failure often becomes clearer.

Yet the cause is not always the gasket itself. Many floods and pipe releases stem from **poor pressure testing** and boundary management after repairs. A spool is renewed, a valve is overhauled, or a blank is fitted and the system is returned to service without a test that truly represents operational conditions. Hydrostatic testing may be done at the wrong point in the system, allowing weak joints to escape meaningful load. Pneumatic tests may be avoided or poorly controlled. Temporary blanks may remain in place or incorrect valves may be cracked open, exposing a repaired branch to a surge it was never tested to withstand. Here the investigator must reconstruct the post-maintenance pathway: what was opened, what was renewed, what was tested, by whom, to what pressure, for how long and with what records?

This is where accident investigation begins to overlap directly with management systems. The ISM Code sets the international standard for safe management and operation of ships and requires procedures for maintenance of ship and equipment, reporting of non-conformities and corrective action. A piping casualty is therefore not judged only on metallurgy and mechanics, but also on whether the company's system identified critical joints, controlled repair quality, specified test procedures and ensured that defects were not normalised. A culture of "tighten it a bit and watch it" looks very different under legal scrutiny after an engine room flood.

A particularly valuable technique in these cases is **failure-surface interpretation**. When a flange or pipe joint fails, the surfaces tell a story if read carefully. Gasket blowout patterns may reveal the initial leak quadrant. Impressions on the gasket can indicate whether compression was uniform. Flange face scoring can show misalignment or trapped debris. Bolt fractures may indicate overload, fatigue or corrosion-assisted cracking. On metallic pipe fractures adjacent to flanges, beach marks may point to vibration-induced fatigue that finally opened under pressure. Distinguishing between a tensile overload caused by the flooding event and a pre-existing fatigue crack that caused the flood is one of the investigator's most important tasks.

This interpretive work becomes even more important in high-consequence cases. Consider a sea-water line flange in the engine room that fails and floods electrical equipment, causing blackout and loss of propulsion in

restricted waters. Or a ballast line joint that opens during transfer and sends water into a void or machinery flat, damaging pumps and switchboards. Or a fuel return line flange that leaks onto hot surfaces and starts a machinery-space fire. In each case, what appears at first to be a "pipe leak" can trigger a multi-casualty chain with salvage exposure, third-party damage, pollution risk and prolonged off-hire. Once the event expands beyond the pipe itself, the owner's financial exposure rises sharply.

The legal consequences for owners can be severe because piping failures often go directly to the question of **seaworthiness and due diligence**. If the joint failed because of defective repair, wrong parts, ignored seepage, overdue renewal, poor support arrangements or lack of proper testing, claimants may argue that the vessel was not seaworthy at the commencement of the voyage. Charterers may place the ship off-hire. Cargo interests may claim delay or damage. If flooding disables propulsion and the vessel grounds, collides or blocks a channel, the cost multiplies into tug assistance, salvage, dry-docking and infrastructure claims. Insurers, meanwhile, will study maintenance records, class recommendations, repair histories and SMS procedures to determine whether the loss was fortuitous or the predictable result of poor technical management.

In this sense, piping casualties are often disproportionate: a relatively cheap component can produce a very expensive outcome. The direct repair cost of a new flange set, gasket and bolts is negligible compared with the downstream cost of a flooded engine room, damaged switchboard, class detention, port delays, charterparty dispute and legal defence. That is precisely why investigators should never treat flange failures as trivial. They are small hardware with large causal authority.

From a prevention standpoint, the lessons are plain. Joint integrity depends on disciplined design selection, proper assembly, controlled bolt loading, correct gasket choice, sound support arrangements and meaningful testing after any intervention. Critical service lines deserve special scrutiny, especially where failure can lead to flooding, fire, loss of propulsion or environmental release. Operators should also remember that repeated minor seepage is rarely harmless; it is often an early warning that the joint has already lost its design margin.

The best accident investigations do more than identify the failed gasket or broken bolt. They reconstruct the whole engineering story: why the joint was vulnerable, why the vulnerability was not recognised, why warning signs were tolerated and why the boundary failed when it did. That is the real value of forensic examination in piping casualties. It turns a wet flange and a damaged compartment into knowledge that can prevent the next sudden flood.

Conclusion

Piping failures demonstrate that relatively inexpensive components can have disproportionately severe operational, commercial and legal consequences. Successful accident investigations therefore require far more than identifying a failed gasket or fractured bolt; they demand reconstruction of the complete chain of engineering, maintenance, operational and management decisions that allowed the failure to occur. Through disciplined forensic examination, adherence to international standards and continuous organisational learning, the maritime industry can significantly reduce the likelihood of recurring piping casualties. Ultimately, preventing future floods, fires and machinery failures depends not only on sound engineering design but also on consistent maintenance practices, rigorous testing, effective safety management and a culture that responds proactively to early warning signs.

About the Author

Capt. Gajanan Karanjikar, Master Mariner, marine surveyor and US-based casualty investigator, has extensive experience in ship command, technical surveys, regulatory compliance and marine casualty investigations. Combining practical seamanship with modern forensic expertise, he advises owners, insurers and regulators while championing safety culture, professionalism and continuous learning across the maritime industry.

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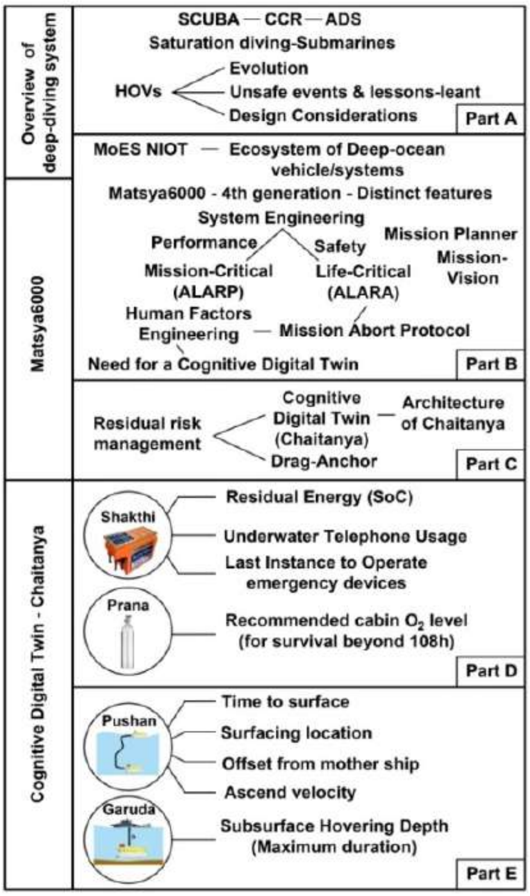
Cognitive Digital Twin "Chaitanya" for India's Deep-Ocean Human Submersible Matsya6000-Part E

N.Vedachalam, VBN Jyothi, J.Preetha Roselyn, R Ramesh , S.B.Pranesh, S.Ramesh

Abstract

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 last (fifth) part describes the development and validation of Pushan and Garuda modules of CDT Chaitanya.



Description of sub-modules of CDT Chaitanya

Pushan – Position tracking

The Navigation and Positioning System (NPS) of Matsya6000 comprises of an Inertial Navigation System aided by a Doppler Velocity Log (DVL), depth sensor and redundant Acoustic Positioning Systems (APoS). The navigation system initialised with the position input from the GPS receiver (when at the ocean surface) works in dead-reckoning (DR) mode during underwater operations. In DR mode, based on the last known (GPS or APoS) or estimated geo-coordinates, DR-based navigational algorithm estimates the current position based on the inputs from navigation sensor suite. During the failure of the NPS, based on the Emergency Operating Protocol (EOP), Matsya initiates an ascent to the ocean surface from the deep-oceans. It is important to predict in-advance, the ascend trajectory, likely surfacing position (LSP) and time-to-surface (TTS) in real-time, enabling precise positioning of the deployment ship for early retrieval. **In order to predict these HTPS, module Pushan (Figure.1) is developed to support the deep-ocean mission during outage of the NPS**.

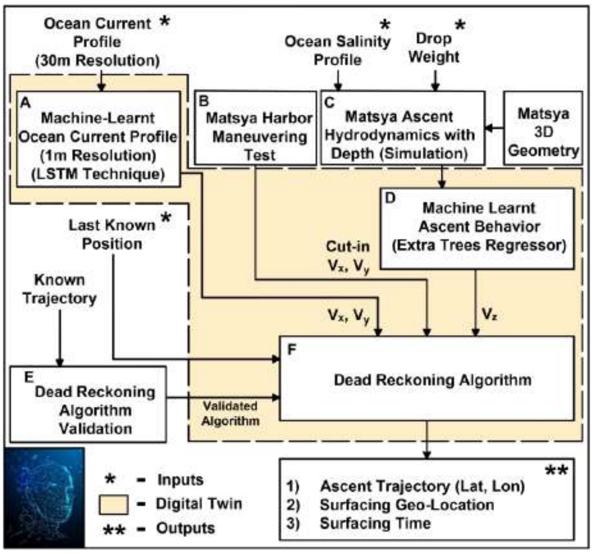


Figure.1. Architecture of CDT Chaitanya-Pushan

In order to compute the ascend trajectory, LSP and TTS, in-advance, the DR algorithm (Block-F) requires Matsya's body frame (BF) velocity in surge (Vx), sway (Vy) and heave (V and) degrees of freedom (DoF). The ascend velocity (V and) of Matsya from 6000m water depths for various buoyancy conditions (due to salinity changes) in various water depths, computed based on hydrostatic calculations and taking into consideration the volume changes due to the compressibility of Matsya subsystems are provided as priori inputs to Pushan (Block-C in **Figure.1).**The in-situ ocean vertical water current profile (casted in the location before Matsya deployment), vehicle buoyancy computed in real-time (based on drop-weight status) and the last position update of the APoS is provided as real-time input to Block-F. Based on these inputs, Pushan simulates the future scenario "ahead-of-

time" and displays the LSP, TTS, as well as the ascend trajectory (3D) in real-time.

Machine-learning of ocean current profile

The ocean water current profile (Water depth Vs Velocity) in Central Indian Ocean Basin (where the water depth is 5500m is logged during a scientific cruise in NIOT's Ocean Research Vessel Sagar Nidhi using Acoustic Doppler Current Profiler (ADCP). It has the provision to measure and log the 3-axis water current velocities and directions, at 50m depth intervals. In order to interpolate and machine-learn the depth-series data in 1m depth interval, RNN-LSTM ML technique is identified (with MAE of R^2 compared to other regression models) and used. RNN-LSTM has the capability to handle sequential data and learn long-term dependencies. Its unique memory cell structure and gating mechanisms enables capturing relationships over extended sequences. Hence LSTM is a proven technique used to model and predict ocean currents. The results of the machine-learnt Vx and Vy vectors using RNN-LSTM technique having a depth-wise resolution of 1m is plotted in **Figure.2.**

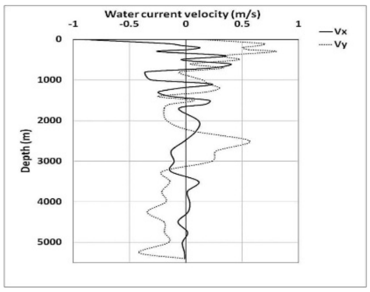


Figure.2. Learnt ocean current profile with a resolution of 1m

The effectiveness of the ML interpolation and learning process is analysed using Mean Absolute Error and closeness between the predicted and actual velocity vectors is within 0.01m/s. **Table.1** provides the comparison of proposed RNN-LSTM against other time-series forecasting ML models. The proposed RNN LSTM is more accurate than other ML models in predicting the ocean current profile.

Table.1. Comparison of ocean current profile estimation using proposed RNN LSTM

Method	MSE	RMSE	MAE
ARIMA	2.95	1.71	2.1
GRU	2.12	1.46	1.85
LSTM	1.86	1.36	0.96
Proposed RNN LSTM	1.05	1.024	0.65

Determination of cut-in velocity by manoeuvring tests

The DR algorithm computes the velocity of Matsya in surge and sway DoFs, for which the velocity inputs are provided from the machine-learnt current profile with a depth resolution of 1m. However, in order to move Matsya from rest, a minimum water velocity (here-in defined as "cut-in velocity") is required to overcome initial inertia. The cut-in velocity is experimentally identified from the maneuvering test of Matsya conducted in L&T's ship-building port in Kattupalli, Chennai **(Figure.3).** During the test, it is identified that a minimum water velocity of 0.05m/s is necessary to overcome the inertia and set Matsya to follow the water current. The cut-in velocity serves as an input to DRA in surge and sway DoF.

Figure.3. Identification of cut-in velocity from maneuvering test

The position estimation using the DR principle is carried out, in which the in-situ water current velocities in the X and Y directions are translated into Matsya velocity in surge and sway DoF. To compute the position of Matsya with respect to the navigation/earth frame (EF), the measured Matsya body frame (BF) velocity in X and Y axis are transformed to EF velocity resolved in the North and East directions. The conversion of BF velocity to EF velocity is done using the Direct Cosine Matrix (DCM) transformation, which is used for computing the distance traversed in X and Y directions. Further, based on the deployment ship position, the computed distance is recursively added to prior position to estimate the geo-referenced position.

Computing & machine-learning depth-dependant ascent hydrodynamics

The ascent velocity (V and) of Matsya is an input to the DRA, that depends on weight of Matsya (W), displacement (Δ), depth-dependent sea water density (ρ), drag coefficient in heave DoF (CD) and projected area (AP).

$$V_{\text{ascent}} = \sqrt{\frac{\Delta - W}{\frac{1}{2} C_{\text{DA}} \rho A_{\text{p}}}}$$

Based on the relationship, the descent and ascend velocity of Matsya for a range of upward buoyancy are computed and depicted in **Figure.4.** The ascent speed of Matsya during normal conditions is 30m/min.

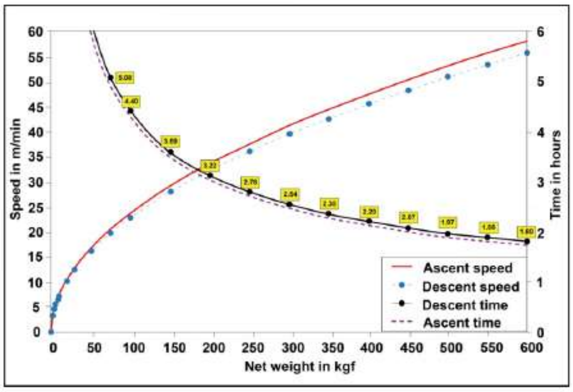


Figure.4. Descent and ascend speed of Matsya with buoyancy

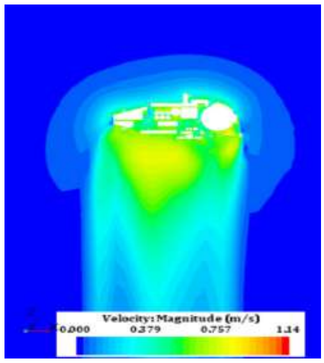


Figure.5. Matsya ascent velocity profile for 300kg buoyancy

The results obtained through calculations are verified using Computational Fluid Dynamics (CFD). A standard RANSE-based CFD package is used in solving the flow around Matsya and estimate V and, as well as visualising flow parameters over her hull surface. Hexahedral meshes were used for meshing and six prism layers are generated adjacent to hull surfaces to capture boundary layer flow accurately. During the analysis, motion in other DoFs is constrained. Numerical simulation was carried out for using STAR-CCM+ software to find out the terminal velocity of Matsya during various ascent scenarios. As an example, the flow field and velocity around Matsya in the longitudinal plane (X AND) plane is shown in **Figure.5.**

The ascend velocities with depth, for various values of buoyancy (ballast drop weights) conditions are computed and shown as envelopes in **Figure.6.** It can be seen that, with an upward buoyancy of 100 kg, ascent velocity which is 0.38m/s at 6000m, reduces to 0 m/s at 2850m and thereafter remains at the same depth. With an upward buoyancy of 500kg, the average ascent velocity is 0.8 m/s. A buoyancy of 300kg is required to ascend with an average velocity of 0.5 m/s.

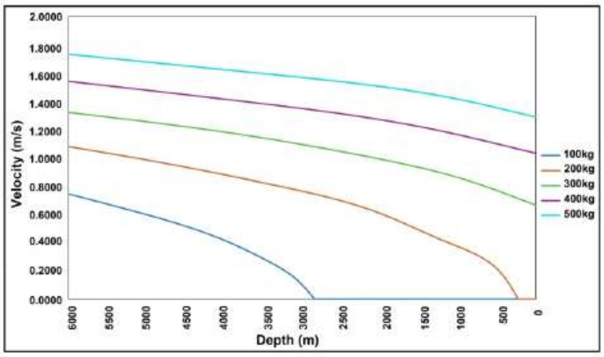


Figure.6. Matsya ascent velocity with depth for varying buoyancy

The ascent velocity of Matsya under various upward buoyancy conditions are machine learnt using Extra Tree Regressor (ETR) ML technique. ETR builds multiple decision trees on random subsets of data and random feature splits to make predictions. It introduces more randomness in the tree construction process, potentially leading to faster training and higher variance in predictions. The performance of the proposed ETR model is compared against Random Forest and Decision Tree models.

NIOT's in-house developed DRA is validated for position estimation performance based on a terrestrial test, in which the DRA along with other validation systems are moved in stable land vehicle at a speed of 0.5m/s for a period of 3h. The trajectory of the vehicle in NIOT campus shown in **Figure.7.** During the test in which velocity inputs to DRA (under validation) is provided from a Commercially-off-the-shelf navigation-grade Inertial Navigation System and found to have a position estimation accuracy of 0.7% of the distance travelled.

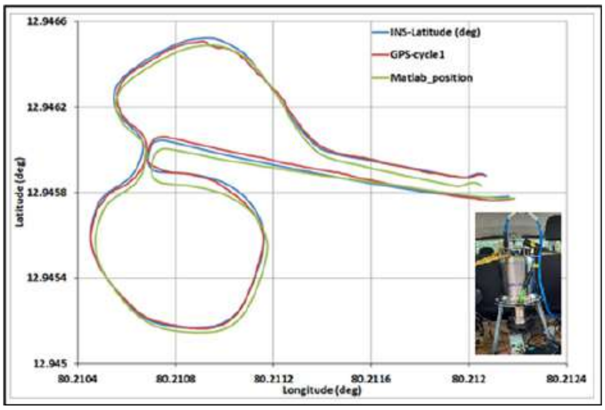


Figure.7.Validation of the DRA based on terrestrial tests

Based on the last known water depth, geo-position and heading of Matsya, the validated DRA computes "ahead-of-time" (hence described as Cognitive) the ascend trajectory, surfacing position and real-time of surfacing. Based on the iterative ascend process, during each iteration, with 1m depth resolution (bin), from the last known depth, DRA fetches corresponding Vx, Vy and V and water velocity vectors of the respective bin, from the respective machine-learnt databases. If Vx and Vy are greater than the cut-in velocity, the velocity is used for iteratively updating the geo-location of Matsya, which finally provides the likely ascent trajectory and the surfacing geo-location. Based on the bin-wise V and, the DRA computes the likely TTS.

The trajectory and surfacing position of Matsya during an ascent from 5500m water depth (with a typical ocean vertical water velocity profile obtained in the Indian Ocean as input and upward buoyancy of 300kg) predicted using Pushan during a NPS outage is shown in **Figure.8.** The accuracy of Pushan shall be validated during forthcoming Matsya qualification trials with deployment location-specific water velocity profile as input.

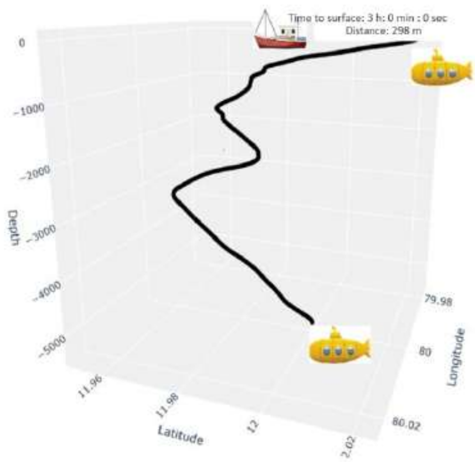


Figure.8.Pushan tracking position of ascending Matsya

Garuda – Subsurface hovering

During the mission, Matsya shall be deployed using a human-riding Launching and Retrieval System (LARS) on-board NIOT's Ocean Research Vessel Sagar Nidhi. According to the design, launching shall be done under Sea state 3 and retrieved under Sea state 4. After completing the deep-ocean mission, Matsya shall surface

after getting clearance from the deployment ship. In case of high sea states (rough sea) or technical degradations in the deployment ship, retrieval cannot be done immediately after surfacing and Matsya remaining in the sea surface is challenging for the crew. Under such circumstances, Matsya shall hover below the ocean subsurface, until clearance is given to surface. Hovering in the subsurface and remaining within the acoustic voice communication range is essential.

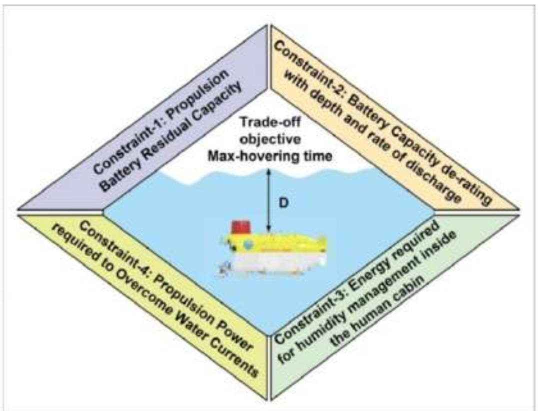


Figure.9. Trade-off to identify optimal hovering depth

After completing a typical subsea mission, during ascent phase, Matsya shall have on-board residual propulsion battery energy of 20kWh. With the available on-board energy, the objective is to achieve a maximum hovering duration. Achieving maximum hovering duration is a trade-off between four key factors, including residual on-board propulsion battery capacity, propulsion power required for position-keep below the ship by overcoming the water currents prevailing at particular depth, battery capacity de-rating due to ambient water temperature prevailing at particular depth and the energy required for dehumidification of the human cabin to maintain human comfort **(Figure.9).**

By considering these four factors, Garuda module shall support the crew (HTPS) by identifying the water depth at which maximum hovering duration could be achieved. **Figure.10** shows the algorithm including ML models, inputs and outputs. The effective propulsion battery energy (after the completion of the mission) available at various water depths, machine-learnt oceanographic conditions (temperature profile and water current profile), power requirements (for hovering and dehumidification) at various depths are provided as inputs to the Garuda. The cut-in velocity identified (in Pushan module) is taken as an input.

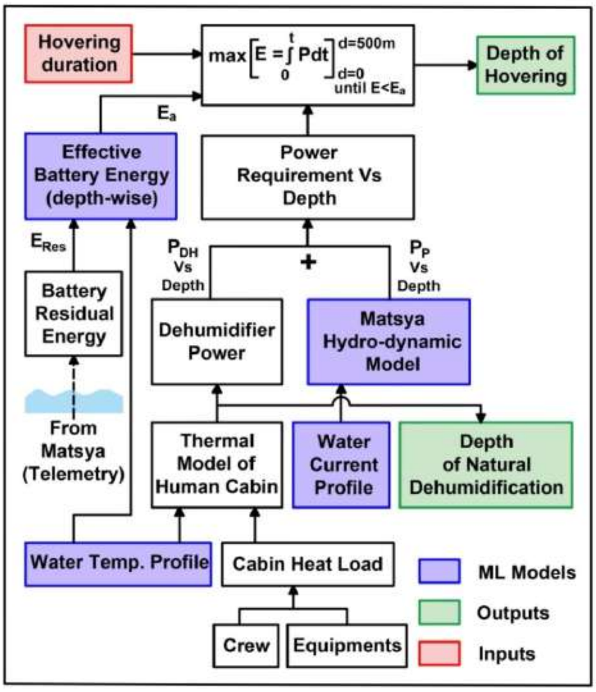


Figure.10. Architecture of Garuda module

Hydrodynamic behaviour (Pp Vs Depth) - Machine learning

Matsya's propulsion in four DOFs is achieved using battery-powered BLDC motor-driven thrusters. The architecture ensures redundancy in power, control and physical damage-tolerance. Numerical analysis using ANSYS is carried out to estimate the total drag-induced resistance in all three DoFs for a range of speeds taking into consideration the mechanical arrangement, quasi-propulsive coefficient and electric motor efficiency **(Table.2).** The identified hydrodynamic propulsion behavior of Matsya6000 is machine-learnt using RNN-LSTM and the effectiveness of the ML interpolation and learning process is analysed using Mean Absolute Error and found that the closeness between the predicted and actual velocity vectors is within 0.01 knots.

Table.2. Hydrodynamic behavior of Matsya

Speed (knots)	0.5	1	1.5	2	2.5	3
Power (kW)	0.6	2.2	4.7	8.1	13.2	19

Effective battery energy at depth (Ea)

Matsya's on-board energy storage comprises of pressure-balanced oil-filled (PBOF) Li-Po batteries with

a total energy capacity of 120kWh. Based on the discharge tests conducted by soaking the batteries simultaneously at various lower ambient temperatures and at 600bar, the observed capacity de-rating is shown in **Table.3.** The identified behavior (under low temperatures) of batteries is machine-learnt using RNN-LSTM.

Table.3. Li-Po battery capacity de-rating with temperature

Temperature (ºC)	30	20	10	2
Capacity de-rating	0 %	98 %	90 %	78 %

Dehumidifier power (P_{DH} Vs Depth)

During the hovering period, the physiological and cognitive state of the crew, including pilot, will be dynamically affected by human cabin microclimate (temperature and humidity), ergonomics, work stress and work intensity. These factors, defined as Performance Shaping Factors (PSF), influence the Human Error Probability (HEP). Hence it is desirable to maintain the human cabin microclimate to the comfort of the crew. As per ASHRAE Standard 55, microclimate inside the HC shall be maintained with an AT of 22ºC and 60% relative humidity (RH).

Based on the crew metabolic activity, body mass and the environmental conditions, ~225ml/h of water vapor is produced by the 3 crew through respiration and perspiration, which results in the increase of humidity inside the human cabin with time. When Matsya is operating in deep-oceans, outside walls of the human cabin is in contact with cold sea water and hence the water vapor in the human cabin gets condensed in the inner wall, offering natural water vapor condensation and humidity control. When Matsya6000 is operating in shallower waters, when the wall temperature (dew point) is not conductive for condensation, three dehumidifiers (100 ml/hr, 210W capacity each) shall be used to reduce the RH level inside the human cabin. The dew point temperature (DPT) depends on the RH levels and the ambient temperature (AT) inside the cabin **(Figure.11).**

The AT in the human cabin (constructed using 80mm thick Titanium alloy) is numerically modeled and simulated using Siemens Magnet-Thermet FEA software. Simulations are done with cabin heat load of 1300 W (100W/crew and 1000W of electronics systems) for ambient water temperature conditions prevailing from surface to 400m water depths in the Central Indian Ocean and the results are plotted in **Figure.12**. The envelopes represent the dew point temperatures (DPT) for RH ranging from 40 % to 100%. The DPT corresponding the AT and RH are obtained from psychometric charts.

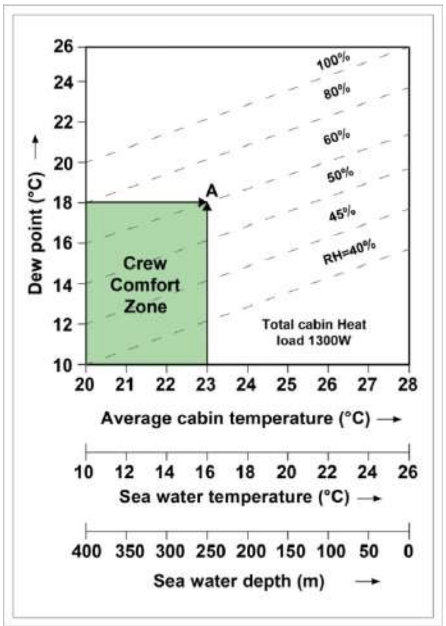


Figure.11. Crew comfort andone under various hovering depths

In **Figure. 11,** shaded region represents the crew comfort andone (AT < 23**°C** and RH < 60%). The simulation results corresponding to Point A for which the DPT is 18**°C** (which prevails close the inner wall of the HC) is shown in **Figure.12.** When Matsya6000 hovers in depths shallower than 250m, dehumidifiers need to operate to ensure crew comfort.

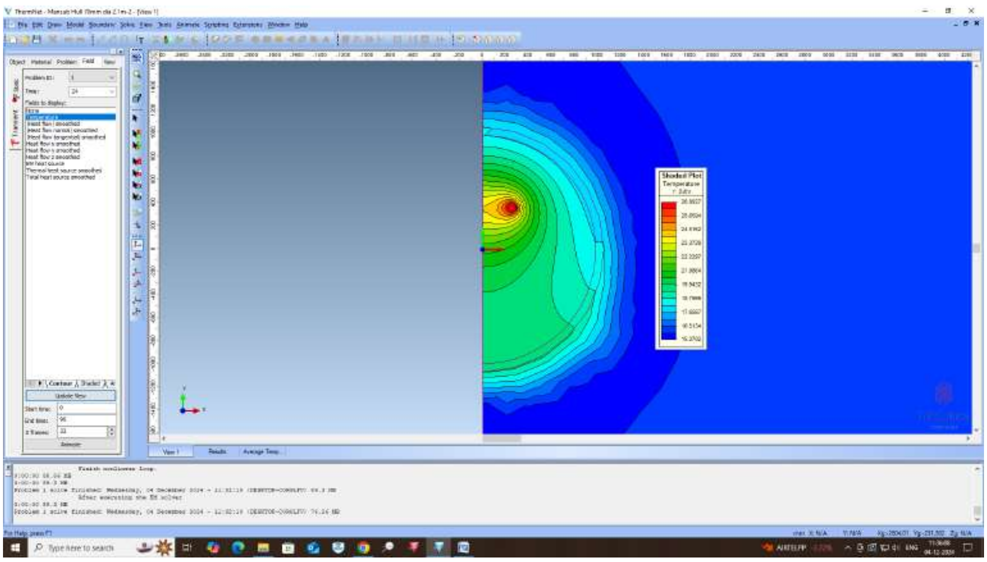


Figure.12. Ambient temperature inside HC at 250m water depth

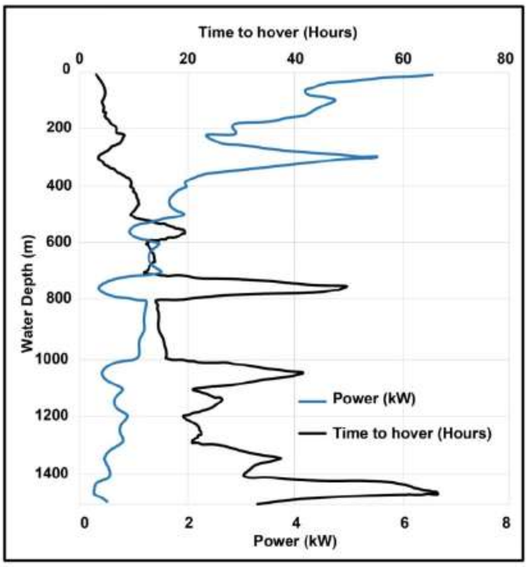


Figure.13. Hovering duration Vs depth for CIO conditions

The hovering durations that could be achieved for a battery residual energy of 20kWh (including propulsion and dehumidification), for the machine-learnt environmental conditions prevailing in the Central Indian Ocean (up to 1500m water depth) is shown in **Figure.13.** It could be seen that hovering durations of 20h, 48h and 63h could be possible at 550m, 760m and 1480m water depths, respectively. The results shall be displayed in the GUI **(Figure.14).**

Deployment of Chaitanya in Matsya

The developed CDT co-pilot Chaitanya is deployed in the human cabin of Matsya6000 **(Figure.14)** as well as in the MCC and the parameters are being tuned. The advisory provided by Chaitanya for the query is also shown.

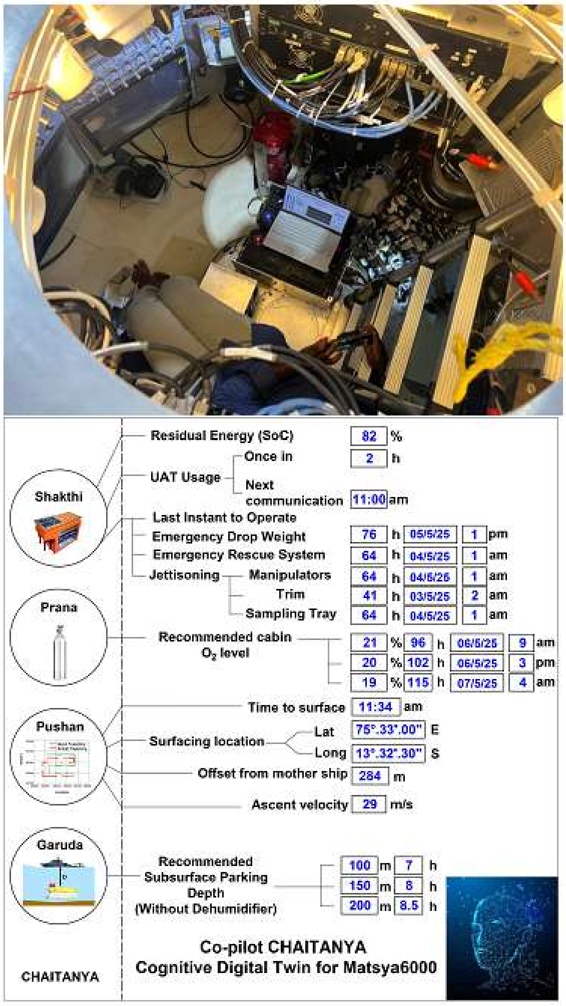


Figure.14. CDT Chaitanya deployed in HC of Matsya6000

Conclusion

Advancements in sensor technology, digitisation, data analytics and machine learning are enabling AI-powered digital twins capable of providing cognitively-intelligent real-time decision-support for critical manned- and unmanned missions. The paper (in 5 parts) described the design and developments of the first-of-its-kind Cognitive Digital Twin Chaitanya, a decision support system for Matsya6000 crew, with abilities to analyse fifteen identified hard-to-predict scenarios and provide updated emergency advisory protocols ahead-of-time. Chaitanya comprising of four modules, Shakthi, Prana, Pushan and Garuda is developed using fourteen numerical and data-driven machine-learnt Human physiology-Equipment-Environment coupled models. The Shakthi module is fully-machine learnt and Prana is partially qualified based on the human physiology data obtained during surface floating condition in maneuvering trails. Further tuning of the models shall be done using the data obtained from the upcoming missions. The novel development approach could be adopted for ensuring safety in deep-ocean human occupied submersibles, based on environment-specific data, submersible engineering and crew physiological information. It is also planned to adopt Chaitanya to reali ande an Integrated Vehicle Health Management (IVHM) system that shall utilise the information from multiple subsystems of Matsya6000 to assess the subsystem health, their effect on the other subsystems and on Matsya6000 as a whole, with reasoning abilities (using unsupervised/reinforced learning) so as to predict potential failures before they become critical. This shall help to transform the present AI-enabled Cognitive Chaitanya to a self-conscious system.

Abbreviations

ADCP	Acoustic Doppler Current Profiler
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
APoS	Acoustic Positioning Systems
AT	Ambient Temperature
ARIMA	Autoregressive integrated moving average
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers

BF	Body Frame
BLDC	Brushless Direct Current
CD	Drag coefficient
CDC	Cognitive Digital Copilot
CDT	Cognitive Digital Twin
CFD	Computational Fluid Dynamics
DCM	Direct Cosine Matrix
DoFs,	Degree of Freedom
DPT	Dew Point Temperature
DR	Dead-Reckoning
DRA	Dead Reckoning Algorithm
DVL	Doppler Velocity Log
EF	Earth Frame
ERB	Emergency Rescue Buoy
ETR	Extra Tree Regressor
FEA	Finite Element Analysis
GPS	Global Positioning System
GUI	Graphical User Interface
HEP	Human Error Probability
HTPS	Hard-To-Predict-Scenarios
IVHM	Integrated Vehicle Health Management
kWh	Kilowatt hour
LARS	Launching and Retrieval System
LSTM	Long Short-Term Memory
LSP	Likely Surfacing Position
MCC	Mission Control Center
ML	Mission Learning
NIOT	National Institute of Ocean Technology
NPS	Navigation and Positioning System
PBOF	Pressure-Balanced Oil-Filled
PSF	Performance Shaping Factors
RANSE	Reynolds-Averaged Navier-Stokes equations
RH	Relative Humidity
RNN	Recurrent Neural Networks
SoC	State of Charge
TTS	Time-To-Surface

Acknowledgement

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Rabindra Sah

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India's maritime transformation is guided by several landmark initiatives as summarised below:

While these initiatives provide a strong national roadmap, successful execution depends on widespread adoption of emerging technologies across the maritime ecosystem.

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The objective is simple yet powerful:

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Rather than discussing technology in isolation, each conclave focuses on solving real maritime challenges using proven digital solutions.

1. Maritime AI Conclave 2026

10 September 2026

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GOVERNMENT OF INDIA INITIATIVES - Maritime Ecosystem

SN	Initiatives	Essence	Key Highlights
01	**Sagarmala** (2015–2025)	Foundation for **port-led economic growth.**	o Built on **5 pillars and 24 categories of projects.** o Port Modernization & New Port Development, Port Connectivity Enhancement, Port-led Industrialization, Coastal Community Development and **Coastal Shipping & Inland Waterways**
02	**Sagarmala 2.0** (2025 onward)	Expansion (shipbuilding & modernization)	o Focus on **shipbuilding, repair, recycling, and port modernization** to enhance global competitiveness.
03	**Maritime India Vision (MIV) 2030**	Sets Efficiency & competitiveness **targets**	o Target-driven roadmap for **efficiency, cost reduction, and competitiveness with huge investment** o Goals: **Reduce logistics costs**, strengthen shipbuilding & repair hubs, and position as global maritime leader
04	**Maritime Amrit Kaal Vision (MAKV) 2047**	Global leadership & sustainability	o Long-term vision for **global leadership** in maritime sector. o Ambition: **Jump in cargo handling, shipbuilding capacity,** renewable-driven ports, **top 5 shipbuilding nations** & Leader in the **Blue Economy** o Workforce Development, Skill, Technologies, Job Opportunity Innovation o Anchored in **Sagarmala 2.0** and **Maritime India Vision 2030**.
05	**Sagarmala Startup Innovation Initiative** (S2I2) : (2025–)	Innovation & entrepreneurship engine	o Boosts **innovation, entrepreneurship & startups** in maritime sector. o Anchored in **RISE (Research, Innovation, Startups, Entrepreneurship).** o Focus on **green shipping, smart ports, logistics tech, and blue economy solutions.**

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operations, maintenance, ports, logistics, compliance, decision-making and customer experience.

The conclave will feature:

- Generative AI and Large Language Models (LLMs)
- AI Agents and Intelligent Automation
- Predictive Analytics
- Digital Decision Support
- AI Governance
- Maritime AI Use Cases
- Cross-industry Success Stories
- Leadership Panels
- AI Strategy for Maritime Organisations

A key objective is to help organisations understand **where to start, how to build an AI roadmap, how to scale adoption and how to create measurable business value.**

Participants will also experience:

- AI solution exhibitions
- Live product demonstrations
- Masterclasses
- Expert-led discussions
- Networking opportunities

The focus is not merely awareness-but **AI adoption with practical implementation.**

2. Maritime XR Conclave 2026

22 September 2026

Extended Reality (XR)-comprising **Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR)**-is rapidly transforming engineering, training, maintenance, inspection and operational excellence.

The Maritime XR Conclave will demonstrate how immersive technologies can revolutionise the complete maritime lifecycle.

Key themes include:

- Virtual Ship Design Reviews
- Immersive Engineering Collaboration
- Crew Training Simulators
- Virtual Maintenance Assistance
- Port Operations Visualisation
- Remote Inspection
- Digital Twin Experiences
- Safety Training
- Smart Manufacturing
- Human-Centric Design

Unlike conventional conferences, this conclave will feature **live demonstrations** where participants can experience technologies firsthand.

Industry leaders will share practical implementations that reduce costs, improve safety, accelerate training and significantly shorten project execution cycles. The objective is to inspire organisations to move beyond presentations and begin adopting immersive technologies in real-world maritime operations.

3. Maritime TECHNO Conclave 2026

19 November 2026

Engineering excellence remains the backbone of the maritime industry.

The Maritime TECHNO Conclave focuses on how advanced engineering technologies are transforming every stage of the maritime lifecycle-from concept and design to construction, validation, operations, maintenance and lifecycle management.

Topics include:

- Digital Ship Design
- Virtual Twin Technologies
- Simulation & Validation
- Autonomous Marine Systems
- Smart Manufacturing
- Port Planning & Logistics Simulation
- Engineering Automation
- Product Lifecycle Management (PLM)
- Smart Supply Chains
- Sustainable Engineering
- Connected Digital Ecosystems

The core philosophy driving this conclave is:

Digital First. Physical Next

By validating designs, processes, logistics and operational strategies in the virtual world before physical implementation, organisations can reduce risks, improve productivity, shorten development cycles and enhance decision-making.

Additional Initiatives to Strengthen the Maritime Innovation Ecosystem

Beyond the three exclusive technology conclaves, several parallel initiatives are being introduced to foster innovation, encourage research, recognise excellence and build a vibrant maritime technology community. These initiatives are designed to bring together startups, researchers, industry leaders, academia and technology innovators on a common platform to solve real-world maritime challenges and accelerate the adoption of next-generation technologies across the sector.

1. Maritime Startup Challenge

A dedicated Maritime Startup Challenge will connect industry challenges with innovative startup solutions.

Startups will be invited to develop Proof of Concepts (PoCs), showcase breakthrough technologies and present their ideas before an expert jury. The most promising solutions will be recognised through the Maritime Innovation Awards, encouraging entrepreneurship and accelerating technology adoption in the maritime sector.

2. Maritime Research & Innovation Forum

To promote research-driven innovation, the conclave will host a Maritime Research & Innovation Forum where researchers, universities, academic institutions and industry professionals can present cutting-edge work in areas such as AI, Digital Twins, XR, Smart Ports, Green Shipping, Cybersecurity, Marine Engineering and Digital Manufacturing. Outstanding research contributions will be recognised through the Best Research Paper Awards, strengthening collaboration between academia and industry.

3. Maritime Excellence & Innovation Awards

The conclave will celebrate outstanding achievements by individuals, organisations, startups and institutions through the Maritime Excellence & Innovation Awards. Entries demonstrating innovation, digital transformation, engineering excellence, sustainability and measurable business impact will be evaluated by an independent jury. The awards aim to recognise best practices and inspire the maritime community to pursue continuous innovation and operational excellence.

4. National Maritime Knowledge Community

The long-term vision extends beyond organising annual events to creating a National Maritime Knowledge Community. This collaborative platform will connect industry experts, policymakers, technology providers, startups, researchers, academia and maritime professionals to continuously share knowledge, exchange ideas, build partnerships and accelerate the digital transformation of India's maritime ecosystem. Together, this community will help build a smarter, more innovative, globally competitive and future-ready maritime industry.

An Invitation to Shape the Future

The future of maritime belongs to organisations that embrace innovation, collaborate across industries and adopt emerging technologies with purpose.

Whether you are a shipowner, port operator, shipyard, technology company, startup, academic institution, policymaker, engineering professional, or maritime enthusiast, these conclaves offer a unique opportunity to be part of India's maritime transformation journey.

Due to the interactive format, **participation is limited**, with a restricted number of delegate seats, exhibition booths, speaking opportunities and strategic partnership slots.

Organisations and individual interested in **speaking, exhibiting, sponsoring, collaborating** and attending as delegate are encouraged to connect as below:

Participant Registration: https://www.cemsacademy.org/s/pages/maritime-ai-conclave

Sponsorship, collaboration and speaking Opportunities Available

Showcase your brand to maritime leaders, technology innovators and key decision-makers. Connect with us to explore sponsorship and partnership opportunities.

→ Contact No: 98196 34596 | Email: contact@cemsindia.org

Together, let us build a smarter, safer, greener and globally competitive maritime ecosystem-powered by technology, driven by collaboration and aligned with India's vision for maritime excellence. greener and globally competitive maritime ecosystem-powered by technology, driven by collaboration and aligned with India's vision for maritime excellence.

Three Exclusive Conclaves. One Maritime Future.
Innovate. Collaborate. Transform.

About the Author

Rabindra Sah, Chief Technology Officer at the Indian Register of Shipping, has over 30 years' engineering experience. He leads digital transformation, AI-driven innovation and Industry 4.0 initiatives, advancing maritime safety, operational efficiency, sustainability and next-generation classification services.

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