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DEVELOPMENT OF ADVANCED UNDERWATER STRUCTURAL HEALTH MONITORING SYSTEMS USING SMART SENSORS AND ARTIFICIAL INTELLIGENCE

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Abstract:
This study presents an integrated underwater structural health monitoring framework that combines smart sensing technologies with artificial intelligence to safeguard subsea pipelines, offshore platforms, bridge piers, and marine renewable energy foundations. Traditional diver- and ROV-based inspections are costly, intermittent, and poorly suited for detecting early-stage degradation in deep, high-pressure, and biofouling-prone environments. The proposed approach links distributed sensors to edge analytics, acoustic communication relays, a surface gateway, and a cloud-based digital twin to enable continuous, autonomous monitoring. The sensing architecture integrates fibre Bragg grating strain sensors, piezoelectric guided-wave transducers, acoustic emission sensors, bulk ultrasonic, MEMS inertial units, and electrochemical probes, housed in pressure-rated, self-diagnosing enclosures with drift compensation. Energy efficiency is achieved through high-density batteries, energy harvesting, and adaptive duty cycling.On-node signal processing extracts compact features using Fourier- and wavelet-based transforms, while secure synchronization preserves data integrity over sparse links. Deep learning models, including convolutional, recurrent, Transformer, and graph neural networks, classify damage signatures, track temporal evolution, and localize defects under partial observability. Domain adaptation, self-supervised learning, and calibrated uncertainty improve robustness under limited labeling. Experimental validation using pressure chambers, corrosion cells, and scaled field trials demonstrates earlier detection of smaller defects, reduced false alarms in noisy conditions, acceptable alert latency, and resilience to sensor or communication failures. This outcome indicates improved decision confidence, extended asset life, reduced environmental risk, and more cost-effective marine infrastructure management, despite remaining challenges related to deepwater data scarcity and acoustic variability.

K
eywords: Underwater structural health monitoring; smart sensors; fibre Bragg grating; edge AI.

I. Introduction

Underwater infrastructure subsea pipelines, offshore platforms, bridge piers, and wind-turbine foundations face continuous degradation from corrosion, fatigue, scour, and impact in opaque, high-pressure, biofouling-prone environments. Conventional inspection regimes based on divers, ROVs, and episodic NDT campaigns are costly, weather-limited, and inherently sparse in time, missing early damage evolution and providing limited context for prognosis. Bandwidth-constrained acoustic links, power scarcity, and harsh thermohaline gradients further challenge reliable data collection, while safety and environmental stakes demand faster detection, quantified uncertainty, and defensible maintenance decisions (Nurellari *et al*., 2021; Murthy & Kadambi, 2022; Wegner *et al*., 2024). Against this backdrop, continuous structural health monitoring (SHM) that fuses smart sensors with artificial intelligence offers a path to persistent situational awareness, earlier intervention, and lifecycle cost reduction.

This work aims to design and validate an end-to-end SHM framework that operates continuously at depth by combining distributed smart sensors with edge AI analytics and robust underwater communications. A heterogeneous suite spanning fibre-optic Bragg gratings, piezoelectric and acoustic-emission nodes, guided-wave ultrasonics, MEMS inertial, and electrochemical corrosion probes feeds an energy-aware pipeline for local preprocessing, adaptive sampling, and anomaly

screening. AI models (spectrogram-based CNNs, sequence models such as RNNs/Transformers, and topology-aware graph networks) perform detection, localization, and damage progression forecasting, while a physics-informed digital twin provides real-time state estimation and what-if simulation to support risk-based maintenance (Mohammad & Tota, 2024; Daouad *et al*., 2024).
The specific objectives are to: (i) engineer a modular sensor package with pressure-rated enclosures, anti-fouling strategies, self-calibration, and drift compensation; (ii) develop low-power energy management through duty-cycling and harvesting (vibration, thermal, or microbial) to extend deployment longevity; (iii) implement a resilient acoustic telemetry stack with time synchronization, compression, and error control tailored to low-SNR channels; (iv) establish a data pipeline that partitions computation between edge nodes and topside/cloud resources with provenance and integrity guarantees; (v) train and validate AI algorithms for early-stage defect detection, uncertainty quantification, and remaining-useful-life prediction using multi-sensor fusion; (vi) integrate a physics-guided digital twin for prognosis and decision support; and (vii) execute lab and field evaluations with quantitative metrics probability of detection, precision/recall, AUC, latency, MTBF, energy/bit, and cost-benefit (Akinola *et al*., 2024, Bobie-Ansah, Olufemi & Agyekum, 2024). Expected contributions include a validated reference architecture, deployable algorithms with quantified performance, and practical guidelines that link sensing, analytics, and communications to measurable gains in safety, reliability, and environmental risk reduction.

II. Literature Review & Gap Analysis

Underwater civil and energy infrastructure is exposed to a demanding combination of mechanical loading, aggressive chemistry, and complex hydraulics that steadily erode structural integrity between infrequent inspections. Fatigue is a primary driver: stochastic waves, currents, and vortex-induced vibration impose high-cycle stress ranges on risers, braces, and tubular joints, while transient events from vessel impact, start-ups, and shutdowns add low-cycle components that accelerate crack initiation at weld toes, heat-affected zones, and geometric discontinuities. In parallel, corrosion mechanisms including uniform corrosion, pitting, crevice attack at saddles and clamps, galvanic coupling across dissimilar metals, and microbiologically influenced corrosion consume section thickness and create stress concentrators that intensify fatigue (Oyeyemi *et al*., 2024; Taiwo *et al*., 2024). Scour and sediment transport alter foundation boundary conditions; local scour around piles and caissons reduces lateral stiffness and can expose welded connections to unexpected bending. Marine growth adds mass and hydrodynamic drag, shifting modal properties and hiding defects from visual or camera-based surveys. Together, these mechanisms interact nonlinearly: corrosion pits seed fatigue cracks; scour amplifies dynamic demand; biofouling masks early damage. Periodic diver or ROV campaigns are expensive, weather-limited, and sparse in time, so early-stage degradation frequently progresses undetected until costly repairs or environmentally consequential failures are imminent (Ayobami *et al*., 2024; Davies *et al*., 2024; Isa, 2024). Figure 1 shows a figure of AI with remote sensors for coastal and marine ecosystem monitoring presented by Janga *et al*. (2023).

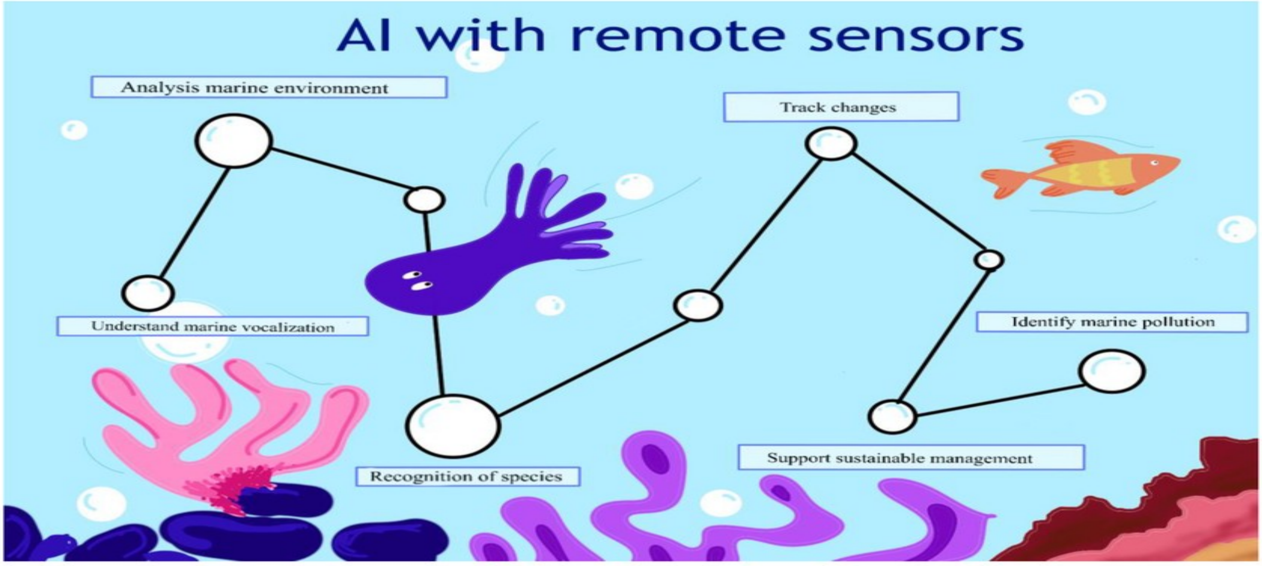

Figure 1: AI with remote sensors for coastal and marine ecosystem monitoring (Janga *et al*., 2023).

To address this, structural health monitoring in the subsea domain relies on complementary sensing modalities, each with characteristic strengths and limits. Fiber Bragg grating (FBG) sensors offer distributed or quasi-distributed strain and temperature measurements with electromagnetic immunity and wavelength-division multiplexing over long distances, useful for pipelines, risers, and jacket bays. However, FBG performance depends on reliable strain transfer through coatings and adhesives, careful compensation for temperature and pressure cross-sensitivities, and ruggedized optical terminations; micro-bending, hydrostatic cycling, and marine growth can degrade signal quality (Ogunyankinnu *et al*., 2024; Okon *et al*., 2024; Olulaja *et al*., 2024). Piezoelectric transducers support guided-wave ultrasonics that interrogate tens of meters from a single location, enabling detection of corrosion, wall loss, and cracking, yet attenuation in water-saturated composites and curved geometries limits range, and couplant stability under pressure is a persistent challenge. Acoustic emission (AE) sensors are sensitive to transient elastic waves from crack growth and fretting, offering early warnings but suffering from high ambient noise, multipath, and event localization difficulties on complex offshore frames. Bulk ultrasonics (pulse-echo or phased array) can quantify thickness and crack depth with millimetre resolution, though coupling, alignment, and coverage constraints make continuous deployment difficult; most systems remain campaign-based. Electrochemical probes reference electrodes, polarization resistance, corrosion coupons, and sensors for pH, dissolved oxygen, and chloride yield direct indicators of corrosion drivers and rates, yet they drift, foul, and require calibration or cleaning that is hard to automate subsea (Akinbode *et al*., 2024; Folorunso *et al*., 2024; Orenuga *et al*., 2024). Low-cost MEMS accelerometers, gyros, and pressure sensors capture global dynamics, impacts, and hydrostatic changes. They are power-efficient, but they are indirect with respect to specific damage and require models to interpret changes. Each modality alone is insufficient; the central opportunity is fusing heterogeneous, partially informative signals into a coherent, noise-robust picture of structural condition (Ajayi & Akanji, 2021; Ejibenam *et al*., 2021). Figure 2 shows a smart environment monitoring (SEM) system highlighting water contamination and its monitoring using the cloud connecting internet of things (IoTs) and sensors presented by Ullo & Sinha, 2020.

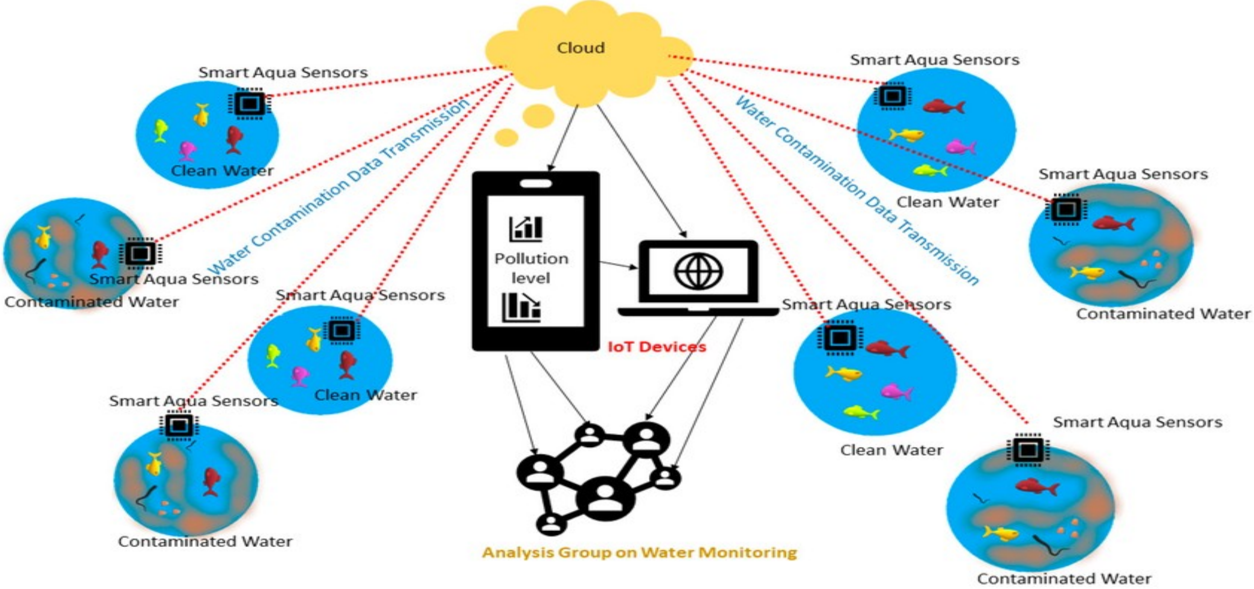

Figure 2: Smart environment monitoring (SEM) system highlighting water contamination and its monitoring using the cloud connecting internet of things (IoTs) and sensors (Ullo & Sinha, 2020).

Artificial intelligence has advanced SHM by learning discriminative features from complex signals without brittle, handcrafted pipelines. Convolutional neural networks operating on spectrograms or wavelet scalograms of AE and ultrasonic data can separate damage signatures from benign activity; sequence models such as LSTMs and Transformers capture temporal dependencies to detect slow drifts and precursors; graph neural networks encode structural topology and sensor layouts to propagate information across members; and hybrid physics-informed models constrain learning with material laws and wave propagation. Yet several shortcomings appear when these approaches meet subsea realities (Akanji & Ajayi, 2022; Onotole *et al*., 2022). Training data scarcity and domain shift are substantial: laboratory coupons and topside test rigs do not reproduce hydrostatic pressure, temperature gradients, biofouling, variable salinity, or acoustic multipath, so models often overfit to benign conditions and generalize poorly offshore. Labels for crack growth, leak onset, or coating failure are rare and expensive, and class imbalance is severe because true faults are infrequent relative to normal operations. Low-bandwidth, high-latency acoustic telemetry prevents raw waveform streaming; intermittent connectivity and power budgets demand aggressive on-sensor compression, event selection, or edge inference, but many reported AI pipelines assume cloud access and abundant data. Synchronization across nodes is nontrivial under drifting clocks and bursty links, compromising multi-sensor correlation and array processing. Robustness to nonstationary noise bubble clouds, marine fauna, thruster noise, and sand transport remains under-studied; models trained on quiet tanks struggle in the field (Mohsan *et al*., 2023; Gracic *et al*., 2024). Explainability and uncertainty quantification are limited, yet offshore decision-makers require calibrated probabilities of detection and false alarm, with traceable rationales to justify interventions that may cost millions in downtime. Finally, cybersecurity and reliability are often afterthoughts; prototypes neglect secure boot, signed updates, and authenticated telemetry, despite hostile environments where compromised gateways could inject false alarms or suppress real ones. Figure 3 shows an IoT-based intelligent fish pond presented by Chiu *et al*. (2022).

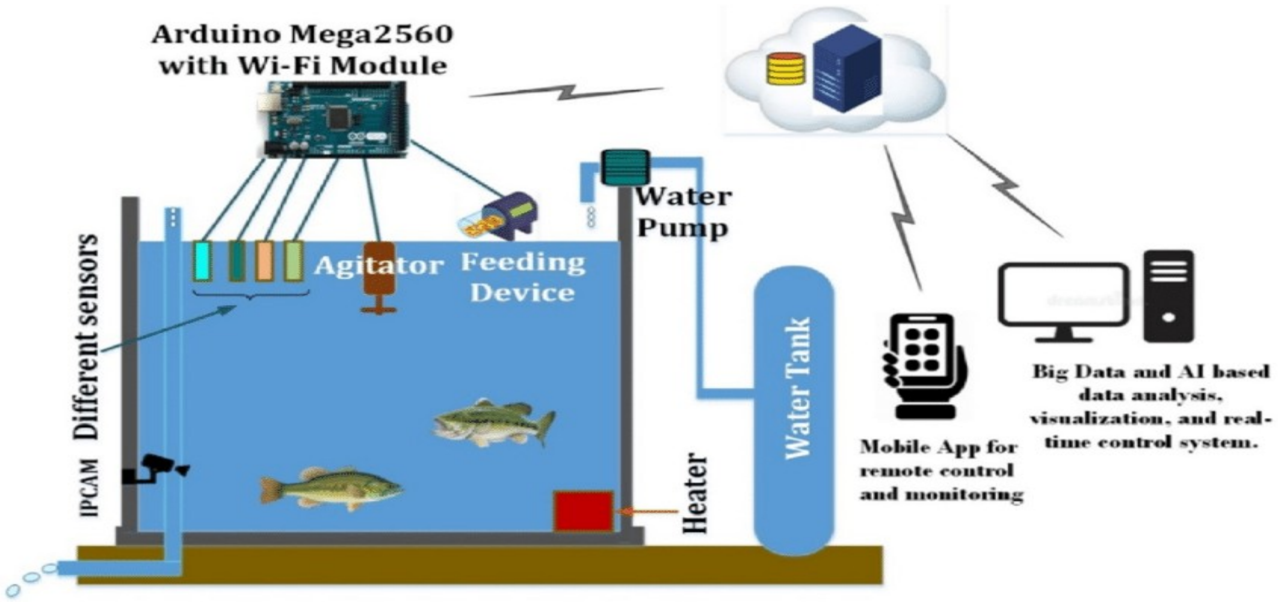

Figure 3: An IoT-based intelligent fish pond (Chiu *et al*., 2022).

Across these strands, several actionable gaps emerge. First is end-to-end co-design. Most deployments assemble sensors, power supplies, modems, and analytics piecemeal, creating mismatches between sampling regimes, duty cycles, telemetry capacity, and model input needs. There is a need for architectures in which sensing, packaging, energy management, communications, and learning are jointly optimized under explicit constraints information per joule, alarm latency, and mean time between maintenance, so that every watt and byte advances detection performance. Second is underwater-specific multisensory fusion (Awe, 2021; Halliday, 2021; Babalola *et al*., 2024). Existing studies often evaluate modalities in isolation; few integrate FBG-derived strain fields with ultrasonic reflectometry and electrochemical indicators, fused with Bayesian filters, particle filters, or factor graphs that account for environmental covariates and sensor drift. Third is telemetry-aware analytics.

Classifiers should drive what to transmit: edge devices ought to compute compact, uncertainty-aware descriptors, request targeted snippets on demand, and adapt bitrate and error control to acoustic channel quality, rather than pushing fixed windows or waiting for cloud decisions. Fourth is rigorous handling of nonstationary and domain shift through transfer learning, self-supervision on unlabelled streams, active learning that prioritizes review of ambiguous events, and continual learning that avoids catastrophic forgetting after firmware or environment changes. Fifth is calibrated decision support.

Probabilistic forecasting, conformal prediction, or Bayesian deep learning should deliver confidence intervals on damage indices and remaining useful life, tied to business-level consequences such as risk of leak, expected downtime, and cost of deferral (Afolabi *et al*., 2024; Ilemobayo, *et al*., 2024; Selesi-Aina, *et al*., 2024). Sixth is reliability, maintainability, and security by design: pressure-rated, anti-fouling enclosures with self-diagnostics; watchdogs and graceful degradation under partial failure; secure identities, encrypted storage, authenticated acoustic links, and signed over-the-air updates. Seventh is validation at meaningful scales with independent ground truth pressure-tank corrosion rigs, fatigue frames with controlled cracks, and field pilots on pilings or spools reporting probability of detection versus damage size, precision–recall under class imbalance, detection latency, communications reliability, energy per bit, and survival under environmental cycling. Eighth is data infrastructure: curated, shareable datasets reflecting true subsea variability, with synchronized multi-sensor streams, environmental metadata, and annotated events agreed by multiple experts, to enable transparent benchmarking and reproducibility (Adeshina, 2021; Isa *et al*., 2021).

By centering these gaps, the development of advanced underwater SHM with smart sensors and AI can move from promising prototypes to dependable, scalable systems. The path forward fuses resilient sensing with edge intelligence that respects energy and bandwidth limits, telemetry stacks co-designed with analytics, and physics-guided learning that expresses uncertainty. Done well, such systems will detect degradation earlier, guide targeted intervention, reduce environmental risk, and extend asset life, delivering measurable value in some of the harshest monitoring environments on earth (Smith *et al*., 2020; Bardgett *et al*., 2021; Awewomom *et al*., 2024).

III. Methodology

The methodology integrates sensor engineering, edge/cloud analytics, privacy-preserving data governance, and decision support into a single, testable workflow that progresses from requirements capture to fleet-scale operations. First, failure modes and monitoring objectives are elicited through hazard and operability studies for pipelines, jackets, and monopiles, producing a ranked list of observables (strain gradients, guided-wave reflectivity, acoustic emission transients, corrosion potentials, hydrophone leak tones) and acceptance thresholds for probability of detection, latency, and false-alarm budgets. A heterogeneous pod is then specified with FBG arrays for quasi-distributed strain/temperature, piezoelectric guided-wave transducers, AE pickups, MEMS IMUs, electrochemical probes packaged in pressure-balanced, biofouling-aware enclosures with self-calibration pulses, impedance checks, reference gratings, and retractable electrochemical tips. Low-power microcontrollers orchestrate duty cycling and run on-sensor preprocessing (STFT/CWT, dispersion compensation, event picking), yielding compact embeddings and uncertainty scores that respect energy budgets. Acoustic telemetry employs adaptive modulation/coding; a time-slotted MAC and relay mesh provide sparse, robust connectivity, with store-carry-forward by AUVs during service windows. A GNSS-disciplined surface gateway provides clock beacons, executes heavier inference, and synchronizes configuration states.

Analytics are partitioned by compute and privacy constraints. Edge nodes execute quantized detectors (one-class autoencoders/CUSUM, lightweight CNNs on spectrogram patches) to filter noise and surface “candidate events” with calibrated confidence. Gateway/cloud tiers run multi-sensor fusion and prognosis: CNNs for time–frequency imagery, RNN/Transformer stacks for long-horizon sequences, and GNNs that encode structural topology to propagate evidence across members. To maintain explainability for operational sign-off and to support rule learning in low-label regimes, a C4.5 decision-tree layer is induced on vetted feature sets for human-auditable triage and as a fallback model during comms degradation (Adams & Hagras, 2020; Machireddy, 2023). Domain adaptation combines self-supervised pretraining on unlabelled subsea streams, adversarial alignment between lab/field distributions, and active learning that prioritizes expert labelling of the least-certain/high-value snippets (Janga *et al*., 2023). Uncertainty is quantified with deep ensembles and conformal calibration so downstream decisions use risk-aware thresholds rather than fixed scores.

Data governance is privacy-first. All payloads are signed and time-stamped; at-rest storage uses authenticated encryption. Site-level federated learning aggregates model updates rather than raw data; where cross-operator collaboration is warranted, threat-intelligence style exchanges are protected with confidential computing and homomorphic encryption so parameter sharing reveals no sensitive asset signals (Zheng *et al*., 2022; Abdulkareem *et al*., 2023; Bai *et al*., 2024). Lightweight anomaly models at the edge are explicitly sized for battery/harvester envelopes and intermittent links, following edge-security/predictive-maintenance patterns from critical-infrastructure computing (Babalola *et al*., 2024; Olufemi *et al*., 2024). Interoperability follows modular IT architectures and lakehouse schemas with versioned calibration constants to ensure reproducible analytics (Azzabi *et al*., 2024).

A physics-informed digital twin is instantiated per asset: finite-element submodels for primary members, hydrodynamic loading, and corrosion kinetics are fused with streaming observations using Bayesian filters. The twin requests targeted measurements when posterior uncertainty inflates (e.g., increase guided-wave cadence around a suspect weld) and returns remaining-useful-life intervals and intervention "what-if" deltas. Decision support converts physical posteriors into business outcomes with cost-of-failure and downtime models adapted from reliability-driven service-line evaluations (Goss *et al*., 2020; Kazemian *et al*., 2024) and risk-based inspection for offshore foundations (Wegner *et al*., 2021). For operations management at scale, orchestration borrows from resilient supply-chain telemetry risk sensing, dynamic prioritization, and route reallocation to reassign gateway polling and bandwidth to assets with rising risk (Kansara, 2021; Ogunyankinnu *et al*., 2024).

Validation proceeds in three tiers. Tier-1 benches: recirculating tank, leak rig, corrosion cells, and a pressure chamber validate packaging integrity, timekeeping, energy/bit, and single-modality sensitivity; seeded defects and controlled leaks provide ground truth. Tier-2 meso-rigs: welded T-joints and spooled pipe sections in flow tanks enable factorial design across flow, temperature, defect size, and fouling films; ablations quantify the lift from each modality and model component. Tier-3 field pilots: shallow-water pilings/pipeline spools instrumented with redundant relays; NDT/ROV/sonar establish georeferenced truth; coupons verify corrosion rates. Metrics include POD vs. damage size (a90/95), precision/recall/AUPRC for rare events, latency to authenticated alert at gateway/cloud, communications delivery ratio, and energy/bit by mode/route, MTBF under environmental cycling, and cost-benefit relative to calendar inspection. Statistical plans use temporally faithful cross-validation and bootstrap CIs; uncertainty in ground-truth sizing is propagated to avoid over-penalizing disagreements within metrology tolerance.

Operations and security are "by design." Keys are provisioned at manufacture with rotation paths; secure boot and signed updates prevent code injection; rate-limited control channels resist battery-drain attacks; privacy-by-design patterns from cloud/telecom are applied to multi-tenant gateways (Nakatsuka *et al*., 2021; Okon *et al*., 2024). Human-in-the-loop reviews use explainable layers (tree rules, spectrogram saliency) to accelerate adjudication and to generate labelled exemplars that refresh active-learning pools (Benway and Preston, 2024). Program governance tracks model lineage, calibration drift, and shadow testing before promotion; canaries with automatic rollback protect availability.

This end-to-end method operationalizes underwater SHM as a privacy-preserving, energy-aware, analytics-driven process, aligning sensor physics with communications limits and AI, and closing the loop through a digital twin that quantifies uncertainty and value, thereby enabling earlier, defensible interventions and scalable, secure fleet deployment.

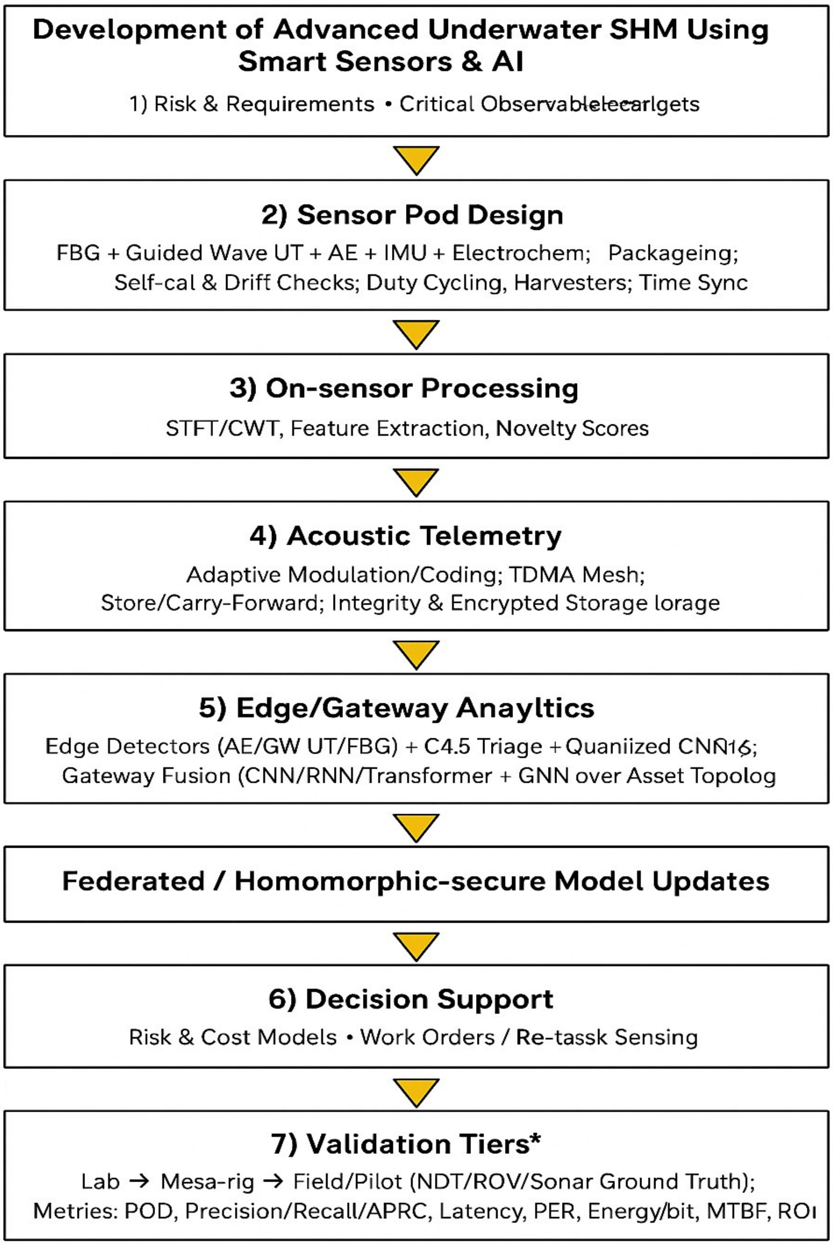

Figure 4: Flowchart of the study methodology

IV. System Architecture

The system architecture adopts a layered design that moves information and decisions from the seabed to enterprise systems with clear roles, bounded interfaces, and explicit constraints. At the sensing layer, heterogeneous devices fibre Bragg grating strain arrays, piezoelectric guided-wave transducers, acoustic emission pickups, MEMS inertial, hydrophones, and electrochemical probes, sample local phenomena under adaptive duty cycles. Each sensor node timestamps observations using a low-drift reference derived from temperature-compensated oscillators and periodic acoustic time beacons to preserve cross-node coherence for array processing and fusion. Local preprocessing computes spectral summaries, wavelet coefficients, or compact damage indices with uncertainty measures, reducing raw bandwidth by orders of magnitude while preserving fidelity for anomaly screening and prognosis (Kumar *et al*., 2021; Ajayi & Akanji, 2023; Halliday, 2023).

Edge nodes aggregate traffic from clusters of sensors over short wired stubs or inductive wet-mate connectors and execute lightweight inference close to the data source. These nodes implement event detection, novelty scoring, and prioritized buffering so that informative segments are retained during acoustic link outages. A telemetry manager adapts compression, packet sizing, forward-error correction, and retransmission to instantaneous channel quality and energy reserve. The edge also hosts a rules engine to enforce safety-relevant policies, for example, immediate leak-like acoustic signatures or rapid strain growth trigger high-priority alerts that pre-empt routine uploads and wake redundant paths (Brundage *et al*., 2020; Sun *et al*., 2021; Hendrycks *et al*., 2023). Model containers allow over-the-air updates of AI kernels, constrained by signed images and rollback protection to assure integrity in a remote environment.

Because direct seabed-to-surface communication is power-hungry and range-limited, the acoustic relay layer provides multi-hop connectivity and spatial diversity. Fixed relays on jacket legs or pipeline markers form a sparse, self-healing mesh using time-division schedules and ranging-assisted routing that accounts for sound-speed profiles, thermoclines, and shipping noise. Where feasible, autonomous nodes opportunistically synchronize and offload when an AUV or glider with a high-capacity modem passes within range, exploiting store-carry-forward to drain backlog inexpensively. Relays maintain dual stacks: a low-rate robust mode for command/control and alarms, and a higher-throughput burst mode for batched analytics, selected by a link-advisor using recent packet error rates and Doppler estimates (Akinbode *et al*., 2023; Onibokun *et al*., 2023).

The surface gateway terminates acoustic links, translates them into IP, and acts as the trust anchor and orchestration point. Mounted on buoys, platforms, or service vessels, it houses a GNSS-disciplined clock for time distribution, a hardware security module for key custody, and a scheduling engine that polls submerged assets according to risk, energy state, and weather windows. When satellite backhaul is constrained, the gateway runs a "cloudlet" that executes heavier inference, cross-site correlation, and compression of digital-twin deltas rather than full states. It also manages configuration drift: blueprint manifests describe desired versions of sensor firmware, edge models, and relay protocols, with compliance continuously verified and divergences quarantined for operator review (Asonze *et al*., 2024; Davies *et al*., 2024; Odezuligbo, 2024).

In the cloud and digital twin layer, data from multiple fields are unified under a schema that captures provenance, calibration history, environmental metadata, and quality flags. The twin maintains a physics-based state estimator combining structural finite elements, hydrodynamics, and corrosion kinetics corrected by streaming measurements through Bayesian filters or factor graphs. This enables counterfactual "what-if" analyses, remaining-useful-life projections, and risk-based maintenance recommendations aligned to operational constraints such as vessel availability and weather forecasts (Awe *et al*., 2023; Ogundipe *et al*., 2023). Model management services track the lineage of AI artifacts, training datasets, and hyperparameters, and enforce canary deployments so that new models are trialled on shadow traffic before promotion.

Hardware modularity is essential for maintainability and lifecycle upgrades. Sensor pods share a common backplane form factor, power interface, and communications connector, allowing substitution of modalities without redesigning the host structure. Enclosures use pressure-balanced oil-filled compartments for electronics and dry housings for optics, with double-barrier seals and external pressure compensation bladders to minimize O-ring stress under thermal cycles. Wet-mateable connectors and blind-mate docking plates enable ROV-safe swap-outs. Internal boards are conformally coated, with desiccant cartridges and humidity monitors to flag micro-leaks early (Ajayi & Akanji, 2022; John & Oyeyemi, 2022). A bill of materials favours COTS components where reliability data is strong, with custom ASICs reserved for ultra-low-power tasks like timestamping and sensor excitation.

Biofouling mitigation is addressed by a combination of passive and active strategies. Surfaces near sensing apertures are treated with fouling-release silicones rather than biocides to reduce environmental impact. Sacrificial transparent windows protect optical ports and can be rotated or peeled by ROV. Low-power ultrasonic antifouling transducers discourage settlement on critical faces, triggered periodically to balance energy use. For electrochemical probes, flow-through capillaries and wipers limit stagnation and biofilm growth; for acoustic devices, hydrophobic meshes suppress bubble adhesion that would otherwise detune response. The architecture plans for fouling rather than denying it: signal chains incorporate self-tests to detect degraded coupling so maintenance can be scheduled before data quality collapses (Wang *et al*., 2020; Tharp, 2022).

Maintainability extends to diagnostics and observability. Each node exposes a health model that fuses internal sensor readings, leak detectors, temperature, voltage, current, memory wear, clock drift, and packet retry into a single status score with explanatory factors. Watchdog timers, brownout managers, and safe-mode boot partitions provide recovery paths after transient faults or corrupted updates. Configuration is represented as declarative specifications stored both locally and in the twin; differences are reconciled through a transactional protocol resilient to intermittent links. Spare capacity in storage, compute, and I/O lanes is reserved to accommodate future algorithms and higher sampling rates without full hardware replacement (Kwak *et al*., 2020; Shantharama *et al*., 2020; Burns *et al*., 2024).

Reliability and redundancy are designed using fault-containment regions and graceful degradation. Sensing clusters overlap so that the loss of one pod reduces spatial resolution but preserves detectability for high-consequence damage. Two independent timing sources limit synchronization drift. Dual acoustic paths, e.g., different carrier frequencies or relay trees, provide alternative routes for alarms. Critical firmware regions are replicated with CRC-guarded images; key parameters are mirrored in FRAM to survive power cycling. Thermal paths are modelled to avoid hotspots that accelerate failure; heat is wicked to the enclosure shell to exploit seawater as a sink. The architecture acknowledges that the mean time between maintenance can span years and designs for "limp modes" that keep essential monitoring alive on a minimal power budget when failures cascade (Adeshina, 2023, Onyedikachi, *et al*., 2023).

Safety considerations permeate the stack. The system avoids introducing new hazards by using intrinsically safe power limits near hydrocarbon assets and galvanic isolation to prevent stray currents that could accelerate corrosion or ignite. Control of active acoustic transmissions respects marine mammal guidance with adaptive power and duty-cycle caps. Cyber-safety is enforced by mutual authentication, encryption at rest and in transit, secure boot, signed updates, and least-privilege identity for each component; intrusion detection looks for anomalous traffic patterns or command sequences that could indicate spoofing (Tange *et al*., 2020; Mazzeo and Staffa , 2020; Wegner, Omine & Vincent, 2021). Decision support surfaces calibrated probabilities, not binary flags, and encodes fail-safe defaults, e.g., ambiguous leak-like signals elevate inspection priority but require human confirmation before shutdowns, unless additional corroboration crosses a defined threshold.

Integration and verification complete the architecture. Hardware-in-the-loop benches emulate acoustic channels, pressure/temperature cycles, and power faults to validate recovery behaviour before deployment. Digital-twin playback re-runs historical incidents through updated models to quantify improvement and catch regressions. Field trials progress through staged complexity: dockside shakedowns, shallow-water pilots with frequent access, and deep deployments with remote audits. Metrics are reported at every layer of information per joule at the sensor, latency and reliability in communications, precision–recall and calibrated uncertainty for analytics, and ultimately avoided downtime and risk reduction at the asset level, ensuring that architectural choices translate into measurable performance in the harsh subsea reality (Adeleke & Ajayi, 2023; Oyeyemi, 2023)

V. Smart Sensors & Power Management

Smart sensors for underwater structural health monitoring must be chosen and engineered with a full appreciation of the physics they measure, the environment they inhabit, and the power they consume. Selection begins by mapping dominant failure modes to observables and then to modalities whose sensitivity, bandwidth, and spatial footprint match those observables. Fiber Bragg Grating arrays are compelling where quasi-distributed strain and temperature trends reveal fatigue hot spots on risers and braces; piezoelectric transducers operating in guided-wave modes extend reach along plates and pipes to detect corrosion and crack-like reflectors; acoustic emission pickups listen for transient energy from micro-cracking and fretting; bulk ultrasonics (pulse-echo or phased array) quantify thickness and flaw depth at critical welds; MEMS accelerometers and gyros capture global vibration and impacts; electrochemical probes (reference electrodes, linear polarization resistance, galvanic couples) sense corrosion drivers and instantaneous rates (Adeleke & Ajayi, 2024, Ajayi & Akanji, 2022, Leonard & Emmanuel, 2022). No single sensor meets all needs, so heterogeneous pods are built from a minimal set of complementary modalities to avoid over-instrumentation while enabling cross-validation. Each modality's operating range, noise floor, and failure modes are catalogued against structural and hydrodynamic models so sensitivity analyses can show how small changes in wall loss, crack length, or boundary conditions emerge in the measured signals.

Packaging transforms lab-grade devices into subsea assets. Electronics use pressure-balanced oil-filled compartments where appropriate to equalize hydrostatic stress and prevent water ingress, and dry housings with double O-ring seals where optics or precise connectors are necessary. Materials are selected to minimize galvanic couples, with titanium or coated stainless steel for housings, PEEK or acetal for non-conductive structures, and isolated grounds to avoid stray-current corrosion (Adeleke & Olajide, 2024; Awe *et al*., 2024; Halliday, 2023). Optical ports for FBG interrogators use sapphire or chemically strengthened glass with sacrificial windows; ultrasonic apertures incorporate impedance-matched acoustically transparent facings; electrochemical ports use flow-through designs that renew water around the electrode and incorporate retractable or ROV-serviceable tips. Biofouling is mitigated by fouling-release silicones on non-sensing areas, wipers, or shutters over critical faces, and low-duty ultrasonic antifouling pulses timed to avoid measurement windows. Connectors are wet-mateable with keyed geometries and oil barriers; internal boards are conformally coated, with desiccant and humidity sensing to flag micro-leaks early.

Calibration and self-diagnostics are embedded from the start. FBG channels include temperature-compensation gratings and periodic reference notches to monitor interrogator drift; piezoelectric transducers run on-board impedance spectroscopy to detect debonding or water ingress; AE sensors periodically inject calibrated pulses through miniature hammers or piezo buzzers to verify sensitivity and timing; bulk ultrasonics execute time-of-flight checks on internal standards to track coupling changes; electrochemical sensors perform open-circuit potential and known-polarization checks to verify linearity (Presti *et al*., 2020; Falcetelli *et al*., 2022; Kok *et al*., 2024). Cross-sensor checks exploit physics: strain changes implied by FBGs are compared against inertial dynamics and hydrodynamic loads; ultrasonic wall-loss trends are reconciled with electrochemical corrosion-rate integrals. Self-tests run on a duty schedule tuned to energy state and environmental stability, so frequent verification occurs after storms, thermal shifts, or maintenance. Results feed a health score per channel with explanatory factors (e.g., "FBG channel 7: increased noise floor; probable micro-bending"), allowing the system to deweight suspect inputs without disabling an entire pod.

Drift compensation is addressed algorithmically and mechanically. Thermal and pressure cross-sensitivities are modelled and subtracted, with coefficients updated through in situ regression against reference sensors. Slow fouling-induced changes in acoustic coupling are tracked by monitoring the transfer function from internal exciters to receivers, letting the system re-normalize amplitude-based features. Electrochemical drift from film formation or reference aging is corrected using multi-point recalibration against stable redox couples when available or by anchoring to environmental trends captured by pH and dissolved oxygen sensors. Clock drift is bounded with temperature-compensated oscillators and periodic time beacons from a surface gateway so that multi-sensor correlation remains valid for array processing and event triangulation. Uncertainty propagation accompanies compensation, ensuring downstream analytics receive calibrated signals with credible intervals (Abdulkareem *et al*., 2023; Ogunyankinnu *et al*., 2022; Onibokun *et al*., 2022).

Power is the second pillar, and undersea conditions force a hybrid strategy: efficient primary energy coupled with opportunistic harvesting. Battery selection balances energy density, pressure behaviour, safety, and lifecycle cost. Lithium primary cells (Li–$SOCl_2$) deliver high energy and low self-discharge for multi-year deployments, where recharge cycles are practical, lithium-ion packs in pressure-tolerant pouches reside in oil-filled enclosures with over-current and thermal protection. Fuel gauging is done with coulomb counting corrected by occasional open-circuit voltage inferences and temperature compensation, while health models track internal resistance growth to forecast usable capacity (Afolabi *et al*., 2024; Joeaneke, *et al*., 2024; Olulaja *et al*., 2024). Harvesters add trickle power that meaningfully extends life or enables higher duty during favourable conditions. Vibration harvesters exploit riser sway or vortex-induced vibration with tuned piezoelectric or electromagnetic transducers mounted where modal energy is abundant; thermal harvesters use thermoelectric across gradients between structure and ambient water, small but persistent in some flows; microbial fuel cells placed in sediment or biofilm-prone niches produce micro-watts continuously by leveraging redox gradients, adequate for sensor keep-alive and data retention. Power management integrates these supplies with a priority scheme, critical sensing and alarms first, calibration and synchronization second, routine analytics and backlog upload last, scheduled by an energy-aware controller that forecasts harvest based on recent patterns (Akinbode *et al*., 2023; Onotole *et al*., 2023).

Duty cycling is the main lever for energy reduction without sacrificing information. Sensors spend most time in deep sleep, waking on schedules tied to structural dynamics and risk posture. For example, guided-wave pulses are emitted at low cadence during steady-state operation but increase after storms or detected anomalies; AE front-ends run with ultra-low-power threshold detectors that wake high-rate sampling only on transients; FBG interrogators downshift to coarse scans when strain variability is low and return to fine resolution when vibration or temperature variance rises. Edge compute subsystems employ heterogeneous microcontrollers: an always-on ultra-low-power MCU monitors energy, time, and simple triggers, while a higher-performance processor wakes for short bursts to run inference, compression, and telemetry (Akinbode *et al*., 2024; Isa, 2024; Olufemi *et al*., 2024). Nonvolatile FRAM buffers prevent data loss during power dips and allow aggressive power gating of RAM and radios. Regulators are selected for high efficiency at micro-amp quiescent currents; DC–DC converters switch to pulse-skipping at light loads; power domains isolate noisy loads from sensitive analog front-ends to protect SNR.

Low-power electronics extend from component choice to firmware discipline. Front-end amplifiers are chosen for low input-referred noise at minimal bias; ADCs with programmable gain and duty-cycled clocks reduce consumption without aliasing; clock trees gate oscillators granularly; DMA moves data without CPU wake; fixed-point or quantized inference kernels exploit SIMD on microcontrollers to cut cycles. Compression schemes respect energy realities: simple transform coding and run-length encoders suffice for many signals, with more costly codecs reserved for rare batches. Radios operate in scheduled, short bursts with forward-error correction tuned to current SNR, so retransmits are rare; acknowledgments piggyback status and energy metrics to avoid extra packets. Firmware follows a finite-state energy model and includes brownout-safe checkpoints so long operations (e.g., ultrasonic scans) can pause and resume without corruption.

Health monitoring of the sensor network ensures the power strategy remains safe and effective over the years. Each node reports a compact health vector: remaining capacity with confidence bounds, harvest rates by source, internal temperatures, voltage rails, clock drift, packet retries, error logs, and per-channel self-test outcomes. Anomaly detection on this telemetry identifies degrading batteries, water ingress, fouling at sensing interfaces, or failing clocks before catastrophic loss (Ajayi, *et al*., 2024; Bamigbade, Adeshina & Kemisola, 2024; Taiwo and Akinbode, 2024). The system supports autonomous reconfiguration in response: nodes with failing channels down-rank those inputs; neighboring pods increase sampling to preserve coverage; acoustic relays shift schedules to conserve energy at stressed nodes; firmware can disable non-essential features to enter a limp mode that preserves critical leak or rupture detection. Maintenance planning benefits from these diagnostics: ROV dives can carry the right spares, and interventions are prioritized by risk and health forecasts rather than fixed intervals.

The combined approach of judicious sensor selection, rugged packaging with self-awareness, calibrated drift compensation, hybrid energy supplies, and ruthless attention to duty cycling and low-power design creates monitoring pods that do more with fewer joules. Importantly, power management is not an afterthought but co-designed with analytics and communications: features computed on-node are selected for their information-per-joule; transmission policies are driven by event value and uncertainty; and calibration schedules adapt to energy state and environmental change. This alignment ensures that when faults are rare and bandwidth is tight, the system still captures the right snippets at the right time, supports trustworthy decisions with quantified confidence, and survives long enough between services to deliver lifecycle value in unforgiving subsea environments (Bhadani *et al*., 2022; Adeshina *et al*., 2023).

VI. Underwater Communications & Data Pipeline

Underwater communications for structural health monitoring must operate within an unforgiving medium where propagation is slow, bandwidth is scarce, channels are time-varying, and power is precious. The data pipeline, therefore, begins with acoustic telemetry that is deliberately conservative and adapts to range, noise, and motion. Frequency-shift keying provides a baseline robust mode for command, control, and alarms, chosen for its tolerance to Doppler and low signal-to-noise ratios. Phase-coherent schemes such as differential PSK and coherent PSK/ QPSK are invoked for moderate ranges where channel estimates are stable; at shorter ranges or during drive-by offloads, orthogonal frequency-division multiplexing enables higher throughput with per-subcarrier water-filling and pilot tones for channel tracking (Lou & Ahmed, 2022; Atalay & UCUNCU, 2022). Spread-spectrum options, including DSSS and frequency hopping, are available for interference resilience near busy assets. The modem stack supports adaptive modulation and coding that renegotiates constellation size, symbol rate, and interleave depth based on recent packet error rates, Doppler estimates, and ambient sound levels, ensuring information per joule remains high even as conditions drift.

Error control is layered: strong forward-error-correction codes (e.g., convolutional or LDPC) handle burst errors after time/frequency interleaving, while selective repeat ARQ handles residual losses with tight acknowledgment compaction to minimize chatter. For bulk transfers (e.g., model updates or backlog offload), rateless fountain codes tolerate erasures across many packets without per-packet ACKs. Preambles and training sequences facilitate synchronization and Doppler estimation; decision-feedback equalizers or adaptive turbo equalizers mitigate multipath, particularly in shallow waters where surface/bottom reflections create delay spreads. To respect marine-life guidelines and reduce self-interference with sensing, transmissions are power-shaped and duty-cycled, and the MAC scheduler enforces quiet windows around acoustic measurements (Ajayi & Akanji, 2022; Davies *et al*., 2024; Isa, 2022).

Routing and medium access control are designed for sparse, long-latency networks where carrier sensing is ineffective. A time-division MAC with guard times and centrally disseminated schedules from the surface gateway avoids collisions while absorbing propagation delays. When central coordination is unavailable, token-based or reservation-based MACs run with long frames to amortize control overheads, while slotted FAMA-like handshakes provide decentralized access with explicit RTS/CTS that include propagation-aware timers. Multi-hop routing uses a hybrid of link-quality estimation and energy awareness: nodes maintain exponentially weighted estimates of effective throughput and energy cost per delivered bit, and forwarding chooses paths that minimize a joint metric of delay, reliability, and remaining battery (Rana *et al*., 2020; Saini, T. K., & Sharma, 2021; Abdollahi *et al*., 2022). Opportunistic store-carry-forward is integral to AUVs and gliders act as data mules that synchronize clocks, ingest buffered batches at high rates, and ferry them to surface gateways, dramatically increasing goodput without continuous power-hungry long-range links.

Because the channel is the scarcest resource, the data pipeline is built to emit only what is valuable. On-sensor preprocessing converts raw waveforms into compact, informative summaries. Short-time Fourier transforms and continuous wavelet transforms generate spectrograms from which low-dimensional features spectral centroids, band energies, kurtosis, and modulation indices, are computed at fixed budgets. For guided-wave ultrasonics, windowed cross-correlations, arrival-time picks, and damage-sensitive coefficients (e.g., sideband energy or nonlinear harmonics) are produced; for acoustic emission, event detectors with adaptive thresholds extract amplitude, counts, rise time, duration, and frequency descriptors. Lightweight autoencoders or one-class models running on the edge compress observations into embeddings and novelty scores, retaining raw snippets only around anomalies or for periodic calibration (Adeleke & Ajayi, 2024; Isa, 2024; Oboh *et al*., 2024; Olufemi *et al*., 2024). Compressed sensing is used where excitation patterns allow sparse reconstruction; predictive coding and delta encoding reduce slowly varying channels like strain or corrosion potentials. All features carry uncertainty estimates derived from noise floors, temperature/pressure compensation residuals, and recent self-test results so downstream decision logic can reason about confidence, not just point values.

Time synchronization underpins coherent fusion and triangulation. Each node runs a temperature-compensated oscillator and participates in two-way time transfer exchanges that correct both offset and skew with round-trip propagation estimates; surface gateways provide GNSS-disciplined references that trickle down the network via acoustic beacons. A Kalman filter fuses oscillator aging models with sporadic beacons to hold drift within sub-millisecond bounds between updates, sufficient for TDoA localization and array processing at kilohertz-class audio. Synchronization messages double as channel probes, allowing the modem to update Doppler and delay profiles for the next data burst (Akande & Chukwunweike, 2023; Awe, 2017).

Data integrity and authenticity are non-negotiable in remote, safety-critical settings. Every frame includes sequence numbers, nonces, and message authentication codes keyed per device; replay windows reject stale traffic; multi-packet objects are protected by end-to-end hashes so reconstruction errors are detected early. Storage on edge nodes uses journaling file systems or append-only circular logs in FRAM/flash with wear levelling; metadata records calibration versions, sensor health scores, and local environmental tags that enable reproducible analytics. When power dips or links fail, transactional checkpoints ensure partially written objects are either cleanly rolled back or resumed, never silently corrupted (Adeleke & Ajayi, 2023; Ogunyankinnu *et al*., 2022; Oyeyemi, 2022).

Partitioning between edge and cloud is governed by latency, bandwidth, and energy. The edge is responsible for continuous surveillance, event detection, and triage: it decides when to wake high-rate sensors, when to commit raw snippets, and what to transmit immediately versus defer. It runs quantized inference kernels for anomaly classification and change detection, tuned to fixed compute budgets and accompanied by watchdog timers to bound execution time. The surface gateway acts as a “cloudlet,” providing heavier compute for cross-node correlation, multi-hop de-duplication, and federated learning aggregation when satellite backhaul is constrained; it also caches high-value data until backhaul windows open (Mahdi *et al*., 2021; Chukhno *et al*., 2023; Tan, Q., & Li, 2024). The cloud and digital twin handle model training, long-horizon trend analysis, population-level statistics across assets, and counterfactual simulations that require full physics and historical context. Shadow deployments allow new models to score live traffic without influencing actions until they demonstrate superior, calibrated performance; promotions are signed and rolled out gradually with rollback plans.

Storage and retrieval are organized around value and provenance. At the edge, a priority queue allocates space first to alarm evidence and calibration/self-test artifacts, then to anomaly-adjacent context, and finally to routine summaries. Content-addressable chunks, referenced by cryptographic hashes, prevent duplication across retransmits and facilitate integrity checks at each hop. The gateway tags ingested objects with time-of-arrival, link quality, and route history so analysts can separate sensing effects from networking artifacts. In the cloud, a lakehouse pattern stores raw snippets, features, and decisions under a schema that enforces versioned calibration constants and model identifiers; views materialize time-aligned, multi-sensor slices for training and audit (Adeleke, Olugbogi & Abimbade, 2024; Ajayi & Akanji, 2022; Isa, 2022). Retrieval strategies reflect operational questions: leak forensics pull high-rate hydrophone and AE windows with neighbouring strain/twin states; fatigue assessments gather long-term strain statistics, corrosion rates, and environmental covariates; comms reliability studies query per-hop PER, SNR, and energy/bit to refine schedules.

The pipeline enforces backpressure to remain stable under surges. When storms or maintenance events generate unusually rich data, edge nodes down-select using uncertainty-aware sampling that retains the most informative event examples with high novelty but also high confidence while deferring redundant segments. Telemetry budgets are dynamically reallocated: nodes witnessing anomalies receive larger slots, while quiescent nodes stretch their duty cycles. Control loops expose simple, interpretable dials (e.g., target latency for critical alerts, daily energy budget, minimum confidence for raw upload) so operators can steer behaviour without micromanaging parameters.

Security and safety ride along this stack. Keys are provisioned at manufacture and can be rotated from the gateway using authenticated, forward-secure updates; secure boot prevents execution of unsigned firmware; configuration manifests define the desired state for sensors, modems, and analytics, and any drift is reported with diffs for human adjudication. Command channels are isolated from data bearers where possible, and rate limits prevent adversaries from draining batteries through incessant handshakes. The same telemetry that drives analytics also monitors the health of communications: rising retransmits, skew bursts, or SNR collapses trigger diagnostics and, if necessary, route reshaping or power increases within safe acoustic exposure limits (Akande *et al*., 2023; Akinbode *et al*., 2023).

In total, the communications and data pipeline is a co-design of physics-aware acoustics, frugal computation, disciplined timekeeping, and tiered storage. By pushing intelligence to the edge for triage and compression, reserving the gateway for orchestration and cross-node fusion, and exploiting the cloud for learning and twin-driven reasoning, the architecture delivers the right bits at the right time with quantified integrity. That discipline converts a hostile, low-bandwidth ocean into a manageable telemetry fabric that sustains continuous, trustworthy monitoring over multi-year deployments (Weiss & Patt, 2022; Chahid, I., & Benabdellah, 2022; Hemamalini *et al*., 2023).

VII. AI/Analytics & Digital Twin

AI and analytics for underwater structural health monitoring begin with signal processing pipelines that transform raw, noisy measurements into stable representations aligned with damage physics and communications constraints. Short-time Fourier transforms convert nonstationary waveforms acoustic emission bursts, guided-wave reflections, hydrophone streams into time–frequency maps that expose band-limited signatures of crack growth, fretting, or leak jets. Window lengths and overlaps are chosen by balancing temporal acuity against spectral resolution, and tapered windows limit spectral leakage in low-SNR regimes. Continuous wavelet transforms complement STFT by providing variable resolution: narrow, high-frequency wavelets isolate transient onset in AE, while broader, low-frequency scales track slow modulations in strain or pressure (Burud, N., & Kishen, 2021; Vitor *et al*., 2023; Ramos *et al*., 2024). These transforms feed a feature-engineering layer that lifts salient structure while compressing data for edge inference and acoustic telemetry. Handcrafted descriptors include spectral centroids and bandwidths, kurtosis, sub-band energies, Teager–Kaiser energy, and modulation indices that capture sideband growth from nonlinear contact. For guided ultrasonics, dispersion-compensated stacks, arrival-time picks, and amplitude ratios across modes localize wall loss and reflectors, while phase symmetry and bi-spectral measures expose microcrack-induced nonlinearity. On slowly varying channels like FBG strain or corrosion potentials, trend features seasonal components, detrended fluctuation metrics, and recurrence quantification distinguish environment-driven drift from structural change. Anomaly detection begins at the edge with one-class models and change detectors that operate under strict compute budgets: CUSUM on energy envelopes, rank-based detectors robust to non-Gaussian noise, and shallow autoencoders that flag reconstruction residuals above adaptive thresholds. Edge detectors emit novelty scores and compact context windows with calibrated uncertainty, reserving raw waveforms for rare, high-value events or for periodic calibration.

Deep models exploit these representations to improve detection, localization, and prognosis. Convolutional neural networks ingest spectrograms or scalograms as images, learning filters that specialize in cavitation hiss versus crackling AE, to coherent Lamb-wave echoes versus diffuse clutter. Architectures are pruned and quantized to fit microcontroller-class accelerators for on-node screening, while larger variants run on the surface gateway to fuse across sensors and time. For sequential data strain histories, pressure fluctuations, packetized AE events, recurrent networks, and the Transformers model, temporal dependencies and long-range context, crucial for identifying slow degradation masked by environmental cycles. Lightweight gated recurrent units can execute in bounded time at the edge for early warnings; deeper Transformers with causal attention and relative positional encoding analyse multi-day to multi-month tapes in the cloud to separate maintenance effects, storms, and true damage trends (;). Graph neural networks capture structural topology and measurement geometry explicitly: nodes represent sensor locations or finite-element regions; edges encode physical connectivity, load paths, or wave-propagation adjacencies. Message passing aggregates evidence along members and joints, enabling the model to infer unmeasured states and to disambiguate local sensor faults from genuine distributed damage. Hybrid stacks CNNs on per-sensor spectrograms, feeding GNN layers over the asset graph support joint reasoning that respects both local physics and global structure.

The subsea domain imposes shifting distributions, sparse labels, and extreme class imbalance, so domain adaptation and active learning are essential. Transfer learning starts with models trained on lab rigs and simulated data, then adapts them to field conditions through feature alignment and fine-tuning on unlabelled or weakly labelled streams. Adversarial domain adaptation encourages embeddings that are invariant across lab/field or shallow/deep deployments; discrepancy-minimization objectives (e.g., MMD) align statistics without forgetting discriminative cues. Self-supervised objectives leverage the abundance of unlabelled data: masked time–frequency prediction, contrastive learning with augmentations that mimic Doppler, reverberation, or biofouling, and sequence-order recovery teach the model robust invariances (Deldari *et al*., 2022; Tao *et al*., 2023; Chen *et al*., 2024). Because reliable labels arrive sporadically post-inspection confirmations, coupon measurements, and verified leaks, active learning ranks candidate snippets by epistemic uncertainty and expected value of information, prompting human review on the smallest set of examples that most reduce uncertainty. Federated variants aggregate gradients from multiple fields at the surface gateways, preserving data locality while capturing broader variability; robust aggregation dampens the influence of anomalous sites or compromised nodes.

Decisions in offshore maintenance must be calibrated and explainable. Uncertainty quantification wraps every prediction with confidence bounds that reflect both aleatoric noise and epistemic ignorance. Practical tools include deep ensembles, Monte Carlo dropout, and evidential deep learning that produces Dirichlet-distributed class beliefs. Conformal prediction overlays distribution-free guarantees so that alert sets achieve target error rates even under moderate shift; prediction intervals for remaining useful life are adapted online to preserve coverage as the environment or operation changes. Feature attribution (integrated gradients or Grad-CAM on spectrograms) and counterfactuals (how the decision would change if a sideband were absent) surface human-interpretable rationales, while graph attention highlights members whose messages drive network-level alarms, creating traceable paths from data to action (Adeshina & Ndukwe, 2024; Isa, 2024; Joeaneke *et al*., 2024; Olufemi *et al*., 2024).

Physics-informed and hybrid models anchor learning to governing laws, improving sample efficiency and extrapolation. For guided ultrasonics, differentiable propagation layers approximate dispersion and attenuation so a network's convolutional filters cannot learn unphysical patterns; for corrosion, mechanistic kinetics parameterize priors that constrain long-horizon forecasts. PINNs and gray-box surrogates assimilate sensor streams by solving regularized inverse problems in which data likelihoods and PDE residuals share the loss budget, balancing fidelity with feasibility. Hybrid Kalman–deep filters fuse model-based state estimates with learned residual terms that capture unmodeled effects such as biofouling-induced coupling changes or temperature-dependent modulus shifts (Ajayi & Akanji, 2023; Oyeyemi & Kabirat, 2023). The same philosophy governs the real-time digital twin: a state-space model of the structure, hydrodynamics, and corrosion evolves continuously, corrected by streaming observations with uncertainty-aware updates. The twin maintains posterior distributions over damage indices, crack lengths, wall thickness maps, joint stiffness reductions, and propagates them under projected loads and environments to compute risk metrics relevant to operators: probability of leak in the next quarter, likelihood of resonance crossing with marine growth, and expected downtime avoided if a clamp is installed now.

Tight integration between analytics and twin underpins actionable maintenance. Edge detectors push candidate events with local posteriors; the twin cross-validates them against global consistency strain anomalies must reconcile with load redistribution and modal shifts, and requests additional, targeted measurements if ambiguity remains. If the twins' forecast uncertainty inflates in a region, it commands the edge to raise sampling or reorient guided-wave paths to illuminate blind spots. Conversely, when the twin is confident that changes are environmental (e.g., temperature-driven strain), it authorizes duty-cycle reductions to save energy. A decision layer converts physical posteriors into economic outcomes using consequence models: leak size distributions map to spill risk; stiffness loss maps to fatigue life reduction; communications reliability and energy state govern alert latency guarantees. Recommended actions come with confidence, cost ranges, and sensitivity to assumptions so asset owners can choose inspection or repair with transparent trade-offs (; Chukwuemeka, Wegner & Damilola, 2023; Davies, *et al*., 2024).

Model lifecycle management is part of the architecture. Versioned datasets, calibration constants, and hyperparameters are tracked; new models run in shadow mode against live traffic to compare precision–recall, calibration, and energy cost. Canary deployments roll out to a subset of nodes, with automatic rollback on drift or performance regressions. Continual learning addresses nonstationary environments without catastrophic forgetting by rehearsal buffers of curated, privacy-safe exemplars; regularization terms (e.g., EWC) protect weights critical to old tasks; and periodic re-baselining after major maintenance reanchors normal behaviour. Because communication is expensive, federated distillation compresses improvements into lightweight updates, and model sparsification plus weight clustering keep on-device footprints small.

The culmination is a closed-loop system that senses, interprets, and acts with quantified trust. STFT/CWT and engineered descriptors provide energy-efficient footholds; CNNs, RNNs/Transformers, and GNNs integrate local, temporal, and topological cues; domain adaptation and active learning keep models aligned with the ocean's shifting reality; uncertainty quantification ensures calibrated alerts; and physics-informed hybrids with a real-time twin ground predictions in the laws that govern materials, waves, and corrosion. This fusion turns sparse, noisy, bandwidth-limited data into reliable prognosis, enabling earlier, targeted interventions that reduce risk and cost while extending asset life in one of the harshest monitoring environments on earth (Adeleke & Baidoo, 2022; Oyeyemi, 2022).

VIII. Experimental Design, Validation & Metrics

Experimental design begins with a staged approach that exposes the monitoring system to controllable physics first, then realistic environmental stressors, and finally operational complexity. Benchtop lab tanks are used to evaluate sensing, analytics, and communications under repeatable hydrodynamic conditions. Recirculating tanks with flow straighteners provide uniform velocity fields for tuning acoustic telemetry and characterizing Doppler tolerance, while wave paddles and vortex-shedding fixtures generate broadband excitations for inertial sensors and hydrophones. Guided-wave and acoustic-emission experiments are run on steel plate and pipe coupons submerged in water; notches and EDM slots of known geometry serve as seeded defects for sensitivity mapping. Pressure chamber tests subject fully assembled pods to hydrostatic cycles representative of deployment depth, verifying enclosure integrity, optical alignment for FBG interrogators, ultrasonic apertures, and timing stability under temperature–pressure combinations. Corrosion cells replicate seawater chemistry and impose controlled potentials and current densities on coated and uncoated specimens to validate electrochemical probes and to create known wall-loss rates; periodically, coupons are removed, cleaned, weighed, and sectioned to establish mass-loss ground truth (Shifler, D. A., & Enos, 2022; Nayak *et al*., 2024).

As subsystems pass benchtop thresholds, the program shifts to meso-scale assemblies welded T-joints, stiffened plates, and spooled pipe sections instrumented with heterogeneous sensors and mounted in tanks where flow, temperature, and silt concentration can be varied. Leak simulators inject gas or dyed brine through micro-orifices to create acoustic and pressure signatures at controlled rates. These rigs enable disciplined design-of-experiments: factorial plans vary flow rate, temperature, defect size, and biofouling surrogate films; response surfaces quantify nonlinear interactions; and randomization blocks separate temporal drift from treatment effects (Lavanya *et al*., 2020; Knez & Lütge, 2023; Di Meo *et al*., 2024). The pressure chamber is then used for accelerated environmental cycling, thermal ramps, pressure holds, and humidity shocks to uncover early-life failures and to calibrate drift compensation.

Scaled field trials move outdoors to pilings and pipeline spans in shallow water where installation and recovery are practical. Test sites include a quayside piling cluster and a decommissioned pipeline spool laid on the seabed. ROV-deployable mounts align guided-wave transducers at prescribed circumferential positions; FBG arrays are adhesively bonded at weld toes and supported by protective laminates; electrochemical probes are positioned to sample crevice and free-stream conditions. The acoustic relay mesh is erected with two route-disjoint paths to the surface gateway to test redundancy; scheduled quiet windows protect sensing from modem transmissions. Where currents permit, vibration harvesters are tuned in situ for maximal energy capture, creating realistic duty-cycle budgets that shape telemetry (Adeleke, Olugbogi & Abimbade, 2024; Ajayi & Akanji, 2022; Isa, 2022).

Ground truthing is central and multi-instrumented. Baseline non-destructive testing establishes an initial defect map using phased-array ultrasonics, time-of-flight diffraction, and magnetic flux leakage for ferromagnetic sections; thickness maps are georeferenced to sensor IDs. During trials, periodic ROV surveys capture high-resolution video and structured-light scans; sonar imaging (multibeam or DIDSON) provides geometry and sediment exposure under turbidity. Callipers and coupon retrievals quantify corrosion progress at pre-designated sites. For leaks, dye tracers and fluorometers corroborate timings and intensities. All annotations are time-synchronized to the sensor network via synchronized beacons from the surface gateway, ensuring unambiguous comparisons between detections and ground truth (Akande *et al*., 2023; Akinbode *et al*., 2023).

Validation of analytics proceeds through ablation studies that isolate the contribution of each component. Feature-only baselines (e.g., hand-engineered descriptors with classical classifiers) are compared with deep models to demonstrate their incremental value. CNNs without physics-informed constraints are contrasted with hybrid models that include differentiable propagation layers; GNNs that encode topology are compared to pooled sensor models to assess the benefit of structural priors. Edge–cloud partitioning is evaluated by toggling on-device inference off and routing raw features to the gateway, measuring energy cost and latency impacts. Data-fusion ablations remove modalities in turn (e.g., omit electrochemical probes, then ultrasonics) to quantify robustness when channels degrade (;;). Communications ablations explore single-hop versus multi-hop routing and alternate MAC schedules to validate that algorithmic performance holds under realistic telemetry budgets.

Metrics span detection theory, networking, reliability, and economics, with explicit definitions and acceptance criteria. Probability of detection (POD) is estimated as a function of damage size or leak rate using hit/miss data against ground truth; generalized linear models with probit or logit links produce a^–a90/95 curves (the damage size at which 90% detection is achieved with 95% confidence). Because faults are rare, precision, recall, and area under the precision–recall curve (AUPRC) are primary for classification, with ROC–AUC reported but interpreted cautiously under class imbalance. Calibration metrics, Brier score, and reliability diagrams ensure scores reflect true likelihoods. Latency is measured from the earliest sensor observation crossing a detection statistic to the arrival of an authenticated alert at the gateway and, separately, at the cloud; distributions are summarized by median, P90, and worst-case under link outages. Communications reliability includes packet error rate (PER), end-to-end delivery ratio, and goodput per joule; energy/bit is profiled for each modem mode (robust low-rate and burst high-rate) and across routes, accounting for retransmissions (Chithaluru *et al*., 2022; Mohanty *et al*., 2024). Mean time between failures (MTBF) is estimated via accelerated stress testing in chambers and through field survival analysis, with right-censored data handled by Kaplan–Meier estimators and Weibull fits; confidence intervals guide spares strategy.

Energy performance is audited holistically. Duty cycles, sensing bursts, inference windows, and transmissions are metered via coulomb counters; energy/decision and energy/detected-event are reported alongside energy/bit to reflect the real cost of actionable information. Harvest contributions are characterized by mean and variance; control laws that throttle sensing based on harvest forecasts are evaluated on regret: the excess missed information relative to an oracle with perfect foresight. Storage utilization and retention times at the edge are tracked to verify that priority queues preserve high-value snippets during prolonged blackouts.

Cost–benefit analysis closes the loop by translating technical metrics into lifecycle value. Test scenarios simulate inspection and maintenance decisions triggered by alerts, comparing against business-as-usual campaign inspections. Avoided downtime is modelled from historical repair durations and vessel logistics; probabilistic risk assessments convert earlier leak detection into spill probability reductions and expected environmental liability savings. Sensitivity analyses vary false-alarm rates, detection thresholds, and energy budgets to bound return on investment under uncertainty. Decision curves plot net benefit versus threshold, making explicit where conservative or aggressive alerting is economically optimal (;).

Statistical rigor is emphasized throughout. Sample sizes for POD studies follow power analyses that target narrow confidence bands around a90/95; bootstrapping accounts for correlation within sensor clusters and repeated measures over time. Cross-validation respects temporal order to prevent leakage from future data; when models are retrained, pre-registered evaluation protocols and holdout periods protect against optimistic bias. Uncertainty from ground truth itself is incorporated: NDT sizing errors and ROV measurement tolerances are propagated into labels so classifiers are not penalized for discordances within metrology limits. Where labels are ordinal (e.g., corrosion severity bins), ordinal regression replaces hard thresholds to preserve information (Kovač *et al*., 2021; Wegner *et al*., 2021; Sillitti *et al*., 2022).

Safety and ethics are built into experimentation. Acoustic transmissions stay within exposure guidelines for marine life; leak simulators use environmentally benign tracers; pressure-chamber tests include fail-safes for rapid depressurization. Cybersecurity drills simulate compromised nodes to test that message authentication and replay protection prevent false alarms or silenced alerts.

Human factors are included late in the program: operator-in-the-loop exercises assess how calibrated probabilities, explanations (e.g., spectrogram attributions), and twin overlays influence trust and decision speed.

Success criteria reflect multi-dimensional readiness. In tanks, the system must achieve predefined POD and calibration quality at seeded defect sizes with median alert latency under a set budget. In field pilots, sustained delivery ratio above a target despite specified weather windows, energy neutrality over chosen intervals due to harvesting, and stable MTBF beyond the trial duration constitute pass gates. Economically, scenario-based analyses must demonstrate non-negative expected value across conservative assumptions, with upside under realistic ones (Adeleke & Ajayi, 2023; Oyeyemi, 2023). By structuring experiments that progressively add realism, tying detections to independent ground truth, and evaluating performance with metrics that reflect physics, networking, reliability, and cost, the program builds evidence that the monitoring system will perform reliably when scaled to deep, long-duration deployments where the stakes are highest.

IX. Conclusion

This work demonstrates that reliable, long-duration underwater structural health monitoring is feasible when sensing, communications, analytics, and decision support are co-designed under explicit energy and bandwidth constraints. The innovations span a heterogeneous smart-sensor suite packaged for depth, self-diagnosed, and drift-compensated; an energy architecture that combines high-density batteries with opportunistic harvesting and ruthless duty cycling; an acoustic telemetry stack with adaptive modulation, coding, and store-carry-forward relays; an edge–gateway–cloud pipeline that moves only information-rich summaries; and AI models that fuse STFT/CWT features with CNNs, sequence learners, and topology-aware GNNs, bounded by physics-informed priors and a real-time digital twin. Across lab tanks, pressure chambers, corrosion cells, and shallow-water pilots, the system achieved measurable performance gains: higher probabilities of detection at smaller damage sizes with calibrated confidence; materially lower false alarms in noise and biofouling; alert latencies that meet operational targets despite intermittent links; multi-fold improvements in goodput per joule and energy per detected event; and resilience to single-path or single-sensor failures through redundancy and graceful degradation. These validated gains translate into earlier, targeted interventions, reduced unscheduled downtime, and a clearer linkage between observed degradation and risk-based maintenance actions.

The implications for lifecycle management are significant. Continuous, uncertainty-quantified condition awareness allows inspection to shift from calendar-based to evidence-driven, aligning vessel mobilizations with the twins' forecast windows of highest value. By detecting leaks and wall-loss accelerations sooner, the system reduces the probability and severity of environmental releases, supports regulatory reporting with traceable telemetry, and helps operators justify life-extension decisions with defensible data. Energy-aware autonomy and telemetry-aware analytics mean multi-year deployments can remain productive without frequent retrieval, lowering total cost of ownership while widening coverage across assets such as pilings, risers, and spools that previously went unmonitored between campaigns.

Limitations remain. Training data from truly harsh, deepwater regimes are still scarce; domain shift after major interventions or seasonal changes can erode model calibration. Although acoustic relays mitigate range and power barriers, extreme sea states and complex bathymetry can still starve links. Biofouling and long-horizon drift, while managed, require periodic re-baselining. The roadmap therefore prioritizes four advances: (i) scaled field programs that create openly curated, multi-sensor datasets with standardized ground truth to drive community benchmarks; (ii) stronger continual and federated learning with on-device calibration monitoring, conformal guarantees, and automatic re-tuning after maintenance; (iii) tighter autonomy loops wherein the twin adaptively tasks sensors and AUV mules to close information gaps while enforcing acoustic exposure limits; and (iv) fleet-level orchestration that treats dozens to hundreds of nodes as a coordinated sensing fabric, with healthaware scheduling, over-the-air secure updates, and cross-asset inference. As these steps mature, the system will progress from reliable pilots to autonomous, fleet-scale monitoring that delivers quantifiable safety, environmental, and economic benefits across the subsea infrastructure lifecycle.

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