

Comprehensive review of leak detection and localization in subsea oil and gas pipelines

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Abstract—Detection of underwater pipeline leakage is essential in the oil and gas sectors because of its potential to cause environmental harm, financial loss, and safety hazards. This article compares several leak detection systems, including classical and emerging technologies, and addresses localization strategies for pipeline breaches. Significant problems, including sensor malfunctions, data integrity, signal disruption, and scalability, are also discussed. Case studies are used to bridge the gap between theory and practice by illustrating practical applications and assessing their efficacy, limitations, and lessons learned. A comparative study of previous research highlights existing gaps and future research directions focused on improving detection accuracy, localization precision, and cost-effectiveness. This review offers critical insights to enhance next-generation underwater pipeline monitoring systems.

Keywords—Subsea pipelines; Leak detection; Localization; Artificial intelligence; Acoustic monitoring; Sensor fusion; Emerging technologies

I. INTRODUCTION

SUBSEA pipelines are an essential component of offshore oil and gas infrastructure, providing efficient transportation of hydrocarbons from production locations to processing and distribution systems. However, their operation in severe marine environments is challenged by factors such as high hydrostatic pressure, corrosive seawater, strong ocean currents, and complex fluid–structure interactions, which increase the possibility of leakage and structural degradation [1]. Leak detection and localization are crucial for operational safety, reduction of economic losses, and protection of marine ecosystems. Detecting leaks in subsea pipelines is much more difficult than in land-based systems [2]. Leak signatures are often weak and distorted owing to signal attenuation, high background noise, multiphase flow, and changing ambient conditions [3]. Conventional approaches, including pressure, flow, and acoustic monitoring, can be less sensitive or slow to respond in underwater settings [4]. These constraints have driven the development of advanced monitoring solutions, including distributed sensing, fiber-optic technology, wireless sensor networks, remote inspection systems, and artificial intelligence (AI)-driven analytics. Recent advances in machine learning (ML) and data-driven monitoring have shown great potential to improve leak detection accuracy and reduce false alarms by extracting meaningful information from various sensor data. At the same time, data availability, implementation costs, robustness under various operating conditions, and the

transfer from simulation to reality still pose challenges to widespread industrial deployment [5]–[7].

This paper provides a comprehensive review of both traditional and new technologies for leak detection and localization in subsea pipelines. It discusses the operational principles, advantages, and limitations of the primary detection and localization techniques, reviews current research trends, identifies key technical challenges, and highlights potential future directions for the development of reliable and deployable subsea monitoring systems.

II. OVERVIEW OF OIL AND GAS PIPELINE LEAKAGE DETECTION AND LOCALIZATION

A. Characteristics of Leakage Detection in Onshore and Underwater Pipelines

Leak detection in underwater pipelines differs fundamentally from that in onshore systems because of their different operating environments. Pipelines on land are generally more accessible and are laid under relatively stable conditions. This allows the use of direct monitoring techniques, such as visual inspection, infrared thermography, soil-gas measurements, and mass-balance methods [3]. In contrast, subsea pipelines are exposed to high hydrostatic pressure, persistently low temperatures, and hydrodynamic forces that vary with ocean currents and waves. These factors strongly influence both the formation of leaks and the propagation of their signatures in the surrounding medium. A conceptual diagram of a localized pipeline leak is shown in Fig. 1. This schematic serves as a reference for analysing the different leakage characteristics and detection difficulties in terrestrial and aquatic environments.

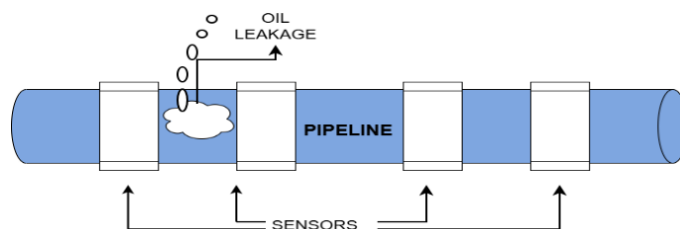


Fig. 1. Simplified schematic representation of a pipeline segment with a leakage point.

Onshore pipeline leaks tend to saturate the soil, pool on the surface, or produce visible vapor plumes. Consequently, onshore leaks are relatively easy to detect. Underwater leaks, by contrast, usually produce complex multiphase jets with rapid velocity decay and buoyancy-driven upward plume motion as gas bubbles fragment within the water column. This weakens

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the resulting signals and reduces their spatial coherence, making them difficult to detect and localize, particularly for small or nascent breaches [2]. Acoustic and vibration-based monitoring also differ between the two settings. Onshore acoustic emissions travel through air and soil with little background noise, whereas ambient noise in aquatic habitats is greatly increased by marine organisms, vessel traffic, and flow-induced turbulence. The resulting degradation of the signal-to-noise ratio (SNR) hinders conventional threshold-based and spectral detection approaches, creating a need for advanced signal-processing and learning-based methods.

The gap between onshore and subsea systems is further widened by practical constraints on sensor placement. Onshore pipelines are densely instrumented and routinely inspected manually, whereas underwater pipelines are monitored by sparsely distributed sensors, remotely operated vehicles

(ROVs), autonomous underwater vehicles (AUVs), or permanently fixed monitoring nodes. These methods raise operational costs and restrict the amount of data available [8]–[10]. Hence, underwater leak detection relies more heavily on multimodal sensing, data fusion, and model-based inference to handle incomplete and noisy observations. These differences make it difficult to transfer leak detection methods used for onshore pipelines to subsea systems without significant modification. Successful detection of underwater leaks therefore requires specialized sensing architectures and noise-tolerant, physics-informed, or data-driven models adapted to subsea operating conditions.

Table I summarizes the main differences between onshore and underwater pipeline leak detection, emphasizing the environmental, sensory, and algorithmic issues specific to subsea systems.

TABLE I
COMPARISON OF LEAKAGE DETECTION CHARACTERISTICS IN ONSHORE AND UNDERWATER PIPELINES

Ref	Aspect	Onshore Pipelines	Underwater (Subsea) Pipelines
Ref [2], [5]	Operating environment	Relatively stable terrestrial conditions; accessible terrain	High hydrostatic pressure, low temperature, dynamic currents and waves
Ref [2], [3]	Signal-to-noise ratio (SNR)	Moderate to high	Typically low, especially for small leaks
Ref [3], [8]	Sensor deployment	Dense placement feasible; easier maintenance	Sparse deployment; high installation and maintenance cost
Ref [8], [10]	Inspection accessibility	Direct human access feasible	Requires ROVs, AUVs, or permanent subsea installations
Ref [2], [4], [10]	Leak localization accuracy	Relatively high due to clear spatial cues	Reduced due to signal dispersion and environmental uncertainty

B. Types of Pipeline Leakage and Detection-Relevant Characteristics

Leakage from subsea pipelines poses a major environmental and economic threat, yet such events are difficult to detect. The difficulty depends on the leak size, leak rate, and surrounding environment. For monitoring purposes, leaks are typically classified as chronic (slow) or rupture (burst) events. Minor defects, such as pinholes, microcracks, or progressive material degradation, usually cause chronic leakage. Because the amount of fluid discharged at any one time is very small, these leaks are easily overlooked, particularly in their early stages [2]. They can persist undetected for long periods, allowing damage to accumulate. The problem is compounded in deepwater environments by high hydrostatic pressure, elevated ambient noise, and signal attenuation, which make it challenging to distinguish faint leakage indicators from normal operational fluctuations. Pressure-based monitoring can detect moderate to large leaks under stable, single-phase conditions, but its reliability is reduced under transient or multiphase flow conditions [11]. Because of these limitations, various alternative methods have been investigated over the years. Real-time transient monitoring (RTTM) coupled with statistical decision techniques such as the sequential probability ratio test (SPRT) has been used to detect slow leaks in complex flow environments. Fiber-optic sensing techniques, such as

distributed temperature sensing (DTS) and distributed acoustic sensing (DAS), provide continuous spatial coverage and are sensitive to small changes along the pipeline. However, their offshore utilization is often hampered by installation costs, difficulties in retrofitting existing infrastructure, and long-term maintenance issues. Sonar systems mounted on AUVs are used for inspection, particularly for identifying gas bubbles or plume-related anomalies [8], [12], but their intermittent deployment precludes continuous monitoring.

Rupture leaks represent a distinctly different scenario. Such events are often caused by sudden failures due to corrosion, mechanical impact, fatigue, or extreme seabed conditions [9], [13]. Quick detection is more important than accurate initial quantification, as large volumes of hydrocarbons can be released in a short time. Once released, the plume's evolution is strongly influenced by local currents, turbulence, and fluid properties, which govern its dispersion and the likelihood of it reaching the surface [7], [14]. Release rates and plume dynamics are frequently assessed with computational fluid dynamics (CFD) models based on the Reynolds-averaged Navier–Stokes equations and multiphase flow properties. Although these models provide valuable physical insights, they depend heavily on external inputs, and their computational requirements may challenge real-time responsiveness [6], [7].

Operationally, leaks can also be classified by whether their cause is internal or external. Internal leaks are usually linked to

corrosion, pressure cycling, or material fatigue and are principally monitored by pressure, flow, or chemical measurements. Pipelines buried in seabed sediments are less exposed to aerobic corrosion; however, microbiologically influenced corrosion remains a major threat, and internal monitoring is required. External leaks are generally due to mechanical damage, environmental exposure, or third-party interference [5]. These are usually studied using acoustic methods [15], infrared imaging, or underwater visual inspection. In subsea environments, however, these methods are hampered by poor visibility, biofouling, and high deployment costs, which reduce their effectiveness and limit long-term reliability [10].

Recently, the focus has shifted to hybrid and multimodal detection systems that combine multiple sensing principles rather than relying on a single approach. Combining pressure, acoustic, visual, and chemical measurements help overcome the limitations of each individual method. Advanced acoustic imaging techniques such as synthetic aperture sonar (SAS) and sub-bottom profilers (SBPs) can provide additional spatial data by revealing sediment disturbances or plume formations [16]. Advances in non-uniform sampling and frequency-domain analysis have also increased sensitivity to subtle leak-related features in complex seabed environments. Experience from both research and field applications shows that subsea pipeline leak detection cannot be achieved with a single universal solution. Detection strategies should be chosen according to leak type, ambient conditions, sensor availability, and required response time. Chronic leaks require continuous and accurate monitoring in low-SNR environments, whereas rupture events require rapid detection and approximate localization to allow emergency intervention. Internal and external leakage also need different monitoring strategies. These practical differences motivate the systematic examination of detection scenarios and technical constraints presented in the next section.

C. Leak Detection Technologies and Their Application Limits

Leak detection systems are not universally applicable to the monitoring of underwater pipelines. Their performance relies heavily on local environmental conditions, pipeline configuration, and the level of localization required for a particular application [10]. Thus, most detection methods are effective only within specific operating envelopes and are better suited to particular subsea scenarios than to general-purpose use.

1) Traditional Physics-Based Technologies

Traditional methods such as pressure or flow imbalance analysis and acoustic emission monitoring are usually used in environments with reasonably stable operating conditions. Pressure transient analysis works best for linear, elongated pipeline sections with few branches, where hydraulic behaviour can be modelled accurately and sensor timing is consistent. In deepwater pipelines, however, variable flow regimes and large hydrodynamic loads often mask the pressure signatures of small leaks. This increases the false-alarm rate and reduces sensitivity [17].

Acoustic methods are attractive for early leak detection because nascent leaks generate turbulence and cavitation, which emit detectable sound. However, they are highly sensitive to

environmental noise [15], [18]–[20]. In shallow or coastal waters, leak-related signals may be masked by noise from maritime traffic, aquatic activity, and environmental disturbances. As a result, acoustic systems in these scenarios are often geared toward detecting anomalous events rather than providing accurate leak localization.

2) Fiber-Optic and Distributed Sensing Technologies

Fiber-optic sensing systems such as DTS and DAS allow continuous monitoring along the pipeline and are often used for high-value or environmentally sensitive assets [21]. These systems must withstand high pressure and temperature variations. Installation requires close contact between the fiber and the pipe surface, which makes deployment difficult and the retrofitting of existing subsea equipment costly. Moreover, despite good spatial resolution, performance can degrade in regions with uneven thermal gradients or inconsistent seabed contact, limiting large-scale application across different seabed environments.

3) Vision-Based and Remote Inspection Technologies

ROV- and AUV-based inspection systems are commonly employed for specific inspections and post-event assessments. They are particularly useful when visual confirmation of damage or plume activity is desired. However, they are limited by water turbidity, poor visibility, and finite mission duration. Although these platforms can achieve high localization accuracy under favorable conditions, the episodic nature of their data collection makes them unsuitable for early-stage or real-time leak detection [8], [12].

4) Data-Driven and AI-Based Technologies

ML and deep learning techniques have received much attention because of their ability to deal with complex and chaotic signals in underwater environments. Such approaches are particularly useful when data from different sensors, such as acoustic, vibration, pressure, and chemical measurements, are available. Their success depends strongly on the amount and representativeness of the training data [22], [23]. Models trained on limited field data or on large amounts of simulated data can have difficulty generalizing to unseen environments. Moreover, precise localization remains challenging in sparse sensor networks, which has led to increased interest in physics-informed learning and graph-based formulations.

5) CFD-Integrated and Digital-Twin-Based Approaches

ML and digital-twin methodologies integrated with CFD are typically used for critical subsea assets, where the increased computational expense is justified. By incorporating hydrodynamic constraints, these models are better suited to complex flow regimes and irregular seabed geometries. They can improve the prediction of leak evolution and spatial effects, but their practical use is limited by model accuracy, processing needs, and real-time implementation issues [24].

6) Summary of Application Boundaries

Several applications have shown that no single sensing method works optimally in all subsea conditions. The environment, operational goals, and localization requirements govern the choice and integration of methods for an effective monitoring strategy. A hybrid or layered system architecture is often a more pragmatic answer than reliance on a single technique. Identifying these boundaries clarifies where existing

technologies can be applied and where adaptive, integrated approaches are still required. Table II summarizes the application range and technical limitations of the main

underwater pipeline leak detection technologies, showing their suitability for different environmental conditions, flexibility, and localization difficulty.

TABLE II
APPLICATION SCOPE AND TECHNICAL BOUNDARIES OF UNDERWATER PIPELINE LEAK DETECTION TECHNOLOGIES

Ref	Technology Category	Typical Application	Environmental Constraint	Localization Difficulty	Key Limitation
Ref [10], [17]	Pressure / Flow-based	Long, stable pipelines	Flow variability, model uncertainty	Moderate	Low sensitivity to small leaks
Ref [15], [18], [20]	Acoustic sensing	Early-stage leak detection	Marine noise, turbulence	High	Low SNR in shallow or busy waters
Ref [21], [25], [26]	Fiber-optic (DTS/DAS)	High-value pipelines	Fixed installation required	Low	High cost, poor retrofitting
Ref [22]–[24], [27]–[29]	ML / Data fusion	Sparse, noisy sensor networks	Data availability	Moderate–High	Generalization and sim-to-real gap

D. Traditional Leak Detection Methods

Most industrial monitoring systems are based on traditional leak detection methods, mainly pressure and flow measurement, acoustic sensing, and chemical sensing. These techniques are popular because of their solid theoretical foundation, simple implementation, and compatibility with existing pipeline infrastructure. Pressure- and flow-monitoring techniques detect leaks by identifying deviations from the expected hydraulic behavior. Leak incidents are often accompanied by local pressure losses, flow imbalances, or transient disturbances such as negative pressure waves (NPWs), which can be detected by spatially distributed sensors along the pipeline. These methods are widely used and often based on hydraulic models, but their performance can be compromised by operational changes, sensor noise, and varying flow conditions, which can result in false alarms and a reduced ability to detect small leaks. Recent work increasingly combines pressure-based measurements with data-driven algorithms to improve detection reliability [11]. Acoustic sensing techniques listen for the noise created as fluid escapes through an opening. Hydrophones, accelerometers, or fiber-optic sensors can be deployed to detect sonic emissions due to turbulence, cavitation, and fluid–structure interactions. Signal-processing methods such as the wavelet transform, spectral analysis, and empirical mode decomposition are often used to extract leak-related features from noisy data. Acoustic technologies provide fast leak detection and localization, but their performance is often limited by signal attenuation, environmental noise, and variable propagation conditions, especially in subsea environments [20].

Chemical sensing offers a direct indication of a leak by measuring the concentration of hydrocarbons or dissolved gases released into the surrounding environment. Sensors that detect variations in hydrocarbon concentration can identify leaks even when physical signs are subtle or difficult to interpret. Chemical sensing devices generally provide localized coverage and are often expensive to install and maintain, and sensor fouling and environmental degradation can affect their long-term performance [3], [10]. Classical detection technologies still play an important role, but they often suffer from limited sensitivity, robustness, and tolerance to environmental variability. As

a result, contemporary subsea monitoring systems increasingly integrate multiple sensing modalities and advanced data-analysis techniques to enhance detection accuracy and operational reliability.

III. EMERGING TECHNOLOGIES FOR SUBSEA PIPELINE LEAK DETECTION

In recent years, the focus of subsea pipeline monitoring has shifted from conventional single-sensor approaches to intelligent, interconnected, and data-driven detection systems [22]. These new technologies aim to overcome the shortcomings of conventional techniques in challenging underwater environments characterized by high noise levels, sparse sensor deployment, and changing operational conditions. The main objective of these developments is to improve detection sensitivity, localization precision, and operational reliability while enabling continuous monitoring of large pipeline networks.

AI and ML are integral components of modern leak detection systems. Unlike classical threshold-based methods, AI models learn complex relationships directly from sensor data and are thus better suited to dealing with noisy and diverse measurements [23]. Supervised learning techniques, including support vector machines, Gaussian process regression, and multilayer perceptrons, have been used for structural integrity assessment and leak detection [30]. Deep learning models such as convolutional neural networks (CNNs) and long short-term memory (LSTM) networks have proven effective in processing vibration, pressure, acoustic, and magnetic-flux leakage signals. More recently, hybrid learning architectures involving several AI algorithms have shown better robustness and dependability, especially when data are scarce or ambiguous. The increasing availability of distributed sensing infrastructure has accelerated the deployment of intelligent monitoring systems [27]. Internet of Things (IoT) and wireless sensor network (WSN) architectures facilitate continuous collection of pressure, flow, temperature, vibration, and acoustic data from widely distributed pipeline sites. Sensor data can be transmitted to centralized platforms for analysis and decision-making support in near real time using low-power communication technologies

and underwater networking frameworks. These technologies provide the foundation for intelligent monitoring environments, including predictive maintenance and early anomaly detection [31]–[33].

Sophisticated acoustic, ultrasonic, and fiber-optic sensing technologies have become important elements of today's leak detection systems. DAS and DTS enable continuous monitoring along long stretches of pipeline and can detect small leak-related anomalies that traditional point sensors may fail to detect [25], [26]. In recent years, significant improvements in signal processing and ML have led to better interpretation of acoustic and ultrasonic data, with improved feature extraction and reduced influence of environmental noise [34]. Optical-fiber-based ultrasonic sensors have also shown good robustness against harsh subsea conditions, such as high pressure and electromagnetic interference [21]. Remote sensing and autonomous inspection technologies improve monitoring capabilities, especially for large-scale surveillance and post-incident evaluation. Unmanned aerial vehicles (UAVs), ROVs, AUVs, and satellite systems are being used to detect environmental anomalies, hydrocarbon plumes, and damage to infrastructure [8], [12], [35]. These platforms integrate automated image analysis and deep learning techniques to rapidly evaluate large pipeline systems, reducing the need for manual inspection. One of the main trends of current research is the integration of multiple sensing modalities by means of data fusion and sophisticated decision schemes. Data from pressure sensors, acoustic systems, fiber-optic networks, chemical sensors, and imaging platforms can be combined to increase

detection reliability and localization precision. Statistical fusion techniques, Bayesian inference models, Kalman filtering approaches, and deep-learning-based fusion designs have all been shown to reduce false alarms and improve system robustness compared with single-sensor solutions [28], [29], [36].

Recently, integrated physics-informed and digital-twin frameworks have been proposed as attractive options for next-generation subsea monitoring systems [24]. These methods integrate ML with CFD, hydrodynamic models, and real-time sensor data to improve model interpretability and generalization. Digital twins use operational data to update virtual models of pipeline assets in real time, enabling predictive maintenance, risk assessment, and simulation-based decision-making. Although these frameworks are very promising, challenges such as computational complexity, uncertainty quantification, real-time deployment, and lack of rigorous field validation remain major hurdles to their widespread use. New technologies are thus changing subsea leak detection from single-sensor systems to integrated intelligent monitoring platforms. The integration of AI, distributed sensing, advanced signal processing, data fusion, and physics-informed modeling is expected to play a significant role in the development of reliable, scalable, and deployment-ready systems for future subsea pipeline monitoring applications [28], [29]. Table III provides a system-level comparison of emerging pipeline leak detection technologies, highlighting practical trade-offs in accuracy, scalability, energy consumption, and robustness.

TABLE III
COMPARATIVE ANALYSIS OF DIFFERENT EMERGING TECHNOLOGIES

Ref	Technology	Detection Accuracy (%)	Sensitivity (L/min or dB)	Response Time (s)	Energy Use (W)	Robustness (% retention)	FPR (%)	FNR (%)	Scalability (nodes)	Computation Time (ms)	Interoperability	Security Level
Ref [22]–[24], [27]	Machine Learning	92–97	0.5–1.0 L/min	3–10	~20	85–90	3–5	4–7	100+	50–200	Medium	High
Ref [27], [31]–[33]	IoT-based Sensors	85–92	1.0–1.5 L/min	5–15	~5–10	80–85	5–8	3–5	1000+	20–100	High	Medium
Ref [15], [18], [34]	Acoustic Sensors	90–95	0.3–0.8 L/min or 2–4 dB	5–10	~2–5	90–95	2–4	4–6	50–100	10–50	Low	Medium
Ref [21], [25], [26]	Optical Sensors	95–99	0.1–0.3 L/min	1–5	~25–30	90–95	1–3	2–4	50–100	100–300	Medium	High
Ref [24], [28], [29]	Hybrid Approaches	96–99	0.1–0.5 L/min	1–5	~15–25	95+	1–3	1–3	500+	100–250	High	Very High

FPR: false-positive rate; FNR: false-negative rate.

IV. LEAK LOCALIZATION

Localization is the process of determining the position of a leak along a pipeline and is a key component of pipeline integrity management. Accurate localization reduces repair time, lessens environmental impact, and allows targeted maintenance

activities [36]. As shown in Fig. 2, pipeline leak localization techniques can be divided into three main categories, namely signal-processing methods, ML methods, and hybrid localization frameworks, with emerging technologies such as UAVs and AI-based fusion forming the top tier.

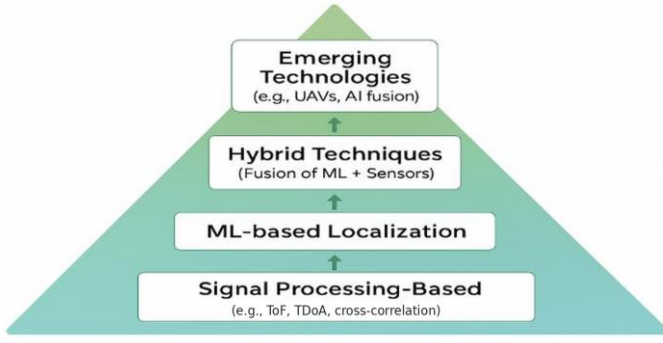


Fig. 2. Conceptual hierarchy of pipeline leak localization technologies reported in the literature.

A. Signal-Processing-Based Localization

Signal-processing techniques remain among the most common methods for leak localization. The most widely used techniques are time-of-flight (ToF) and time-difference-of-arrival (TDoA), which localize the leak by tracking the propagation of the acoustic or pressure waves it generates [37].

For ToF-based localization, the distance traveled by a leak-induced wave is estimated as

$$d = v \cdot t \quad (1)$$

where d is the distance, v is the wave propagation velocity, and t is the transit time. In TDoA methods, the leak location is determined from the difference in arrival times recorded by different sensors, expressed as

$$\Delta t_{ij} = \frac{d_i - d_j}{v} \quad (2)$$

where Δt_{ij} is the measured difference in arrival times, d_i and d_j are the distances from the leak to sensors i and j , and v is the propagation velocity. These methods are computationally efficient and well established, but their accuracy may decrease under noisy operating conditions and complex flow regimes [38], [39].

B. Localization Based on Machine Learning

ML techniques offer a powerful alternative to traditional localization techniques, as they can discover complex correlations between sensor data and leak sites. For example, CNNs can analyze spatially structured representations (e.g., audio spectrograms and vibration maps) to accurately identify the leak region [25], [26]. LSTM networks are particularly suited to temporal localization problems involving pressure transients and acoustic sequences, where leak signatures evolve over time. In recent years, graph neural networks (GNNs) have gained attention for their ability to model the detailed spatial interactions that are common in distributed sensor systems and pipeline networks, making them suitable for large-scale monitoring. Although ML models usually achieve higher localization accuracy than traditional methods, their effectiveness is highly dependent on the quality of the training data and their ability to generalize to new operating conditions [29].

C. Hybrid Techniques for Pipeline Leak Detection and Localization

Recently, hybrid localization frameworks that combine signal processing, ML, and physical modeling have been proposed. Examples include the fusion of ToF and TDoA, signal-processing-enhanced neural networks, and physics-informed learning models that integrate sensor data with pipeline flow dynamics. Hybrid approaches fuse complementary sources of information, increasing robustness to noise, reducing erroneous localization estimates, and improving performance across a variety of environmental conditions [28], [29], [36]. Therefore, hybrid approaches are increasingly regarded as among the most promising for reliable subsea pipeline leak localization.

Overall, the literature shows that both the sensing modality and the underlying localization algorithm significantly affect localization effectiveness. Traditional signal-processing methods such as cross-correlation, ToF, and TDoA are computationally efficient and provide reliable localization in controlled environments, but their performance deteriorates in noisy subsea environments [37]. CNN- and LSTM-based approaches have improved localization accuracy by learning complex spatial and temporal leak features from multisensor data, while GNNs and hybrid frameworks have shown better robustness to sparse sensor deployment and environmental variability. Most reported methods achieve localization errors below 1 m or detection accuracies above 95% under laboratory or simulated conditions; however, few studies have validated these techniques in realistic subsea environments. This highlights the need for standardized benchmarks, extensive field validation, and improved sim-to-real generalization before widespread industrial deployment [39].

V. CASE STUDIES AND IMPLEMENTATION CHALLENGES

Industrial case studies demonstrate that the integration of wireless sensor networks, fiber-optic sensing, acoustic monitoring, IoT platforms, and AI has greatly improved the accuracy of pipeline leak detection, localization efficiency, and response time in onshore and offshore environments [22], [27], [32], [33]. Examples include a real-time sensing system designed and tested for predicting subsea pipeline leakage [32], WSNs for the detection and localization of subsea oil leakages [33], and AUV platforms for tracking subsea plumes and gas leaks [8], [12]. Recently, hybrid monitoring systems that integrate multisensor measurements and ML have demonstrated superior reliability compared with conventional single-sensor approaches [27], [28].

Despite this progress, many practical challenges still prevent large-scale implementation. In the field, signal attenuation, low SNR, sensor drift, communication delays, sparse sensor distribution, and high installation and maintenance costs are common problems. Moreover, ML models trained on laboratory or simulated data tend to perform poorly in real-world operating conditions because of environmental uncertainty and variable flow characteristics.

These findings suggest that future pipeline surveillance systems should be built on robust multisensor fusion, adaptive learning, decision-making under uncertainty, and comprehensive field validation to increase deployment readiness and long-term operational reliability.

VI. CONCLUSION

This work reviewed recent developments in subsea pipeline leakage detection and localization, including traditional sensing techniques, novel monitoring technologies, and modern localization approaches. While conventional techniques remain relevant, recent research increasingly focuses on AI-based analytics, multisensor fusion, distributed sensing, and hybrid frameworks to improve detection accuracy and localization reliability in complex underwater environments. However, deployment costs, environmental uncertainty, limited sensing, and sim-to-real generalization remain major obstacles to practical deployment. Future work should combine sophisticated algorithms with reliable sensing technologies and validate these systems in real operational environments.

VII. DIRECTIONS FOR FUTURE RESEARCH

Future research should focus on the development of robust and deployable leak detection technologies that can operate in real subsea environments. Key priorities include graph-based learning for topology-aware monitoring, physics-informed and digital-twin frameworks, uncertainty quantification, multisensor data fusion, and sim-to-real transfer using field data. Advances in these areas are expected to enhance detection reliability, localization accuracy, and the practical application of intelligent subsea pipeline monitoring systems.

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