Advanced Pipeline Monitoring Systems for Early Leak Detection in Remote and Environmentally Sensitive Areas

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Abstract- The transportation of hydrocarbons via pipelines is a cornerstone of global energy infrastructure, yet the environmental and economic consequences of leaks, particularly in remote and ecologically sensitive regions, necessitate advanced monitoring systems for early detection and rapid response. This paper provides a comprehensive analysis of state-of-the-art pipeline monitoring technologies, including fiber-optic sensing, acoustic monitoring, satellite-based surveillance, and AI-driven predictive analytics. Each technology is evaluated for its strengths, limitations, and applicability in diverse operational contexts, with a focus on enhancing pipeline integrity and minimizing environmental damage. The study begins by addressing the challenges inherent in underground leak detection, such as geographical constraints, environmental sensitivity, and technical limitations. It then delves into the principles and applications of advanced monitoring systems, highlighting the transformative potential of integrating multiple technologies to create robust, real-time detection frameworks. For instance, fiber-optic sensing offers unparalleled sensitivity and coverage, while AI-driven analytics enable predictive maintenance and anomaly detection, significantly reducing false positives and improving response times. In addition to technological advancements, the paper explores the regulatory frameworks and industry best practices that govern pipeline monitoring. Compliance with international standards, such as those set by the American Petroleum Institute (API) and the Pipeline and Hazardous Materials Safety Administration (PHMSA), is emphasized as a critical component of effective leak detection strategies. The study also examines case studies from the oil and gas sector and water utilities, illustrating the practical applications and benefits of advanced monitoring systems in real-world scenarios. The paper concludes with a forward-looking perspective on future trends and innovations in leak detection. Emerging technologies such as satellite remote sensing, fiber Bragg grating (FBG) monitoring, and mobile robotics are identified as key drivers of progress, offering new possibilities for enhancing detection accuracy and operational efficiency. The integration of IoT and cloud-based data analytics is also highlighted as a transformative approach to real-time monitoring and response coordination. By synthesizing the latest research, industry practices, and regulatory insights, this study provides a comprehensive roadmap for advancing pipeline monitoring systems. It underscores the importance of continuous innovation, interdisciplinary collaboration, and regulatory compliance in addressing the challenges of underground leak detection. This work serves as an essential resource for researchers, industry professionals, and policymakers committed to ensuring the safety, sustainability, and efficiency of global energy transportation networks.

I. INTRODUCTION

Energy transportation pipelines are critical infrastructure for the global economy. Customarily they operate as a mature technology and serve as the most cost-effective and safe means of oil transportation between oil extraction and refining facilities and consumers. Unquestionably, dispensation and utilization of petroleum resources cannot be detached from its transportation. Compared to transportation by rail or vehicles, pipeline transportation has the advantages of high efficiency, high quality, relatively low cost and superior reliability. Nonetheless, the competition in petroleum resources between nations has driven the exploration of oil fields to locales with an inferior ecological environment. Effectively, exploration endeavors are taking place in remote and environmentally sensitive areas such as ice areas or deserts, where it is arduous to ensure pipeline safety. Development and conservancy of the global petroleum industry are principally hinged on the security of pipeline transportation. Pressure testing is employed extensively for leak detection, as established pipelines can be decommissioned, and it is relatively easy to isolate a section of the pipeline. Pipelines costs billions of dollars to install, repair, and maintain, and any successful technique for live monitoring, particularly in a location such as undersea, where the pipeline is already submerged, will be highly payable within the petroleum industry. In the event of a spill, it is predominantly of oil, which is usually transported for a while at a temperature higher than the surrounding ocean. Due to the large disparity in specific heat and conductivity in oil and seawater, such a release is adequately detected. These pipelines are, by necessity, draped on the seabed, giving rise to a high hydrostatic pressure, which aids the early detection of a leak.

1.1. Background and Significance

A large number of pipeline systems have been implemented worldwide for the transportation of water, gas and oil. Those types of pipeline systems play a very important role in supplying people needs and transferring crude supply to refineries and facilities where it will be refined and transformed into the desired materials. Also, some leaks could happen when pipes are carrying corrosive materials. It is important to consider long term effects of the transportation of crude oil, water or other materials in the pipelines, which can arise from material interface and effect on the pipes; if these changes happen, pipes could be cracked. In about 10 years more than 1000 exacted leaks happened in the pipelines in Alaska. Along with time there is a deterioration for the system components and for the system as a whole that should be taken care of with frequent maintenance operations.

If a leak occurs, for whatever reason, it is essential to detect the leakage promptly to avoid potential economic losses due to dissipation of the product, inflating operational costs, due to excessive pumping, and the likelihood of fire and safety risks. In case of deep-water spillage in the Arctic, the spreading of oil under ice can make it difficult to identify the source of the spill and to take appropriate containment action, this will lead to significant impacts on wildlife. From an environmental perspective, there is a strict requirement to detect and contain oil spills within a short time period. In the situation where the monitoring sites are placed in a remote area, communication with the main data center is expensive and power consumin. In this case, monitoring the pipeline from remote monitoring sites and occasionally delivering monitoring reports on fuel storage and the related pipeline networks to the data analysis center is beneficial.

1.2. Research Objectives and Scope

Over the past few decades, pipeline networks have become indispensable for transportation of fluids and gases. However, damaging substances that can have a severe effect on the environment and human health are also commonly transported via pipeline networks. Most of the major long-distance pipelines either cross remote locations or areas that are ecologically sensitive, such as large water reservoirs and natural parks. Moreover, in some countries, many major pipelines cross national borders which make the transportation network of that pipeline network difficult to be visited or controlled by the local operating personnel. Therefore, the need for early detection of leakages in pipelines has emerged as a major research topic in recent years. To achieve the fast and effective response against leakages in critical areas, methods and systems have been developed for deploying a wide network of active and passive pipeline monitoring technologies.

Leakage detection methods for monitoring applications range from traditional ones such as mass balance and pressure drop method, to more advanced such as vibration monitoring, optical fibre distributed temperature and strain sensing, and acoustic leak detection systems. Source localisation in the leakage of a pipeline requires the maximum utilisation of available sensing technologies. The best estimation of the position of the leak source can be obtained by fusing information from multiple sensors. This paper presents a review of available technologies, sensors and frameworks to maximise their advantages. Additionally to the passive monitoring methods that are generally used to detect leakage incidents, approved smart pig inspection can be applied as an early assessment to detect potential problems within a given segment of the pipeline. As a good practice in this direction, pipeline networks that are close to consumption, population or nationally important and critical regions, should be monitored for potential leakages at regular time intervals. On the other hand, in order to detect rapidly the location of substance leaking within the critical pipeline segment, an acoustic sensor network should be deployed for monitoring segments between manual control leakage detection installations where the possibility of a sudden leakage is crucial. Wide implementation and operation of this system are a necessary requirement for proof of the correct functionality of the acoustic monitoring system.

II. PIPELINE MONITORING TECHNOLOGIES

The pipelines are very critical components for transporting commodities such as crude oil, natural gas, and water, among others, over long distances. So, pipeline leaks can have many serious consequences, including environmental pollution, the possible loss of life, and the loss of valuable commodities. The detection of a pipeline leak is difficult and a challenge due to different factors. In past decades researchers have addressed methods for detecting pipeline leakage in remote places and environmentally sensitive areas. The overall approach is based on the deployment of field sensors besides the pipeline network which monitor the field surrounding the pipeline. When a leak occurs, it is detected by the sensors located in the region where the fuel emits in the field. Therefore, the deployments of sensors need careful problem analysis, and a combination of different technologies and solutions, making it challenging to tackle the problem effectively. Recently, new monitoring technologies and advanced detection systems have been developed to detect accidental pipeline spills effectively and to minimize the human and financial impacts of environmental harm. The most common problem when fuel is transported by pipelines is leakage caused by both external and internal factors such as mechanical damage, material defects, malfunction, functional errors, etc. Leak detection methods can be classified in roughly patterns. The most common approach measures operational parameters along the pipeline and assess changes that may be indicative of a leak event . The general approach measure pipe flow and pressure and assess the difference between measured values and expected values. If the difference exceeds a threshold value, an alarm is triggered. An alternative approach used remote-field sensors which monitor the field surrounding the pipeline. In remote areas, the pipeline does not come into contact with the pipeline and fuel. When a leak occurs, it is detected by the sensors that monitor the field. Monitoring field technology is relatively new. At the arrival of the leak the field parameters of the phenomenon change abruptly. After detecting this relative change, a confirmation process is carried out using the same technology. The leak detected in this way is called passive leak detection. In active leak detection, changes in field parameters are achieved with one or more excitation units installed in the field. Output signals are used to detect leaks. Whenever a leak from the pipeline causes a large amount of gas/liquid to accumulate on the surface, it creates a spectral abnormality compared to the characteristics of the surface. Using this abnormality, the passive method is created where the spectral abnormality of the hyperspectral data is checked periodically and if the leakage is detected, the advance and the necessary action is taken.

2.1. Traditional vs. Advanced Technologies

Pipelines are an efficient means of transportation; they cross remote and environmentally sensitive areas such as forests, mountains, deserts, rivers, lakes and seas. The remoteness and vulnerability of these areas, however, renders the detection and location of leakage more difficult. The timely detection and location of these leaks are essential for public safety, to prevent environmental, health and economic damages to the surrounding area. Pipeline monitoring systems have been set up to detect leaks, and several techniques have been developed for this purpose. Traditionally, internal systems based on Volume Balance and External systems based on the Rate of Pressure/Flow Change are used. It is reported that approximately a fifth of the detected leaks are not reported due to inaccurate monitoring systems.

Advanced Pipeline Monitoring (APM) systems are being developed. These utilize more refined techniques and are equipped with more advanced sensors and monitoring technology. Current research suggests the use of an APM increases the likelihood of leak detection considerably, and results in leaks being detected over 25 days faster than with traditional systems. Specifically, advanced systems can be much more sensitive to leak detection as they are able to detect the existence of smaller leaks. A white paper is presented, which compiles all necessary information needed to understand and replicate the methodology presented. The indications that the research model suggests an APM geared towards Excavation of Third-Party Damage (TBD) as the preferred option for detecting leaks is rapidly established.

2.2. Sensor Technologies

Pipeline networks are considered the safest, cheapest, and most effective way to transport oil-based products, gas, and water. Modern pipeline monitoring systems can collect a large quantity of raw data, which can be processed by trend analyses to assess the pipeline's health conditions and to detect possible leaks. Several algorithms have been developed to estimate the leak rates, considering either the pressure drops or the fluid dynamic equilibrium. Moreover, microcontroller-based technologies can provide a portable, cost-effective alternative for monitoring environmental contamination, as well as an early leak detection by using passive acoustic techniques. Advanced leak detection systems can be interfaced and specifically designed to manage and analyse in real-time the time series of the variables returned by the PIMS, as well as the alarms issued by the SCADA system and by other sensors. Cross-correlation on the estimated flow rates, obtained from the gravimetric method and hot tapping, has been applied to provide a principle of detection on line losses. A technology has been developed for the remote monitoring and early detection of leaks of hydrocarbon liquids based on the acoustics of the leak spray, which pulses into a high-frequency pressure wave when it impinges on a surface. This pressure variation can be detected, even if the leak is stopped, creating the so-called Acoustic Fence. Litvin Vanes for Oil Seal Improved Torsional Rigidity of Centrifugal Machinery has been developed to improve the torsional rigidity of a centrifugal machine. The geometric discharge pipelines, comprising a ballast system for controlling radial and axial thrust, ensuring consistent and efficient transfer of flow to the impeller section are mounted on the central bowl structure. This results in a lighter and cheaper construction compared to the known systems. A novel monitoring system has been designed to remotely monitor the drainage flow of an area and provide a real-time indication of the amount and properties of the liquid collected. The effectiveness of the patented acoustic method has been demonstrated by laboratory and full-scale tests involving different types of fluids.

2.3. Communication Systems

Modern and sophisticated pipeline monitoring systems use various machine learning or AI techniques which help operators to have extra time to respond to the threat of leaks either due to external interferences, corrosion, or leaks on flanges and other components. Most of these technologies typically need professional installation in which long term training and tuning process should be carried out. However, such a system may not be suitable for some remote areas where the leaking medium exists, or environmentally sensitive location where spillages can cause huge environmental damage . This is because such systems may be costly and need extra additions for protection. Therefore, a simple portable prototype installed on a pole for remote leak detection operation has been developed. This system can be easily deployed on site to monitor hydrocarbon spillages anywhere regardless of the environment based on reflection spectral characteristics of contaminants. Even though, the system only requires commercial implementation of spectral scanners. This equipment operates with lower power consumption and can be powered by small battery units making it an ideal simple to use portable system. Moreover, this system is operable wirelessly at a distance where an efficient line of sight is established. It can be applied for up to 15 km monitoring operations. By having portability, the system can also be useful for operators that need to commission environmental monitoring in sensitive areas for a short duration, such as forests or wildlife crossings by on-shore pipelines.

III. CHALLENGES IN REMOTE AND ENVIRONMENTALLY SENSITIVE AREAS

Pipelines are widely used to transport such fluids as water, petroleum, chemicals and natural gas over large distances. They are relied upon to deliver resources from their point of extraction to eventual consumer. However, the nature of pipeline structures means that leaks can occur. These range from minor, normal operational losses, to large-scale environmental disasters. For this reason, leak detection systems (LDS) have been developed to address this peril. Modern LDS technologies fall into two main categories : Internal and external. Externally based leak detection methods involve hardware instruments being placed around and along a pipeline. Variations in operational parameters, such as drop in fluid pressure, discharge in flow or changes in temperature result from a pipeline leak providing a physical dynamic phenomenon. These changes are typically measured and used to determine if a leak has likely occurred. Internal leak detection systems are those that are part of the inner fabric of a pipeline. Key advantages are continuous monitoring and ability to detect smaller leaks in comparison to external LDS. This work will focus on the context of remotely placed sensors required to monitor pipelines that cover vast, otherwise challenging to observe terrains, as well as LDS providing methods to approximate the location of a leak.

3.1. Geographical Constraints

Oil and gas are moving frequently through long pipeline networks of various lengths. They are an essential means to transport commodities from production to consumption regions. These pipelines span both onshore and offshore territories and can pass through environmentally sensitive areas . Examples of vital water resources, national parks or densely populated cities are regarded as environmentally sensitive areas. Moreover, onshore pipeline networks can also pass through mountainous or desert regions that render visual on-site inspection difficult. In these situations, development of advanced remote pipeline monitoring systems for early detection of oil leakage is of critical importance. When an underground oil pipeline fractures, the consequences have the potential to be extremely serious since oil can pollute the soil and ground water, both of which can be difficult to restore. During the past decades, numerous efforts have been made to apply various methods and implement digital systems to manage and monitor the oil pipeline condition. These include techniques such as acoustic leak detection systems and distributed temperature systems: distributed fiber-optic technology used to monitor pipeline temperature changes. However, problems regarding the accuracy and reliability of the methods still exist and it is a fact that when a pipeline operates in certain conditions. Moreover, the mountainous environment in this area can be complex and traditional methods of oil pipeline condition management can be difficult to apply efficiently. On that basis, a tailored methodology becomes a necessity. This methodology has as its object the Doxato-Chrisoupoli pipeline network in the North of the Greek peninsula. The methodology is capitalized by applying geophysical research, fieldwork and the relevant technological advancements.

The challenging part is not only the development or deployment of cost-effective sensor networks capable of detecting oil leakage in remote locations or environmentally sensitive areas, but also the data processing and communication technique of these monitoring deployments. A variety of pipeline leakage detection methods have been proposed, but their performance varies depending on the approach, on the operational conditions and on the pipeline network. However, there exist guidelines which include principles for a leak detection system. Minimum requirements are set in terms of the sensitivity, accuracy, reliability and adaptability that have to be met before we can consider any leak detection system suitable for production solutions. These guidelines, although useful, do not provide a unique method to design a system meeting the recommendations while transferring the design into the actual system; in fact, the development of the system has proven to be particularly challenging. Moreover, from the spill prevention viewpoint, it is essential that not only a leak is detected, but also its localization as well as an estimation of the leakage rate are known. These allow spillage containment and maintenance to take place at the early stage of the incident, avoiding the occurrence of serious environmental damage. The simplest way this can be achieved is the deployment of a vast number of leak detection sensors in the pipeline network. In this context, the use of wireless communications technology as a means to structure a sensor network between the upstream and the downstream of the pipeline network becomes an attractive option to monitor the network remotely ignoring the geographical constraints. Using a network like this, the construction of a control algorithm able to minimize the time needed to detect a leak while ensuring robustness to false alarm is necessary so that the network can be efficiently operated.

3.2. Environmental Impact

The leakage of substances from buried pipelines can have serious environmental implications in sensitive regions. For this reason, interest has grown lately in advanced pipeline monitoring technologies. Advanced pipeline monitoring systems can help in localising and addressing leakage problems before any severe environmental consequences occur. A remotely-controlled group of mobile sensor nodes travelling through pipelines can act as an advanced monitoring system. The use of mobile sensor nodes in pipeline environments is particularly important since it creates redundancy in the network, i.e., a sensor node that is out of order can be replaced by another sensor node that can come and take its place. Redundancy is hard to acquire in linear WSNs with traditional stationary sensor nodes. Since fixed ground-based monitoring systems are unable to provide unified surveillance, mobile sensor nodes are very advantageous for enhancing coverage. Another important advantage of mobile sensor nodes is that the network can be recovered from any failure by sending a new mobile sensor node. The implementation cost of sensor nodes equipped with GPS capability is extremely high. In many available wireless camera products, the cameras construct and store the map of the deployment venue during their operation, which is inconvenient for the deployment phase in pipeline monitoring environments. An additional prerequisite for a successful object localisation was that the camera locations were known, i.e., marked using GPS and stored permanently in the map. Consequently, it is impractical to use these kinds of portable cameras as the eyes of the desired advanced pipeline monitoring system. If all sensor nodes in the pipeline environment are static, their locations have to be marked using GPS equipment. Some sensor nodes should still be tagged and their deployment has to be carried out manually which is time-consuming and ineffective. The pipeline environment is an uncontrolled area with open soil. The buried pipelines in the middle of other numerous cables and pipes are usually difficult to visually access. Therefore, it is very hard to manually deploy sensor nodes at predetermined positions. If all sensor nodes are mobile, predetermined paths with good coverage must be planned in advance, which is in most cases very hard or even impossible in pipeline networks . From the environmental perspective it is important to detect, localise and address leakage problems as quickly as possible so that severe environmental consequences can be avoided. Such leakage incidents can cause fires and explosions in urban regions, and can lead to important environmental penalties if they occur in protected or sensitive regions. Vaccines and other contamination threats used against bioterrorism attacks can be transported through pipelines. Discharge of such substances into the environment can cause massive loss of life and environmental pollution. Detection of the leakage is essential for recovery or non-spreading of a contamination attack. Safety-related considerations and stricter monitoring make many pipeline operators look for external pipeline monitoring systems. There are many approaches to pipeline monitoring, however, localization of a leak is still a challenge. Leak maintenance of buried pipelines is an important topic in both industrial and research fields. One important aspect of this maintenance is the location of the leakage point(s). Infrared cameras are used to search for temperature anomalies on the ground as they indicate the presence of leaked substances. Periodical aerial surveys can also be performed. Evaluation of the obtained image or data is a laborious process. Moreover, typical pipeline leakages are pinholes, and usually leaks do not reach the ground level since leaked substances are heavier than air. Special gas sniffing vehicles move along pipeline roads, and one of their responsibilities is to detect pipeline gas leaks. The exhaustion systems are the key element for localising the leak due to sudden changed sound levels in the pipeline. This approach is also used in water-pipe networks. Fixed or moving units are used for moving over the pipeline, inspecting it with acoustic or piezoelectric sensors. Leakage is localised applying detection theory while moving over the pipelines where sensor nodes are deployed at the same time without any external equipment. Fixed ground-based systems are always at the same specific local positions and they lack 3D sensing capabilities. Additionally, fixed ground-based systems are unable to provide unified surveillance of the entire pipeline network. Deployment of stationary sensor nodes on UAVs would create aerial mobile sensor nodes that could travel from standpipe to standpipe through the air and improve the surveillance of the entire pipeline network. This is impractical in large-scale networks, due to UAV malfunctions, large network monitoring sprawl and complex vehicle control because of the elimination of obstacles in the flight path of the UAVs. It is also well known that liquid distribution pipelines are pressurised during many phases of the pumping cycle. Therefore the leaked liquid will not get to the ground since its densities are higher than the soil and the insulation. Smaller holes are liable to leak gases, which are not visible for an untrained eye. Liquid pipelines are usually cubed during the day and the ponded water, mud and snow provide good insulation for leaks. Signatures are usually noise amplitude based. Leakage detection systems are prone to a high degree of false alarms. One approach to avoid false alarms are complex algorithms to estimate large-leak mass flows. Other approach is monitoring the pipeline flow on a per-event, or statistics. Creation of rare mechanics faults in that event due to a high acceleration from accelerometer malfunctions. In the underwater environment, accelerometer readings are noisy and are distorted by the acoustic wave. Software to use the information from the incoming video stream to automatically detect the start of the leakage event. However, a system with video capabilities cannot be used to monitor inside a pipeline environment. In brief, access to the buried pipeline is visually unaccessible. Broadway pipelines buried in ditches along the highway as an existing detection method. Acoustic waves can travel through the pipeline wall and the fluid and reach the soil. These standing waves are then directed downwind and amplify the noise on the ground above a leakage. Instead, either sensors are located in the ground above the pipeline or acoustic sensors are mounted on a pipeline. However, leak detection and localisation becomes increasingly complicated. Using implanted monitoring system sensors are arranged along the pipeline. Sensors are mounted along pipeline or deployed on an unmanned pipeline submarine devices. Standalone piezoelectric or hydrophone-imbued sensors are added onto the outer shell of the pipeline spacing. This technology is not needed in regions with calm environments. However, in municipality or urban environments with heavy traffic, the above realistic scenarios render this technology useless. This may not be possible in the unplanned event of environmental leaks in vast regions. Dissemination takes time, and a lot of media coverage and social media postings are critical. An alerting mechanism for a population group only works while a population is within predefined region. For these reasons, it is of interest to pipeline operators to deploy additional sensors along the pipeline in order to increase the plausibility of detecting the locations of leaks. The leaking fluid interacts with a noise sensor mounted on the pipeline due to pressure variations. Time and frequency noise signature pruning allow for the localisation of the near-maximum pressure variations coming from the leaks. Pressure transients leak noise propagation through pipeline energy transfer occurs. The postulated technology fails when considering that not all of the leaking substances are liquid. Technology that can be worked in noisy and bad weather conditions. There are many closely deployed underground or underwater pipes and cables in industrial areas, near habitation, in agriculture reaches or water supply walls. Unless advanced algorithms for time and energy shared by multiple platforms are necessary to interact in an intelligent network for possible collision free motion with the environment. Millions of soon weakened ships leaking oil near the shore such as the Exxon Valdez to occur, pipes that are closer to experimental accidents, leak due to the sudden wall stress. Assist the flow-path. Although not visible in visual and near-infrared sensors, may be bloated by visible and NIR radiation occurring due to the warm. It is important to detect identifying early to take timely recovery measures in order to lessen the pressing environmental impact.

3.3. Regulatory Compliance

The regulatory requirements for the storage and transport of hazardous materials are becoming more stringent to address public safety and environmental concerns. Pipeline operators and hazardous material facility operators are required by federal and state laws and regulations to have DPMS that can either detect and locate a release of hazardous materials or monitor the pipeline or facility for leaks using material balance techniques. The regulations require pipeline operators to perform pipeline leak detection evaluations. The results of these evaluations have been submitted to the appropriate Regional DOT Office since 1982. The rule was designed to mitigate unintended fluid transfer within High Consequence Areas (HCA) by either eliminating the threat of a release, typically through the installation of protective pipe sleeves or by providing operational controls that will reduce the time a release can remain undetected. Instigating preventative measures can be performed by the use of fixed systems capable of continually monitoring pipeline integrity and warning the operator of anomalies that may be potentially dangerous. Therefore, there is a concerted effort to design sophisticated DPMS for the early leak detection of pipe content, thereby supporting remediation activities that result in improved treatment and protection of the environment . This has significantly reduced the number of incidents reported, thereby supporting the transportation of hydrocarbon products in a safe and efficient manner. The application of these methods in remote regions can be cost prohibitive, a number of field inspections are necessary in addition to the installation of fixed monitoring systems. Alternatively, the integrity of pipe infrastructure can be determined and preserved using advanced DPMS for automatic leak detection. To date, a number of techniques have been developed for the sensing of pipe content emanation. These methods are based on the detection of temperature, pressure, flow, acoustic, vibration, and chemical changes in the vicinity of the pipeline. Each of the leak sensing methods has corresponding physical and operational limitations regarding sensitivity, leakage spotting, and false alarm rates. An alternative is the use of system-wide pipelines leak detection, taking into account the pipeline flow dynamics through alarm data analysis.

IV. STATE-OF-THE-ART LEAK DETECTION ALGORITHMS

This section presents an overview of the state-of-the-art of leak detection algorithms. Since pipeline monitoring is a very active research field with nearly monthly publications, the focus is on papers published in the last 2–3 years. It benchmarks current algorithms based on a set of defined criteria like scalability, cost of data acquisition, setup complexity, required infrastructure, on-line data access, or portability. Advantages and disadvantages are discussed for each algorithm reviewed based on the defined criteria. A critical review about the potential of the reviewed methods for early detection in remote, hazardous, and environmentally sensitive areas like permafrost are also given.

For energy transportation, pumping of the medium is typically used, and monitoring infrastructure is costly. Pressure and temperature sensors, as quite simple and cheap monitoring infrastructure, can be used. These flowmeters generate many false alarms and fail to detect many real leaks. The latter is an issue known from the literature. A large collection of model-based leak detection methods have been developed in the academic and industrial area. The pipeline network is partitioned into several discrete canals. After the pumps and/or compressor stations, observability is guaranteed for all connections of the pipelines. Measurements like mass flow rates, pressures, or heating values are considered in the models. All of the known model-based detection approaches are either deterministic, and in some cases analytical, iterative and model-based methods, or system-identification-based approaches. In contradiction to this, some other leak detection algorithms are based on data-driven or data-mining techniques. Machine learning based classification receives a lot of interest in the academic area and is elaborated on below. Pipeline applications are discussed in few publications. These are limited because of several complications like the detection of small leaks, modeling uncertainties, or false alarms of the methods.

4.1. Machine Learning Approaches

Monitoring critical infrastructure, such as oil pipelines, is a key task since any problems can lead to economic and environmental consequences. Fault detection and localization should be dealt with in a timely manner. Pipelines transmitting oil over long distances are generally monitored through a series of sensor systems, but to ensure safe detection of major accidents. Pipeline safety and security have attracted extensive attention in society and the field of scientific research. Oil transmission pipelines are exposed to a variety of threats, including changes in physical environment pipelines due to corrosion, ground movement, ground sliding, damage from trees and power tools, and construction and nearby buildings, mechanical damage, and various geological factors. To ensure smooth oil delivery and reduce waste and environmental pollution, it is very important to implement an automated monitoring system for pipeline management.

To achieve this, the main goal of this work is to investigate modern sensor systems and testing equipment that can be used for leak detection. Analyzing the data collected from the sensor system makes it difficult to identify sophisticated features. To address this challenge, advanced machine learning algorithms will be tested and adjustments and preparations will be made to obtain optimal performance. To demonstrate the applicability of the designed system, it will be implemented at selected test pipelines located in remote and difficult to access areas.

A review of the literature suggests that the bulk of research on LDS has historically focused on model-based leak detection methods suitable for installation in SCADA. With the emergence of more advanced and cost-effective sensor technologies and ML algorithms, a new generation of sensor network-based leak detection methods has been developed to detect smaller leaks in less time, with fewer false alarms. Thus, the overall goal of this work is to determine the best commercial and advanced sensor systems and laboratory testing equipment for leak detection of both oil and non-conductive fuel pipelines, as well as to develop improved, data-driven algorithms to better understand, explore, import data patterns, and then use the patterns to control the physical experiments with the goal of enhancing sensitive leak detection.

4.2. Statistical Methods

Pipeline monitoring systems are of utmost importance to ensure the safe transport of resources. In remote and environmentally sensitive areas, there is a lack of monitoring systems that can detect the occurrence of damages, which might lead to economic and environmental issues. The aim is to develop an acoustic monitoring system that is able to detect pipe ruptures. However, monitoring acoustic signals in this type of environment is quite challenging, due to high noise levels. This study uses hydrophones, as they are less sensitive to some noise sources due to being pressure sensors. The idea of the monitoring system is to deploy several hydrophones within the water body, and locate the pipe on the seafloor. If during the pipeline's operation a break occurs, it will produce acoustic signals that will propagate through the water. These signals will differ in time and amplitude when received by the hydrophones due to the large distances that they have to travel. Through proper processing, it is possible to locate the break.

A pipeline system consisting of propane gas and air is used to carry out several experiments on a testbed. When there are no damages in the pipeline, there are no acoustic signals. However, a gas or air leak produces a pressure difference that results in a sound wave. This signal reaches the water, has its intensity reduced due to spherical wave propagation, and travels large distances to the hydrophones, where it is detected. The first stage of processing consisted of noise reduction and compression of the data. Waterfall diagrams are then produced using Short-Time Fourier Transform (STFT) from the compressed data. In an ideal environment, a high pressure gas flow generates a strong signal that is detected by the low-noise level hydrophones, and from the waterfall diagrams, it is possible to estimate the Time Difference of Arrival (TDOA). These estimated times are used to calculate sound speed and find distances to the pipe. It is essential to perform indoors experimental tests in a known environment, in order to increase the repeatability of the experiments.

4.3. Hybrid Algorithms

This paper showcases a deep-learning-based algorithm that includes a hybrid approach to the classification stage. The input features to the convolutional neural network (CNN) are scalograms produced by the combination of CWT and STFT, which provide an integration of deep learning and signal processing perspectives of acoustic emission signals the AE-Signal Hybrid Analyzer. The CNN was designed to learn and extract significant features from the scalograms and classify them as normal or leaky. Once trained, the CNN can be used to detect leakage in real-time hydrocarbon and gas pipeline monitoring. Experimental results demonstrated that the proposed pipeline monitoring system equipped with the AE-Signal Hybrid Analyzer produced accurate, immediate, and reliable classification results. The false positive rate (FPR) and false negative rate (FNR) were maintained below 5% for the different types and sizes of pipeline leaks. The obtained results were compared with the conventional FFT-based and CWT-based leak detection system. The findings showed that the proposed AE-Signal Hybrid Analyzer achieved higher accuracy and real-time performance primarily due to the integration of the proposed hybrid algorithm.

Pipeline leak detection systems are used to protect the safety, efficiency, and operation of industrial pipelines that transport various liquids and gases. Leaks in hydrocarbon or gas pipelines can result in significant economic loss and environmental damage, especially in areas near environmentally sensitive habitats. Thus, the early detection of leaks in pipelines is essential to preventing catastrophe. However, many existing leak detection systems are designed for controlled environments and require a physical connection to the pipelines. It is difficult to apply traditional techniques in remote areas or environments restricted by land ownership. For example, it is challenging to detect leaks in underwater, harsh, or environmentally sensitive areas, and unauthorized connections are often used to steal liquids or gases from pipelines, resulting in leaks. New methods and systems are necessary to address this gap. Therefore, an analysis is presented of a novel pipeline leak detection test system designed to address the aforementioned issues by using wireless Acoustic Emission (AE) sensors suitable for detecting pipeline leaks in remote and environmentally sensitive areas. A data-driven algorithm is also designed to improve the system evaluation credibility for optimal testing accuracy. The test results demonstrate the potential and robustness of the designed system and the proposed evaluation algorithm for early leakage detection.

V. CASE STUDIES AND APPLICATIONS

Leakage is regarded as the most common type of incident in the pipeline industry. It is also a hazardous event that poses major environmental risk to areas surrounding pipelines. It is able to detect pipe wall leaks allowing the direct release of fuel into the soil and the development of a continuous path for water to enter into the pipe annulus. Leaks may already be present upon the pipeline installation. Sometimes the insulation gets damaged during the construction activities and the pipes break down sooner or later in those locations. Moreover, some damages remain hidden until fuel passes through the pipeline. In the worst-case scenario, fuel could be constantly leaking without anyone realising as happened with a Shell pipeline in Texas, which leaked oil for almost a decade until the whole pipe section was replaced. In another recent case, fuel was continuously leaking from a pipeline into the ocean. More innovative leak detection systems have been proposed to safeguard these systems from leakage events jeopardizing the surrounding environment. One particular approach using satellite synthetic aperture radar images is suggested to locate pipeline leak incidence in remote areas in a rapid manner. Data acquired from satellite synthetic aperture radar images are processed to realise displacement vectors to infer potential leakage occurrence. Detection strategy includes pipeline proximity and change detection on land surface displacement by implementing the differential synthetic aperture radar interferometry. Special polynomial fitting algorithm is employed to smooth the resultant displacement vectors to mitigate the atmospheric effects. Using sparse data points experiment, superior noise structure and variation capable to detect pipelines leakages in Napier wellhead production facilities in Sabah Malaysia was realised within 0 to 6 cm accuracy.

5.1. Success Stories

This section discusses the area of pipeline monitoring and the stimulation of data fusion between wireless acoustic sensors and ground-based multispectral imagers according to the specific needs of pipeline leak detection. In the last years, many techniques have been developed, taking advantage of the technological evolution, that have led to the proliferation of several methods and solutions available on the market. Unfortunately, currently, there are no solutions capable of being effective in remote and ecologically sensitive areas: the aim was to fill this gap. It was clarified how the attention to specific pipeline-related aspects and sensor fusion logic leads to innovative solutions. An ad-hoc wireless sensor network for acoustic sensing has been designed and developed; the same has been done for a ground-based imaging system operating in the SWIR spectrum. Both solutions were designed by analyzing various configuration layouts, focusing on the choice of technology, and upper layers data processing towards data fusion. Furthermore, aims, need, and methods have been studied to realize a functioning monitoring system that demonstrates the capability of functioning for leak detection: the setup and procedures to operate in a calibration/reference pipeline have been defined. In the last years, the issue of pipeline leak detection halved the loss in terms of economic revenue and valuable belongings; nevertheless, 410x109 liters of oil and derivatives were so far released in the environment. Given that one leak detected on three is reported not by the operators, mainly due to difficult inspection and the need of a large amount of workforce, aiming for more accurate, efficient, and low-preventive solutions is of paramount importance. Activism and request of more effective measures are also enforced by the govern and by environmental movements. Unfortunately, no fully satisfying solution was so far put on the market. In the technological report linked to the project, the state-of-the-art situation for both acoustic and multispectral imaging technologies was described. Methodologies surveyed in document boarders most for the current develop: algorithms and methodologies where acoustic and spectral analysis play a role other than technology, implementation, applications, etc. Looking at the technologies, over the last years, thanks to the advance of computational power, COTS of the shelf components, and the Gardner effect, have been an increase in the development of small and low-power-acoustic sensors and datalogger. A bunch of scientific and industry papers now report low-cost and easy to use designs. Generally, sensors come in the form of handheld sticks inserted in the ground of buried five bars for typical acoustic applications and irruption feeding moving tool in others. Convergence-standard electrets, 3-pulse sensors, are used to measure SPL in the range 30–130 dB. Equipments come with microprocessor, have autonomy up to 5 days. Software run in on the cloud or on portable devices and provide online and real-time data streaming and basic features for data acquisition and recording . In this case, pipelayers also keep into utmost account the data transmission from the sensor to the control center by implementing an acoustic modem or transferring of calibration files from battery-powered dataloggers via SMTP-S and satellite Giglet. On the other side, pipelines leak detections are available, but the latter are firmly connected within the business of the suppliers; collaboration in data acquisition and sharing is prevented, external control is skipped, and wellbeing of the system is only known by the suppliers. Modern systems are based on the thermodynamic or acoustic principle and can be used as-is, as add-on, or retrofitted on the plant. The use of P/TM sensors restates on the installation of a few additional sensors along the lines to monitor the first order from the standard PT sensors or on the integration of special algorithms in the standard control system. Retrofitting equipment could involve the replacement and adaptation of infrastructure implant with supply records. Both readings the technology dispenses difficult and high costs, and suppliers control the system and related machinery (suppression, data, system control) of economically important sites, such as oil sands, shale, or laden systems. On the performance evaluation of the Pipetech Ltd products, the main technological constraints were estimated and reported. Requiring the device of being cross-linked to automatic value with PT (double line pressure, threshold and decay rate modification time released by a supplier below the expected limit) or wireless monitoring, unacceptable environmental concerns were risen, or devices proved suitable just for liquid w/road transportation. In the beginning, the human technician is by the nature of turn, check, inspect and fix, in a subsequently completely automatic; in this way, irrespective of the systems types (an economic sector where more than 50 types of systems are involved in the market are considering equitable time and cost balance thus leading a single point resource planning well accepted by most of the industry operators) effects of price tag were not a limit. Preventive maintenance, instead, is currently being executed only in the effectance of case where false alert is raised. Maintenance occurs normally twice a year on 10~20 km line sections and spans a 3-month time of inspection and manual digging each detection head (about 200 in a central facilities). Times and costs are about 250 usd/km and more 1000 usd/head, annually corresponding to more 4 M $ for 400 km of line. Efforts were noticed to avoid and hasten inspections, but due to the massive workload and likely inadequateness of equipment inspection is normally performed only after activation, anyway, in most cases, partial information about the problematic section of the line is found, and further damages are already occurred, so as the talk or automatism has to be shifted to prevent the disaster. Allowed time between the alert and repair or go down to 60 h (25% of the cases missed at present should be accomplished) is an unrealistic requirement as the procedure of excavation itself lasts longer. Past accident records show that the majority of the false leaks is produced are on aboveground infrastructures and caused by both public work and vandalism, or, in any case, caused by sudden and violent pressure drop. Both of this kind are unlikely to be intercepted by a standard control system alone. On the other side, the computer monitoring of the standard control systems recorded a higher number of tampering occurring on the theft alert (false negative), where services are cut off but consumption continues.

5.2. Lessons Learned

Oil and gas are used as fuels for heating, cooking and transportation, therefore they are of massive importance to modern life. To cater for the energy demand, significant pipelines are laid down across the continent and cities. However, there are multiple hazards inherent in the transportation of oil and gas over pipelines. Of these, leakages are among the biggest concerns because of the financial and environmental losses during and after a leakage incidence. In order to avoid such catastrophes, and to comply with regulatory guidelines of countries, pipeline companies are constantly monitoring their pipelines for leak detection and developing more sophisticated systems and pipeline integrity. Unfortunately, over 200 million gallons of oil spill into the oceans every year due to pipeline leakages and this statistic is continuously increasing. Several unfortunate incidents have already occurred in gas pipelines, where human casualties and enormous financial losses have shaken the industry. Due to the prevalence of such fatalities, rules from demand the US department of Transportation, make deliberation to make pipelines more reliable; hence significant need of pipeline integrity monitoring systems. Conventional leak detection systems use a computer-based software system that gathers data, identifies potential leaks through a set of predefined rules based on the pipeline analysis model, and then confirms the leak location. This approach is limited in scope and does not provide coverage of the entire pipeline. Remote monitoring of oil and gas pipeline networks is difficult because these systems are spread over vast distances across sometimes hostile environments making it impossible to get accurate real-time monitoring data. It is possible for to build mobile robots that can traverse the pipeline and detect leakages or to lay sensor networks that will detect the leakages. There are several ground robot and UAV-based systems that have been developed that can travel the pipeline. However, it is a non-trivial problem to design mobile robots that can travel the pipeline quickly and accurately.

VI. INTEGRATION WITH GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Oil and gas companies are faced with many challenges in the highly competitive and rapidly changing world of upstream petroleum exploration and production. In that, many multi-national companies face a complex and often diverse set of equipment monitoring and repair arrangements involving many companies around the world with varying level of expertise and resources. Advanced maintenance and repair technologies such as real-time corrosion monitoring systems enable companies to extend component lives, thereby reducing costly shutdowns and avoiding premature failures. Automated monitoring systems are also more effective in harsh, hard-to-reach environments such as underground mines, offshore platforms, and remote deep-sea risers.

It is especially important for oil and gas companies operating in the remote, highly environmentally sensitive areas of the United States, such as the Arctic and Utah, to ensure continuous operation of critical equipment necessitating careful monitoring. Despite huge advances in remote sensing capabilities, oil and gas companies need to have complete assurance that their fleets and equipment are exactly where they think they are, that they are performing correctly, and that problems can be identified as they occur. To mitigate this problem, through a system wide test, a technique for integrating satellite imaging and condition monitoring systems with powerful data mining software and incorporating precise real-time kinematic (RTK) global positioning system (GPS) base monitoring systems is proposed. The basic concept, technology, statistical analysis techniques, and problems associated with the maintenance aspect of the system are presented. The proposed system is capable of localizing leaks to within the vicinity of 1m and, in some cases, before rupture occurs, vastly reducing environmental damage.

6.1. Mapping and Visualization

The use of pipelines to transport oil and gas over long distances is growing rapidly. While pipelines are beneficial in more than one way, leaking of oil and gas will pose a serious threat to the environment. Because most pipelines are laid in remote or environmentally sensitive areas, timely and accurate leak detection has become critically important. Among the various methods to monitor pipeline leakage, wireless technology plays a major role in recent monitoring systems. The focus is on reviewing the progress that has been made in pipeline leak detection methods, using the taxonomy illustrated in the various reviewed methods are presented and the reviewed methods are categorised into three main classes: modalities in the sensed data and in their processing, monitored properties of the pipelines, and application of the method. Following that, research gaps and directions which require further attention are identified. Recent advances in leak detection technology have prompted many industries to establish monitoring systems in their pipeline networks to prevent small leaks becoming major incidents. To facilitate this need, many methods have been developed to monitor pipeline leakage in remote and environmentally sensitive areas. The monitored pipeline leakage detection methods are organised based on the classification illustrated in. The detection of oil or gas leakage as soon as possible is a major concern for oil and gas corporations. Unfortunately, the coiled length of a leaking pipe is usually several hundred meters and it typically takes hours for spilled oil or gas to spread hundreds of meters. By the time leaked oil or gas is found on the surface the amount lost will be considerable. It must be emphasised that pipeline leakage leads to environmental hazards; a leakage that existed for a few days could permanently damage ecosystems. Therefore, effective and efficient monitoring technologies must be investigated to detect leaks at an early stage.

6.2. Data Integration

Pipelines spanning long distances and in various environments require monitoring systems to provide early warning against leaks in real-time. In each environment, different sets of sensors are used; however, not all deployed sensors can detect leaks. Each sensor plays a specific role in detecting potential leaks, but data integration brings more reliable leak detection. Leak detection systems have been proposed for an early warning of leaks. Sensors used to detect leaks report unusual changes in the monitoring conditions, from changes in noise levels in acoustic sensors to unexpected changes in terrain regarding scattered radiation.

Pipeline monitoring systems rely on physical sensors to detect the condition of the pipe or its surroundings. This involves correlating the response of each of the several sensors with the available data. Leak detection systems involve a plurality of sensors positioned in operational proximity to one another. Each sensor has an associated set of sensors, which are positioned in the operational proximity to the sensors. Redistributions are used to process information like data from each sensor-associated set sensors, model historical operating data, defect test data and operating parameters. Model has a test data processor, and a data reconciliation processor. The test data processor processes the leak post-processed according to a predetermined criterion to provide a tester model data.

VII. FUTURE TRENDS AND INNOVATIONS

When monitoring the pipeline networks, detecting the leakages and taking precautions at an early stage provide benefits of reducing environmental catastrophes and financial loss. This is crucial for the networks within highly populated areas and environment-sensitive areas. In remote and environmentally sensitive areas, traditional techniques lack effectiveness as they are unable to provide on-line monitoring and give false alarms due to local anomalies at the monitoring spots. Consequently, novel monitoring systems by using wireless sensor networks (WSNs) have been paid much attention to address such difficulties. Recently, it is observed that considerable effort has been made in the research and on field applications of pipeline monitoring and leak detection systems. Although there are several previous surveys on pipeline leak detection techniques, they typically focus on one aspect of the problem like comparison of different techniques, information fusion and data aggregation of similar sensors. However, these surveys do not sufficiently address the task of detecting and identifying the presence, exact position, size and age of a leak by monitoring the pipeline network. Furthermore, these surveys do not consider use of remotely deployed sensors for monitoring purposes. Recently, this subject has attained growing interest with the increasing deployment of infrastructures upon which pipeline networks are built or are planned to be built.

7.1. Internet of Things (IoT) Integration

Advanced Pipeline Monitoring Systems for Early Leak Detection in Remote and Environmentally Sensitive Areas

The new solution includes radar sensors, a network of cooperative drones, and intelligent IoT technology to detect and classify damage to pipeline infrastructures by any source. A Doppler system detects minor pipe movements from the acoustic radiation of soil or mechanical malfunctions in the pipe. In both cases, an alarm is transmitted to the control center. In a failure detection and location system, pressure pulses are captured on the pipe's exterior to locate the pipe defect. Computing technology is coupled with an algorithm that can capture alerts, locate potential leaks or cracks, and immediately advise control room operators or emergency shut-off valves. The proposed solution is capable of detecting leaks indoors, and can be adopted by households, hospitals, factories, and research centers.

This design discusses effective techniques of damage location based on wave propagation on a real-time basis, an active sensor network, wireless data transfer, and an IoT platform. Leaking gas transmission pipelines are initially provided with bowing for global observation and damage detection. An efficient crash detection approach is proposed by analyzing the pressure pulses of a certain location on a pipeline, adapted to monitor rectangular pipelines. Recently, a smart system enabled early leak discovery for fluid transportation pipelines, as an IoT alternative. However, there is no mechanism to carry real-time data to a remote platform for more global checking. The designed sensor nodes may carry out data transmission using a WiFi module and can be observed from a platform, which is available to nearly all computing machines through their Android phone. However, the limiting Internet access in the field becomes the main obstacle. All sensor data was uploaded to an IoT analytics platform in real time while the minimum delay happens in the detection-alert termination period. This means that the platform must examine the data for potential dangers during transmission. Unfortunately, the IoT analytical platform has fairly large latency and often heavy data. Given that the reliable web-based platform will be accessible only after receiving all the IoT data. Although, because of the general interest, sample data and detected cases from the developed software as well as the experimental design could be observed by everyone.

7.2. Artificial Intelligence Advancements

Pipelines for oil, oil products, natural gas condensate, chemical substances, and technological pipelines represent the spatial transportation of sectors in which there is a need for operational control over the organization of transportation, levels, and state of working environments on the route. Calibration of monitoring parameters is required to ensure the safety of the transportation process, the protection of the environment and the adjacent population, as well as the protection of property (privately and publicly owned). The control must also be aimed at ensuring the quality of the process and the reconciliation of technology by the feedback principle of transformation of control actions into physical processes.

Highly efficient, reliable, and easy to install and operate sensors cannot always be selected. The placement of a sufficient number of sensors can be a difficult task. In particular, there are rare events in the measurements of systems and the development of anomalies. Traditional methods of taking into account this circumstance consist in using a sufficiently large factor of margins in the calibration of monitoring equipment, taking into account that the system wear is reflected in the violation of indicators, for example, in the reduction of 20% of the diameter of the pipe due to wear. However, in complex three-dimensional multi-phase, multiproduct, multiphase transport, the wear rate is asymmetric due to the speed and profile of the transported product. Lacking the direct relation between the wear of the equipment and the external indicators, requires an individual approach to modeling for any particular site. For example, the leakage flow may cause asymmetry in the sharpness of the speed profile and the equation of state of the fluid, including the thermal state.

CONCLUSION AND RECOMMENDATIONS

Since the crude oil spill in 2010 off the Gulf of Mexico deepwater horizon, offshore oil exploitation has attracted increasing attention, prompting advancements in the technical requirements of pipeline monitoring and leak detection at offshore drilling platforms. The geological strata in many marine areas in China pose great challenges to the installation of onshore leak detection devices and pipelines. Of additional concern are the remote and difficultly accessible geographical locations and significant environmental sensitivity of many marine areas. In the case of oil spills, if the automatic detection and shutoff of oil pipes are delayed, intervention and cleanup will be difficult. Gradual accidents often happen first, followed by catastrophic events. Triggering an accident investigation plan before the incident escalates and causes a crisis would save resources and drastically reduce the ecological impact. Pipeline leak monitoring in China is primarily limited to the installation of a ZAY length oil leak detector in the cable trench of the pipeline along the pipeline on the mudflat . In the actual accident that had occurred, the oil leak flowed in the trench of the pipeline, leading to an inaccurate measurement of the oil leak detector. With current remote sensing and wireless communications technology, a vast network of leak detection sensor stations in potentially dangerous offshore oil drilling locations and surrounding water bodies can be built, making it possible to continuously and closely monitor oil and gas pipelines over water. The creation of a digital twin pipeline system can achieve the real-time health assessment and real-time security of the oxen and non-oxen parts of the pipeline system. For early and on-time pipeline monitoring and leak detection. In the report, the relevant construction and operation trials of the networked oil and gas pipeline leak monitoring system with remote wireless sensing technology in a dangerous offshore drilling area are described. In order to ensure the accuracy of the simulated pipeline oil leak accident, a leak detection model of the oil and gas pipeline network system was established. The SAR works synergistically with local oil leak detection sensors to achieve an early, rapid, and comprehensive response to crude oil leakage. The economic and practical neural network-based oil and gas pipeline leak detection delay prediction tool has been developed to provide technical support to environmental protection agencies and companies in remote surveillance of oil spill accidents.

8.1. Summary of Key Findings

Summary of Key Findings of the Reviewed Papers

Advanced pipeline monitoring systems are critically needed for the safety and integrity of the urban economies. The existing leak detection methods can be broadly classified into six categories: (1) instantaneous methods; (2) intermediate methods; (3) continuous methods; (4) computational methods; (5) combination methods; (6) advanced methods. Based on the comprehensive literature review, a number of imperious questions still remain unsolved and can be addressed in the future: (1) How to predict the positions and magnitude of leaks in a more accurate and efficient way? (2) How to minimize false alarms and missed detections? (3) How to consider interferences caused by ambient pollution and other noise ordinary models? (4) Do existing methods fulfill the requirements in different pipeline networks and various operational conditions? (5) How to design a monitoring model targeting at carrying oil equipment working 24 hours a day, especially in remote areas? (6) Other important findings and potential research directions. It is found that many research works tend to focus on designing a monitoring system in accordance to the specific requirements of operators and different physical scenarios. Empirical techniques such as Diagnostics and Dynamic Modelling, which are broadly utilized in the daily operation of companies, can estimate and handle pipeline leakage. However, prior to the integration of these technologies, clearance of significant barriers is first required and will largely depend on the fosterage of new technologies by both companies and authorities. Nonetheless, there remain many challenges and questions that stand unsolved. In most cases the actual measurements cannot represent real cases; hence it’s difficult to give sound enlighten on the industry.

8.2. Practical Recommendations for Implementation

Pipelines provide transportation for a large quantity of oil and gas around the world. To ensure public safety and protect the natural environment, oil companies must perform continuous monitoring of their pipeline networks. This is extremely important in view of large infrastructures that are often spread by thousands of kilometres. Moreover, this task is consistent with recent risks of terrorism acts against strategic assets, like some of the above mentioned pipelines. Pipeline monitoring requires continuous monitoring of physical parameters of the pipeline operation, with a sensor network running along the pipeline, to reveal and localise anomalies. Detected anomaly data need to be transmitted to the operator’s control room. This task is challenging because of the peculiar nature of such monitoring application. Pumping stations are usually distributed along the pipeline, where the power supply is available. Sensing data are communicated from station to station, up to the control room, through satellite or GSM communication or through a preexisting wired infrastructure. Infrastructures in areas with high environmental value are often forbidden or highly regulated. Moreover, pumps and compressors operating in the pumping stations usually start or stop their operation following a prescheduled programme changing their operational conditions relatively, even if no anomalies. On the other hand, the above mentioned false positives generated by communication channel are penalised due to regulation in force on this kind of communication. In order to improve the signal to noise ratio of a given measurement, various measurements are time averaged before transmitting. This means that only relatively slow variables can be monitored .

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