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Review Article

Development of Programmable Logic Controller-Based Instruments for Remote Pipeline Monitoring: Recent Trends and Future Prospects

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Abstract *- Pipelines are an essential means of long-distance transportation, and they must meet significant standards for efficiency, reliability, and safety. A pipeline leak or burst could have a serious negative effect on the atmosphere and the reputation of the corporation running the pipeline. The industries need more versatile, efficient, and reliable control systems in order to automate the pipeline system by minimizing leaks during transportation. One of the essential elements of Industrial Control Systems (ICS) is Programmable Logic Controllers (PLCs) for automating gas/oil pipeline control and water management. This study mainly emphasizes the critical evaluation of the performance of several leak detection and control strategies provided for pipelines carrying diverse types of fluids. In recent years, cyber-attacks on PLCs have increased, and they have had a negative impact on the ICS process, including service interruption, component impairment, human safety risks, and interrelated economic complications. This study provides an overview of the various control methods in the pipeline and investigates their benefits, limits, and performance. Finally, this study finishes with prospective future enhancements based on the results and restrictions of the available literature, which will be useful to academics and engineers in the field.*

Keywords *- Remote Pipeline Monitoring, Leakage Detection, Programmable Logic Controllers PLC, Hardware-Based Methods, Software-Based Methods, Cyber Security.*

1. Introduction

Pipeline networks are the most cost-effective and secure way to transfer oil, gas, and other liquids. Several countries rely on pipelines stretching thousands of kilometres to transport water and oil from distillation plants to their final destinations [1]. Figure 1 represents the form of oil transportation used in India, demonstrating that pipelines have the highest percentage and relevance among other long-term transportation modes [2]. It has been established that the safest and most economical way to distribute crude oil is through oil and gas pipeline networks [3]. Pipelines must adhere to strict safety, uniformity, and efficiency requirements while in long-distance transit. Oil and gas pipelines will eventually fail due to corrosion, weld faults, third-party damage, and other issues. Major catastrophes and monetary losses can result from leaks in gas and oil pipelines. One efficient way to reduce the likelihood of pipeline failure is to identify leaks [4]. Long-distance pipelines are difficult to monitor due to the challenges of maintaining the framework. Instrumentation for efficient leakage detection has advanced significantly during the 1990s. The advancement of technology allows pipelines to be outfitted with fault diagnosis systems [5, 6], leakage detection systems at control centers, safety monitoring, and physical parameter management, among other things. Heavy leaks are simple to recognize because they significantly affect the flow rate and pressure. On the other hand, a top-notch leak detection system is necessary for small leaks. Various attempts have been undertaken to enhance leak location and detection, with differing degrees of success. There are several examples [18–19], including acoustic emission [7-9], fiber optic sensor [10–11], ground penetration radar [12–13], negative pressure wave [14–15], pressure point analysis [16–17], and dynamic modelling.

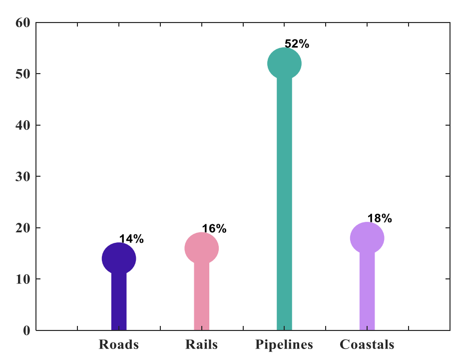

Fig. 1 Type of Oil and Petroleum Carriage in India [2]

These well-known leak detection methods fall into three categories: Software-Based, Hardware-Based, and Biological (Visual Examination, Odour, or Sound Detection) [20]. In hardware-based monitoring, sensors are positioned outside the pipeline to track and notify of malfunctions. In software-based systems, sensors are inserted into the inner side of the pipeline to measure internal characteristics, including Viscosity, Temperature, Flow Rate, and Pressure [21]. Both the software-based and the hardware-based methods have certain drawbacks. When compared to software-based solutions, hardware-based methods typically have longer testing timeframes and are not as good at delivering continuous monitoring. The accuracy of the hardware-based leakage detection system may vary depending on external factors such as seasonality, ambient temperature, soil characteristics, and mobility, all of which must be considered before using hardware-based detection methods. Furthermore, these technologies cannot accurately locate the leak, and the false alarm rate is higher due to a variety of factors, such as fluid blockage within the pipeline.

The control system has to be dependable, powerful, programmable, adaptable, and cost-effective. Because of the features listed above, PLCs are widely used in industrial automated systems. PLCs are computer-based, solid-state, single-processor parts that replicate an electrical ladder diagram to control a variety of fully automated systems and industrial devices [22]. A detailed framework for detection, classification, and real-time control by PLC-SCADA systems is lacking in the majority of the research studies that have reviewed and analyzed different techniques of leak detection and fault identification in oil, gas, and water pipelines. Moreover, the previous reviews have not analyzed the techniques in a comprehensive manner and have not provided a systematic classification that encompasses techniques based on steady-state and transient approaches. Furthermore, there is a lack of adequate research work on the use of PLC in the automated control of substation and pipeline equipment. This study aims to identify research gaps in the field of pipeline leakage detection and assess the most recent advancements in PLC-based pipeline leakage detection systems.

The remainder of this paper is organized as follows: Section 2 explains the purpose of this review study. Section 3 describes the satisfactory review approach. Section 4 summarizes the basic kinds of remote pipeline monitoring and leakage detection approaches. Section 5 covers the fundamentals of PLC development, programming, and architectural enhancements. Section 6 examines current articles on remote pipeline monitoring systems based on PLCs. Section 7 highlights the major problems of present approaches, as well as some potential future research directions. Finally, Section 8 presents the paper's conclusion.

2. Review Objective and Motivation

A pipeline leak during operation can result in financial loss, resource waste, and, in some situations, human loss. Most pipelines are run at high temperatures and pressures, which frequently leads to pipeline breakdowns that cause serious physical injuries and impede the delivery of water, gas, or oil. As a result, these pipelines require dynamic observation and maintenance systems. Nonetheless, the system must be adaptable and cost-effective. In the literature, significant attempts have been made to develop an intelligent approach capable of detecting and correctly localizing leakage. Leakage detection systems based on PLC and Supervisory Control and Data Acquisition (SCADA) have improved oil pipeline performance criteria such as dependability, sensitivity, stability, and accuracy. The current work is a fresh attempt to thoroughly investigate PLC-based systems in fluid pipelines, which had previously been unexplored on any platform. It also emphasizes the important performance of various leak detection methods established for pipelines providing various fluids.

This study will be used to improve designers' awareness of the practical issues of monitoring long-distance pipes using PLC. This PLC is used to achieve the pipeline transportation performance requirements in terms of leakage detection reliability, sensitivity, and leakage localization accuracy. A review of the literature finds that, while PLCs are popular in industrial automation systems, there is still no consensus on how to adequately define PLCs. As a result, in order to program the PLC in the remote pipeline application, an efficient architecture is required. To highlight the key contributions of the current study, Table 1 collects previously published review studies and analyzes their drawbacks in the remote pipeline monitoring application.

Table 1. Comparison of Relevant Survey Papers

Survey	Journal	Purpose	Pipeline reviewed	Remark
Adegboye et al. [3]	Sensors	Reviewed various leakage detection and localization methods in pipeline systems	Oil	Does not review PLC-based monitoring Techniques.
Korlapati et al. [23]	Journal of Pipeline Science and Engineering	Studied the development of various leakage discovery systems	Oil and gas	Does not discuss the problem of controlling the sub-station equipment using PLC and SCADA

Datta et al. [24]	Journal of Loss Prevention in the Process Industries	Studies various pipeline fault recognition techniques	Oil, water, and gas pipeline	No proper classification was done. Transient approaches are not included.
Arifin et al. [25]	Computers & Chemical Engineering	Complete analysis of data-driven steady-state methods	water	Discrimination is unclear and incomplete. Do not include all techniques.
Zaman et al. [26]	Engineering Failure Analysis	Focused on pressurized pipelines transporting various types of fluids	All types of pipeline	Does not investigate the utilization of PLC in the pipeline system.

Many review papers fail to explain in detail how PLC is used in a pipelining monitoring system. These considerations prompted us to reconsider the usage of PLC in remote pipeline monitoring applications. It also describes a modern PLC-based controller that was utilized for remote pipeline monitoring between 2015 and 2023. This research looks into the significance of various leakage detection systems and emphasizes the importance of PLC in complex manufacturing and industrial applications for controlling, measuring, and carrying out tasks. Although this is a review study, this manuscript is unique in the sense that it offers a comprehensive and integrated review of both cybersecurity and PLC-based control design and leakage detection techniques, which are normally provided separately in previous reviews. The current review compares hardware and software-driven approaches, discusses PLC-based control techniques (PID, PI, fuzzy), and identifies the risks of cybersecurity in industrial control systems, as opposed to previous reviews that mainly concentrate on detection techniques. The current review is different from previous publications due to its comprehensive and integrated nature. The investigation of these methodologies may pave the way for future research on this subject to reduce leakages. The key contributions of this work are as follows:

- To provide a complete review of studies that utilize the hardware and software-based leakage detection methods for remote pipeline monitoring.
- To investigate the PLC-based pipeline monitoring scheme and share expertise with the scientific community to gain insight into building a testbed for water/gas/oil pipeline monitoring.
- To study the presentation influence of PLC based on an improved architecture and organization
- To study the impact of different attacks on PLC-based oil and gas critical infrastructure communication
- To present open challenges and difficulties in the existing models in remote pipeline monitoring.

3. Review Methodology

A reliable leak detection method is required to reduce economic loss caused by leaks. As the demand for automation grows, a control system must be programmable, versatile, dependable, resilient, and economical. In recent times, the admiration of PLC has increased due to the tremendous advancement in control operations and services.

In this case, scientific databases on the internet are used for the search procedure to review publications on remote pipeline monitoring. This review focuses on journal publications, conference papers, and book chapters that examine the application of PLC in leakage detection systems. The process for the review is separated into two phases: planning and identifying. The first phase is the planning phase, during which the necessity for a systematic review and research questions is identified. The second phase describes the sort of searching method utilized in journals or research papers investigated, and the examination of the various models used.

3.1. Research Queries

This study mainly intended to answer the subsequent queries:

Q1: What are the broad classifications of Pipeline Monitoring Systems (PMS)?
Q2: How can PLC provide flexibility, robustness, and reliability in the leak detection system?
Q3: How may PLC architecture be enhanced to provide quicker response in time-critical solicitations, like oil and gas pipeline operations control?
Q4: How can PLC be integrated with other controllers like PID to enable precise control, energy efficiency, fast response, and flexibility in industrial applications?
Q5: How can programmable logic controllers be protected against data tampering attacks?

3.2. Searching Strategy

In this study, two well-known resource libraries, Science Direct and Scopus, are utilized to search for scientific papers that cover the majority of the approaches employed in remote pipeline monitoring systems. The keywords “Remote Pipeline Monitoring,” “Leakage Detection,” “PLC,” “Hardware-based methods,” “Software-based methods,” and “Cyber Security” are used in the search. Here, the online logical database limits the search from 2015 to 2023. The distributed papers from journals and conferences for this review paper were chosen using ACM Digital Library, Wiley Online Library, Elsevier, IEEE Xplore, Springer Digital Library, Taylor & Francis, Google Scholar, Science Direct, and others. The papers were chosen by the internet databases based on the search query. Here, a two-stage screening procedure is conducted after the collection of all papers. The first stage looks at the titles, abstracts, and keywords of the papers to find the initial set of relevant publications. After that, the shortlisted articles were thoroughly examined to produce the final set of papers for addressing the issues of the topic chosen for this review.

Figure 2 (a) depicts the geographical dissemination of the most active nations in pipeline leak detection research. A selected criterion considered the countries that published a minimum of three papers on PLC-based remote monitoring applications. It indicates that China is the country with the most scientific contributions, publishing a total of 17 publications, and subsequently, India has 9 publications. The publication trend over time is also investigated, as illustrated in Figure 2 (b). From 2015 to 2023, there was a steady growth in the number of publications, and the maximum number recorded in 2019 was 12 publications. As of 2023, only 5 relevant papers on the subject have been discovered, although more papers are expected to be released throughout the year.

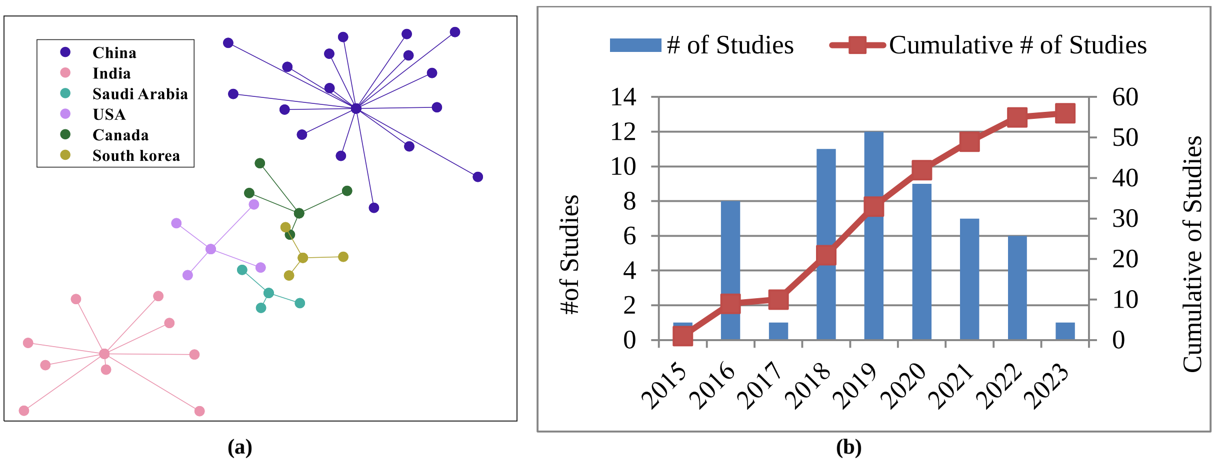

Fig. 2 Publication Trend in Pipeline Monitoring Research. (a) Clustering plot displaying the publication trend over countries, and (b) Publication trend over the years.

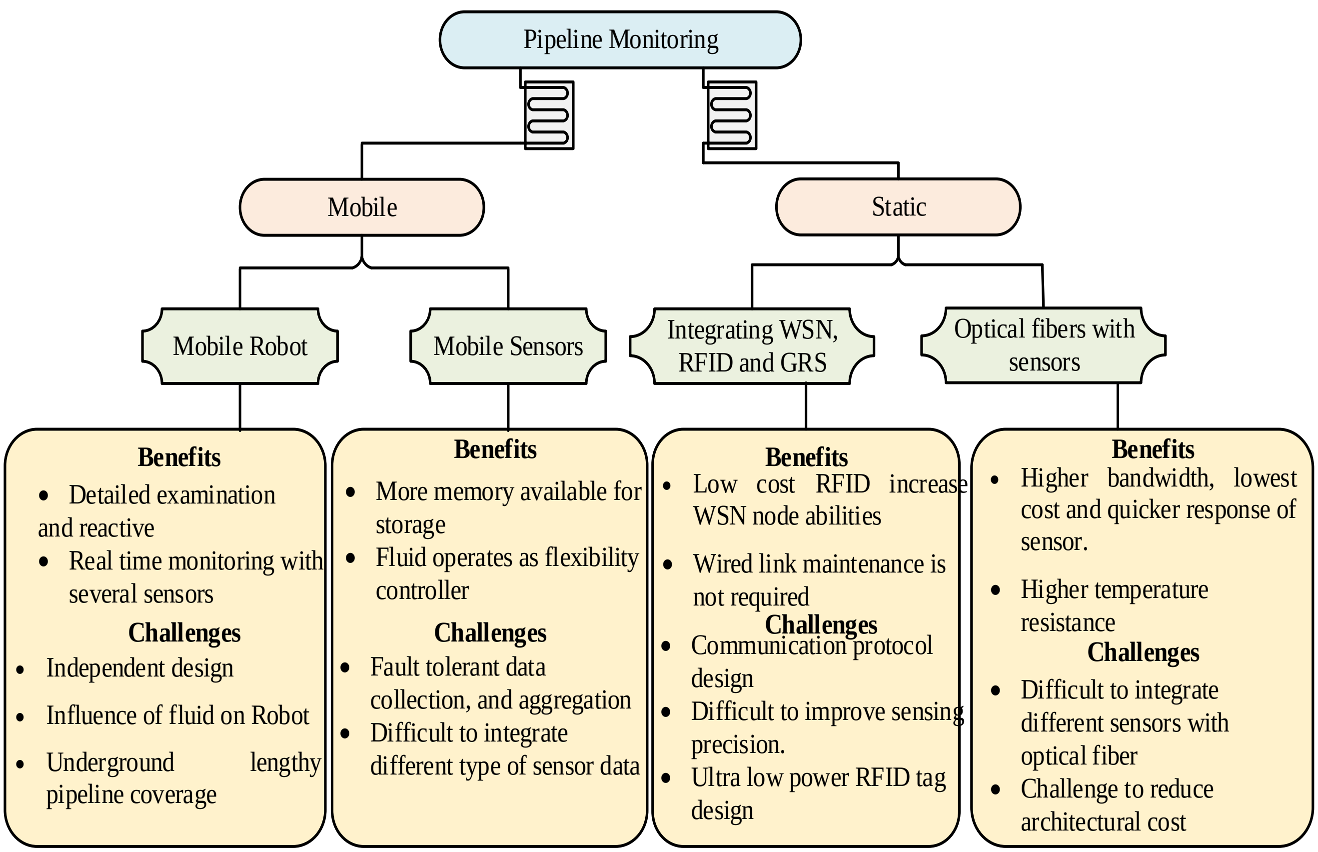

Fig. 3 Pipeline Monitoring Methods

4. Remote Pipeline Monitoring Techniques

Remote pipeline monitoring systems help firms predict potential safety issues before they arise, allowing them to take the appropriate precautions promptly. Figure 3 [27] depicts the distinction between mobile and static remote monitoring. Intellectual mobile sensing components, such as robots, pigs, or crawlers, are usually moving on the inner side or above a pipeline to assess the inner and external states of pipes. Standalone examination systems employ phased array ultrasonic techniques and are positioned on the outside of pipes to identify erosion and flaws at a specific point. Handheld devices are used for physical activity in some places. There has been little investigation conducted by utilizing a distributed sensor network for the examination and observation.

The wired networks can cause a variety of issues because gas pipes are typically buried underground or underwater. After installing the monitoring system, it becomes impossible to physically visit the structure on a regular basis. As a result, the systems need to be monitored and maintained remotely whenever possible. Several sophisticated methods have been developed for monitoring the pipelines remotely. IoT-based solutions are becoming more popular because they can gather data in real time with great accuracy and competence [28]. Leakage detection and localization are major challenges in the pipeline management sector [29]. The established leak detection techniques can be classified into several coherent groups. Figure 4 depicts a pictorial representation of the classification of the main leak detection techniques. The leak detection approaches can be separated into three categories: direct approaches, indirect approaches, and inferential approaches. All the hardware-based leak detection methodologies are direct, and the software-based solutions are typically indirect or inferential. The inferential approaches are rarely utilized for identifying the presence of a leak, and so they are not covered in this study.

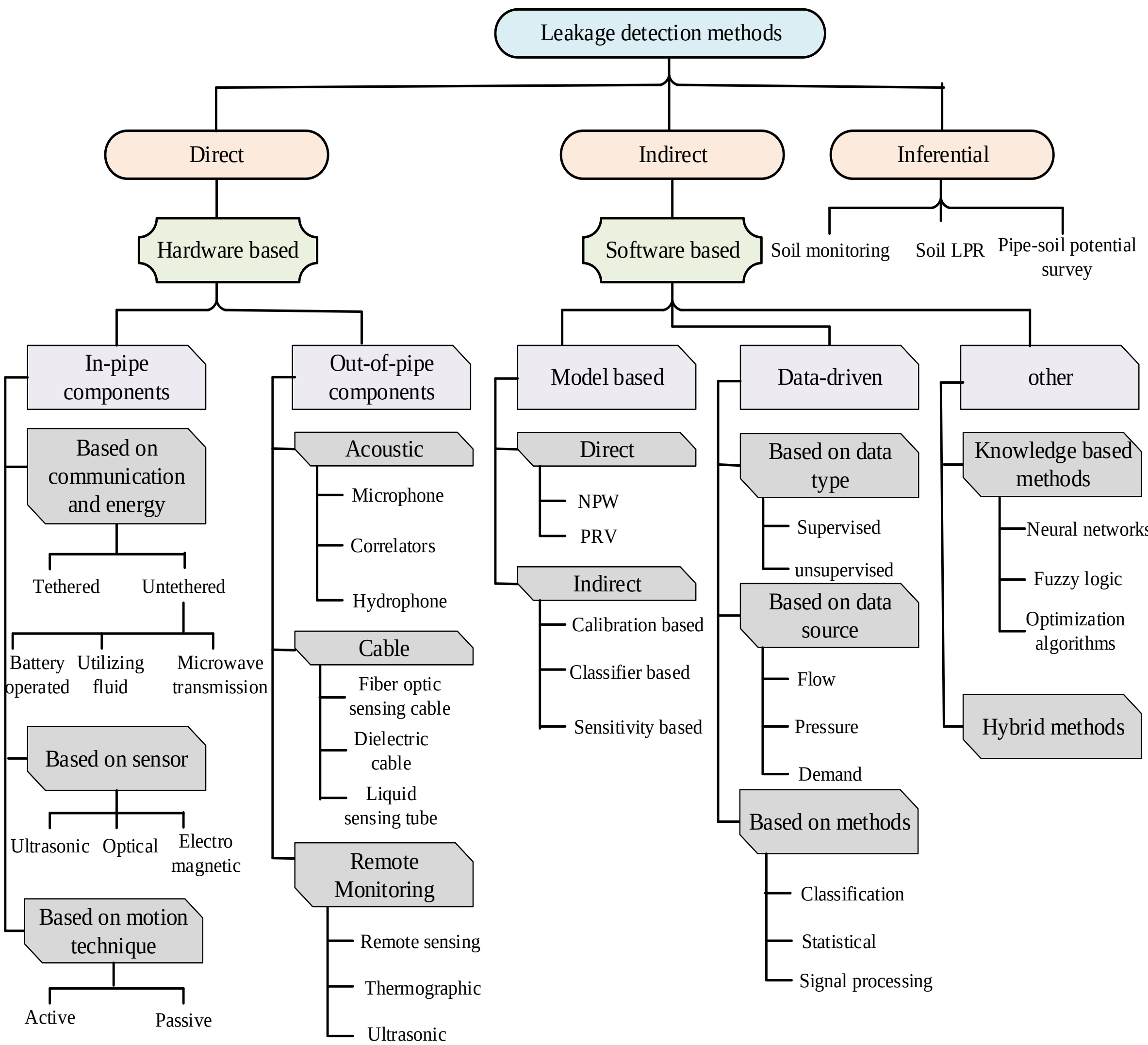

Fig. 4 Classification of Main Leakage Detection Approaches

4.1. Hardware-Based Approaches

In a based method, sensors are located on the outer side of the pipeline for monitoring. There are numerous commercial leak detection technologies available, which are further divided into out-of-pipe and in-pipe components [30]. Acoustic components are the most common type of ‘out-of-pipe’ apparatus. These approaches are based on the discovery of shaking or noise signals caused by leakages, which can be detected externally [31]. Cabled leak detection methods are extensively employed in oil and gas pipelines. They consist of Optical, Dielectric, or Fluid Sensing Cables deployed alongside the pipeline path [32]. Ground-penetrating radar imaging is a standard tool for detecting water leaks in pipelines [33]. However, they are best suited for Greenfield zones with minute concrete surfaces.

‘In-pipe’ components are categorized based on their precise operational features and are often classified as active or passive according to the device’s motion strategy. Other classification strategies include the degree of autonomy, the type of sensor used, and the mode of communication and energy transfer. PIGs, or pipeline inspection gauges, are also offered for thorough pipe cleaning and inspection. Many non-destructive testing techniques have been introduced in recent years for pipeline monitoring. They are Eddy Current testing (EC), Electromagnetic Acoustic Technology (EMAT), Ultrasonic Testing (UT), and Magnetic Flux Leakage (MFL) testing. One method for evaluating a pipeline’s material condition is Magnetic Flux Leakage (MFL) [34]. After polarizing the steel pipe around the saturation flux density, the MFL method finds a nearby leak caused by surface flaws. Also, the accuracy of MFL is decreased as the material thickness grows, and is confined to magnetic materials using the Eddy Current (EC) approach.

Ultrasonic testing technology uses high-frequency motorized signals to determine the wall thickness of the pipeline with great accuracy [35]. It indicates defects when the pipeline wall thickness varies. Background interference is one of the most serious issues with an ultrasonic leak detector. An Electromagnetic Acoustic Transducer (EMAT) follows the hypothesis of electromagnetic coupling [36]. The EC measuring method is a non-contact measurement approach utilized for quick examination [37]. However, because of the skin effect, it examines the surface or near-surface architecture of conductive materials. Moreover, Eddy Current (EC) testing is highly dependent on the distance between the probe and the pipeline surface, which needs to be confirmed.

The scarcity of drinking water supplies, which is exacerbated by the consequences of climate change and the deteriorating urban infrastructure, has emphasized the importance of the real-time monitoring and detection of water loss in the distribution network. The scalability of traditional leak detection techniques is restricted by the fact that, in most cases, single-point analysis is used, and a deep understanding of the hardware and software architecture is not available. Meric Yilmaz Salman and Halil Hasar [38], in their study, lifted these limitations of traditional leak detection systems by developing and implementing a Wireless Sensor Network (WSN) based on FSR technology, where the gateway sends the data to the cloud. The proposed system uses software and hardware components for safe wireless connectivity for the real-time monitoring of changes in the pressure of the pipelines.

Lijia Luo et al. [39] designed a fiber-optic vibration-detection device to detect underground pipes. Deep learning technology is proposed for detecting abnormal situations of pipelines. The proposed method of detection includes a Deep Scattering Network (DSN) along with Kernel Support Matrix Domain Description (KSMDD). First, DSN is applied to extract deep time-frequency features of vibration signals of a fiber optic sensor system. KSMDD is applied to generate signal feature matrices to create a statistical index for abnormal situations. The proposed method of recognition includes a DSN along with a Gated Recurrent Unit (GRU) network.

The nonlinear dynamic behavior of a V/Heart-shaped chaotic system and its implementation have been discussed by Abdul-Basset et al. [40]. For the nonlinear dynamic behavior of the system, modern nonlinear analytic methods such as Spectral Entropy (SE), Power Spectral Density (PSD), Bicoherence, Phase Portraiture, Bifurcation Diagrams, and Lyapunov exponents have been employed. To show the flexibility of the system, two case studies have been presented by varying important system parameters, which reveal many odd attractions. An industrial-grade programmable logic controller with Structured Text (ST) language has been employed to implement the system, making it possible to run the system on hardware. After performing an exhaustive comparison with experimental data from hardware implementations in the lab, outstanding agreement has been found with the simulation of the chaotic system dynamics.

4.2. Software-Based Approaches

In software-based approaches, sensors are located on the inner side of the pipeline for measuring the interior factors such as viscosity, temperature, flow rate, and pressure. The majority of software-based leakage detection approaches fall under the category of indirect approaches. The hydraulic condition of the pipeline network is critical in software-based pipeline monitoring approaches, which can be classed as steady-state, transient-state, or hybrid approaches. Real Time Transient Model (RTTM) [41] uses hydraulic modeling and progressive fluid modeling for simulating pipeline conditions. To measure fluid flow, RTTM software typically employs numerous flow equations, energy preservation expressions, and momentum preservation expressions. By comparing the estimated values with the actual data, this method may predict the location and magnitude of leaks in real time. RTTM necessitates a large number of instruments, controller training, and maintenance, making its exploration very costly. Furthermore, mistakes in equipment calibration could result in a high false alarm rate, making it untrustworthy for certain applications.

Another propitious leak detection approach is Negative Pressure Wave (NPW) [42]. When a pipeline leak occurs, the liquid density decreases in that area. Then, from that breach place, a wave of comparable magnitude but in the opposite direction will circulate over the pipeline. It also has a high rate of false alarms. Pressure Point Analysis (PPA) measures the inner side pressure of the pipeline. There is a spillage when it drips repeatedly [43]. Pressure is regularly measured at several points along the pipeline, and the closeness of a hole is declared when the mean estimate of pressure falls below a predetermined bound. As a result, the PPA approach may encounter issues with unsteady state pipeline operations. Table 2 provides a quick summary of hardware and software approaches reviewed in the literature.

Table 2. Summary of Hardware and Software Approaches

Deployment scheme/ Technique	METHODS		Objective	False alarm	Accuracy	Drawback
	Hardware	Software				
In-pipe leak detection robot [30]	✓		Determine leaks by utilizing electronic pressure sensors	Medium	Medium	Very expensive; Poor results in large-sized pipes.
Cabled techniques [32]	✓		Determine the gas leakage of submerged pipelines	MEDIUM	HIGH	The background's reflection properties affect the system's performance.
Ground-penetrating radar imaging [33]	✓		Exhibits the reflection property of pipes during various leak scenarios, allowing for efficient pipe maintenance methods.	Medium	LOW	Suited for greenfield regions with small concrete surfaces
Magnetic flux leakage (MFL) [34]	✓		Defines faults in pipelines	Medium	Low	Bends and changes in diameter are not tolerated.
Ultrasonic testing [35]	✓		Use a non-contact, non-destructive approach to determine leakage in the pipe remotely	High	Low	Does not give automated leak testing
Eddy current testing [37]	✓		Determine and distinguish inner diameter and outer diameter surface defects in the pipeline.	Medium	Medium	Lift-off distance affects the system's performance significantly
WSN-based FSR technology [38]	✓		For remote monitoring to detect water losses	Medium	HIGH	The operational lifetime of the wireless modules is limited by IoT-based monitoring.
Fiber optic vibration detecting device [39]	✓		For detecting underground pipes	Low	HIGH	High complexity of system composition
V/Heart-shaped chaotic system [40]	✓		To investigate the system's complex dynamical behaviors.	Low	HIGH	Limited by their low-frequency response, which restricted their application in high-speed systems

Real Time Transient Model (RTTM) [41]		✓	Determine leakages with high consistency by concentrating on sudden-onset leakages of different sizes.	HIGH	HIGH	Mistakes in equipment calibration can lead to a high false alarm rate.
Negative Pressure Wave (NPW) [42]		✓	To localize the leakage accurately.	MEDIUM	Medium	The substantial drop in pressure level caused by valve opening and closing is incorrectly evaluated as a leak occurrence.
PPA [43]		✓	To detect the leak events by exploiting the properties of transient pressure.	Medium	HIGH	May encounter issues with unsteady state pipeline operations

From the perspective of the aforementioned shortcomings of current models, it is clear that great efforts are required to develop an intelligent methodology capable of detecting and accurately localizing leaks. This work attempts to analyze an intrinsically intelligent strategy in this direction. The presentation standards of a leakage discovery system are provided by the American Petroleum Institute (API). They comprise dependability, sensitivity, consistency, and accuracy. The implementation of PLC and SCADA-based systems for oil pipelines focuses on enhancing these performance matrices [27].

5. Development of a Programmable Logic Controller

Nowadays, microcontroller-based systems control industrial systems. The most common microcontroller-based system is a PLC. The automobile sector first used PLCs in the late 1960s, and it used discrete circuits comprised of electromechanical relays and coils placed on panels to control the automated equipment predominantly [44, 45]. A PLC is a computer-based system designed to control a process. It connects the data from sensors with the state of certain actuators. In a remote pipeline monitoring system, PLCs collect important measurements such as flow rate, pressure, and temperature from field equipment and transmit them to the host SCADA over a communication network. After that, the operator may send supervisory commands to the field location based on the received information [27]. In general, PLCs offer installation flexibility, minimal space requirements, and adaptable local control functions.

5.1. PLC Programming

The standard IEC 61131-3 describes several programming languages for PLCs [46]. The most common way to program a PLC is to use a relay logic ladder diagram to create the basic control circuit, which is then input into a programming terminal. The ladder diagram can be converted into digital codes via the programming terminal and delivered to the PLC. Sequential Function Charts (SFC), Structured Text (ST), Function Block Diagrams (FBD), and Instruction Lists (IL) are some of the languages available for programming PLCs. However, the ladder diagram is still well-liked by most of the PLC programmers.

Figure 5 illustrates a sample ladder diagram. Here, every line is called a rung. It is used to control the status of 3 outputs labelled as O/0, O/1, and O/2 according to the input states (I/0, I/1, and I/2). Contacts on rungs can be typically open or closed. In this example, the "ON" status of input I/0 (usually open contact) in the 1st rung turns the O/0 to "ON" state. Alternatively, the "OFF" state of input I/1 (usually closed contact) turns the O/0 to the "OFF" state. In the same manner, the "ON" state of inputs I/0 and I/2 in the 2nd rung turns the O/1 to the "ON" state.

Finally, O/2 is set to the "ON" state when input I/1 is "OFF," and input I/2 is "ON." A standard PLC structure repeats the scan cycle execution repeatedly. The sum of the times required to read the inputs, complete all three rungs, and write the outputs is used to determine the scan time of Figure 5. The conventional PLC structure conducts the scan cycle activities consecutively; a longer program results in a longer scan time. As a result, it reduces the performance and response time of the system.

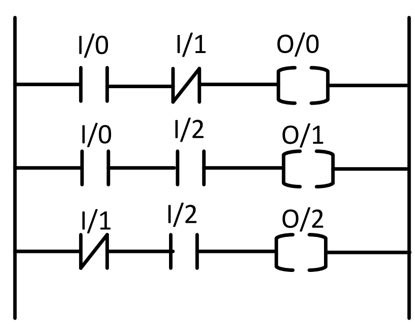

Fig. 5 Sample Ladder Diagram

5.2. Enhanced Architecture for PLCs

Various enhancements to the PLC architecture have been implemented to increase PLC performance in terms of scan time minimization. Some improvements introduced in PLC architectures are Verifying to Execute Improvement (VE) and Searching to Execute Improvement (SE). The main inspirations for VE improvement are the data flow machinery and the philosophy of digital logic simulation. On the other hand, SE improvement depends on the cache memory process and the memorization approach [47]. The VE enhancement inspects the inputs of rungs for the presence of signal value fluctuations and schedules the rungs to execute only when there is an “ON” to “OFF” or “OFF” to “ON” change in their inputs. The VE and SE enhanced architectures contain a PLC core to receive inputs, execute a program, and write output, as illustrated in Figure 6 (a). The standard execution core depicted in Figure 6 (b) functions similarly to a regular PLC Execution Core (EC). The incoming values are utilized for executing all the rungs and updating the outcomes based on the execution module’s outcomes.

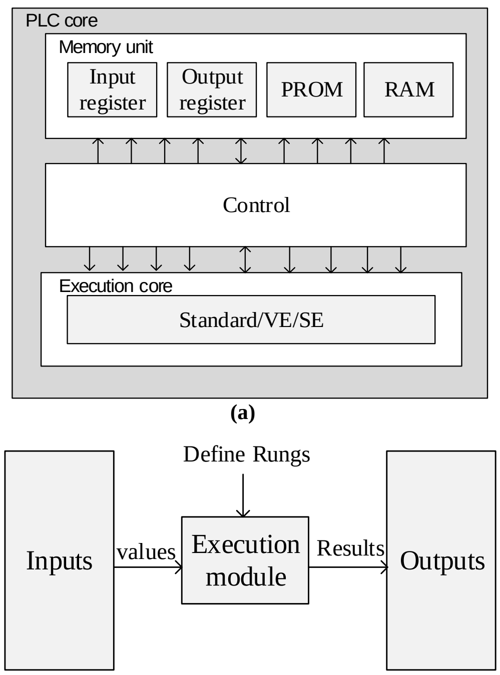

Fig. 6 PLC core (a) Traditional PLC Execution Core, and (b) Standard Execution Core.

The edge detector module in the VE enhanced EC inspects changes in the inputs using rung definitions and verification order. When it detects an edge, the relevant input ID is provided to the rung scheduling unit. It determines which rungs comprise the specified input ID and alerts the execution module to execute the rung, providing its address. The EC considers the rung scheduling unit as a FIFO queue buffer, allowing the edge detection module to perform its authentication operation using either a previously scheduled rung or a rung program fragment that has previously been executed at the EC [48]. The memorization checker is the key constituent of the SE-enhanced EC, as shown in Figure 7 (b). The memorization checking module relates the present input values of a rung with the input values indexed in its memorization memory before transmitting them to the execution module to check the presence of an earlier execution output for that rung. When the memory contains the output of that rung execution, the cached value will be utilized to update the output values. Thus, the execution module can skip the execution of the rung. If not, the rung is sent to the execution module, which signals the memorization checking module to store the outputs for upcoming usage after the execution is completed.

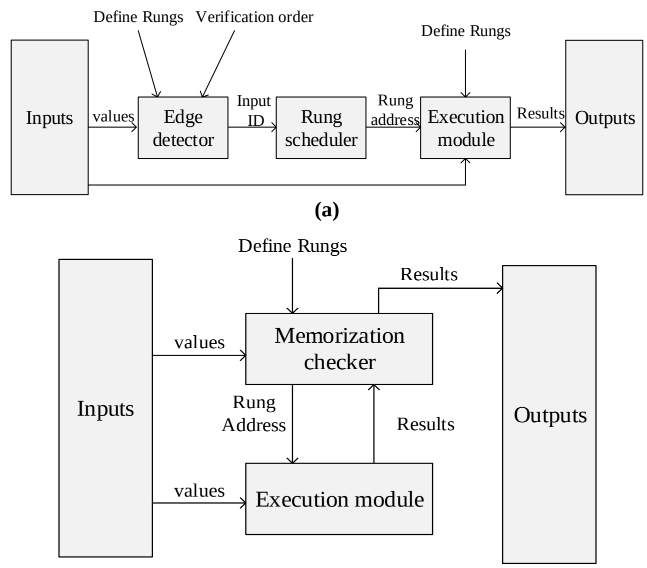

Fig. 7 Enhanced Architectures (a) VE Execution Core, and (b) SE Execution Core.

6. PLC-Based Remote Pipelining Monitoring System

Wang et al. [49] created a PLC-based gas drainage pipe network for improving the controlling efficiency, reducing the worker labour intensity, and ensuring secure coal mine production. The main control unit of this gas drainage pipeline system is a Siemens S7-1200 series PLC. Ultrasonic flowmeters, laser methane sensors, and carbon monoxide sensors were used to measure gas temperature, pressure, flow rate, absorption, carbon monoxide, and the remaining pipeline factors in the pipeline network. The manual valve on the extraction pipeline is replaced with an electric valve, and the PLC was intended to modify and control the electric valve automatically. This system also used the Ethernet bus to communicate data to the monitoring center. The design employed switches as repeaters based on the communication distance of the Ethernet. Optical fibers were used to boost the system’s communication distance and to prevent interference by connecting the switches. This system arrangement is adaptable, and the number of PLCs and sensors can be augmented or reduced in proportion to the number of drainage holes.

Hussein et al. [50] used a PLC controller to increase the effectiveness of the pump station in a pipeline transport system. Here, real pump performance has been examined in terms of pressure, efficacy, and flow rate by considering a 2m long pipeline with pressure-sensing equipment. Piezoresistive and flow rate sensors were utilized to measure the pipeline of an oil pump station. The flow rate transmitter has been used to translate the fluid flow into an analog signal, and the PLC has been connected with SCADA to monitor the load and show the outputs on the LABVIEW screen. The SIMATIC S7- 1214 global control unit was acting as the primary decision-making component that utilized this analog signal to make the necessary judgments.

Wang et al. [51] used a Siemens S7-1500 series PLC as the primary control unit in a gas drainage monitoring system. This system adopted smart sensors to reduce interference by transmitting the signal in a digital format. Also, it utilized PID and cascade PID advanced control techniques for controlling the flow/pressure and improving the drainage system's regulation accuracy. Furthermore, the limit threshold strategy has been adopted with a data mutation strategy and early warnings to reduce unplanned drainage pump shutdowns and improve the drainage system's efficiency.

Venuprasad et al. [52] proposed an automated pressure monitoring and control strategy for pipelines using PLC and SCADA. Here, pipeline security has been established through the propagation of pressure in a one-meter-long pipe. Also, the pressure transmitters have been connected at the beginning and end points of the pipe to quantify the flow rate. This pressure transmitter converted the pressure flow into an analog signal. PLC has been used to monitor the load based on the pressure-flow level. The complete system has interacted with an automation system utilizing PLC and SCADA by quantifying the reading of the pressure transmitter to locate the problem.

Aziz et al. [27] provided the physical architecture of a pipeline monitoring system based on a PLC and SCADA. PLC received output from field input components and continuously checked the status of the system using an application program. The sensing units were used to collect the information from the distributed station. Figure 8 depicts the PLC and SCADA-based remote pipelining control system. A wireless radio transceiver has been used to establish transmission between the control centre and the remote observing station. SCADA allowed the operator to complete jobs remotely. PLC collected critical measurements from field devices such as flow rate, pressure, and temperature, and uploaded them to the host SCADA through the transmission network. In reaction to the received data, the operator might send supervisory directives to the field location. This research study uses the SIEMENS S71200 family member 1214c PLC.

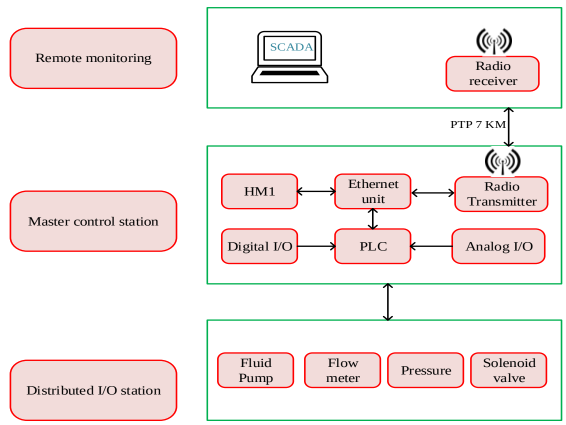

Fig. 8 PLC-Based Leakage Detection System

Ayaz et al. [53] designed and implemented a gas leakage discovery system with a modest control structure and a single sensor unit. This device is intended for monitoring various gases. The PLC and SCADA were used to perform data acquisition, control, and monitoring of the system. Table 3 provides a quick summary of PLC-based pipeline monitoring systems reviewed in the literature.

Table 3. Summary of PLC-Based Pipeline Monitoring Systems

References	Pipeline	Objective	PLC	Sensors	Communication medium
Wang et al. [49]	Coal mine gas pipeline	To control Coal mine gas drainage	Siemens S7-1200 series	Ultrasonic flowmeter, laser methane sensor, and carbon monoxide sensor	SCADA, Ethernet, Switches and optical fibers
Hussein et al. [50]	Crude oil pipeline	For controlling the factors such as pressure and flow in the oil pipeline remotely	SIMATIC S7- 1214	Piezoresistive and flow rate sensor	SCADA
Wang et al. [51]	coal mine gas pipeline	To guarantee the consistent and stable operation of the gas drainage system.	Siemens S7-1500 series	Gas, liquid level, flow, and pressure sensors	-
Venuprasad et al. [52]	Gas	To examine and control the position of leakage	-	-	RS-485 cable, RS-232 cable, SCADA,

Aziz et al. [27]	Gas	To develop a new leakage detecting approach with better accuracy, minimizing the false alarm rate	SIEMENS S7−1200	FS-400A-G1 flow meter sensor and HK1100c pressure sensors	Wireless radio transceiver, SCADA, Ethernet.
Ayaz et al. [53]	Gas	To develop a low-cost gas leakage detection system	Siemens S7-1200 series	H2S – O2 – CH4 – CO gas sensors	SCADA

6.1. PLC-based PID or Fuzzy Controllers for Pipeline Transportation System

One of the most crucial components in a PLC is the PID controller. It is utilized for controlling and regulating the process input and other process variables. PID controllers are created by PLC manufacturers to calculate the error value between the set point and the measured process variable. According to this error, it generates a signal to change the output to keep the process under control. The primary source of petroleum products is the sea. The key issue the worker has faced here is maintaining steady pressure and flow to the extreme ends.

Priyanka et al. [54] used control valves to maintain parameters like pressure and flow based on the transmission pipe's pressure and flow rate. PLCs control the fraction of opening of control valves/pumps for regulating the flow and pressure during petroleum product transmission. An appropriate controller has been developed to get an essential set point for pressure and flow rate by regulating the long transferring concrete pipe. To achieve this, a PLC-based PID controller has been created. Figure 9 depicts the oil transportation system's process flow diagram.

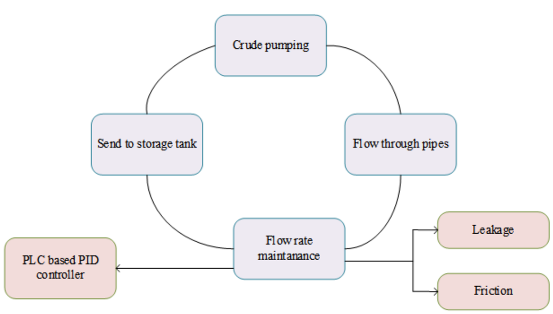

Fig. 9 Process Flow Diagram of the Oil Transportation System

Priyanka et al. [55] suggested a novel PLC-based Fuzzy-PID controller for regulating the flow rate of petroleum pumps in an automatic manner. The SCADA model monitored the complete process remotely and viewed/changed the tuning parameters of the PLC-based Fuzzy and Cascade PID controllers, as illustrated in Figure 10. If the pressure of the petroleum exceeds the safe limit, the alarm light will blink. After reaching the safest bound of pressure, the controller will transmit a control signal to change the flow rate by controlling the proportion of the open/closed state of the control valve. During an emergency, the emergency push button on the control panel is utilized to shut down the whole system. The worker in a remote site uses this front-end screen to monitor the parameter variations.

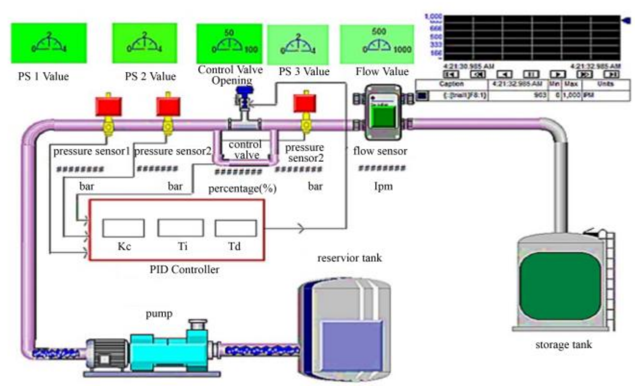

Fig. 10 PLC-based Fuzzy-PID Controller in the Petroleum Products

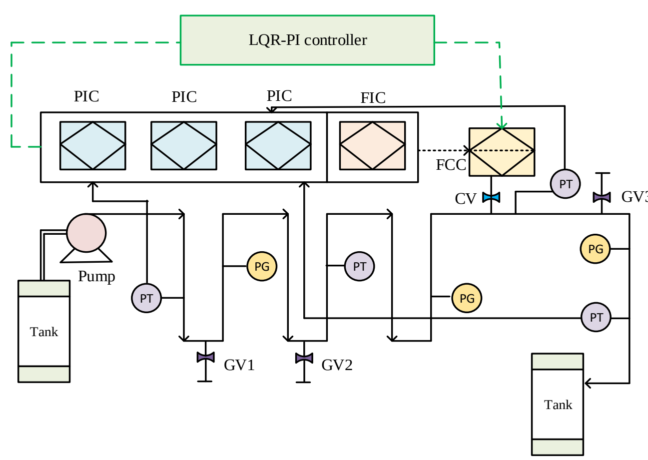

Fig. 11 A Process and Instrumentation Diagram for the Experimental Setup

Priyanka et al. [56] used a Linear Quadratic Regulator-Proportional Integral (LQR-PI) controller to manage the anticipated flow rate by regulating different pressure signals during oil transport via pipes. Figure 11 depicts a process instrumentation diagram. This configuration has three sections: a Pressure Transmitter (PT), a Pressure Gauge (PG), and a Gate Valve (GV). The equal % flow characteristic Control Valve (CV) is installed at the end of the first two sections, and the Flow Transmitter (FT) is installed at the end of the third section. The controller component consists of a Pressure Indicating Controller (PIC), a Flow Indicating Controller (FIC), and a Flow Controlling Controller (FCC). The control valve opening status is detected by a PLC-based FCC based on 3 PIC signals, which are not reachable to the operator and are tuned using the LQR-PI controller for smooth operation in the pipeline transport system.

Adityapriatama et al. [57] suggested a PLC-Based Fuzzy Logic Controller for Water Pipeline Flow Rate Control. The implementation of fuzzy logic in the controller could manage faulty flowmeter sensor data efficiently. Hence, a reliable controller should be used along with an inaccurate flowmeter. This fuzzy system has been simulated on a personal computer to serve as the controller's command center. It retrieved data via the Object Linking and Embedding OLE to control the process server. At the same time, the data obtained from a PLC is linked to the plant. Ethernet connectivity has been used by the PC to communicate with the PLC. PLCs cannot be programmed utilizing mainstream programming languages like MATLAB, and hence, a PC is used in this work. The communication setup for this Control unit is illustrated in Figure 12.

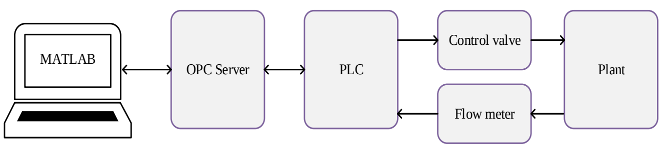

Fig. 12 Communication Set Up for Flow Rate Control

PID-based controllers are widely used in industry as flow controllers. However, they have certain limitations in certain applications, such as extremely nonlinear systems that cannot be overwhelmed by ordinary PID controllers. The PID controller is also limited due to overshoots and undershoots at the control system output, and slow response. To address these issues, Ahmad et al. [58] presented a Neural Network-Driven Flow Controller. This controller is used in a mini-plant that includes a water tank, a water pump, a control valve, and a flow transmitter. PLCs cannot be programmed utilizing conventional programming languages, and hence, the suggested Neural Network Controller is run on a Personal Computer (PC). Figure 13 depicts the communication flow diagram. Table 4 provides a quick summary of PLC-based controllers for pipeline monitoring systems reviewed in the literature.

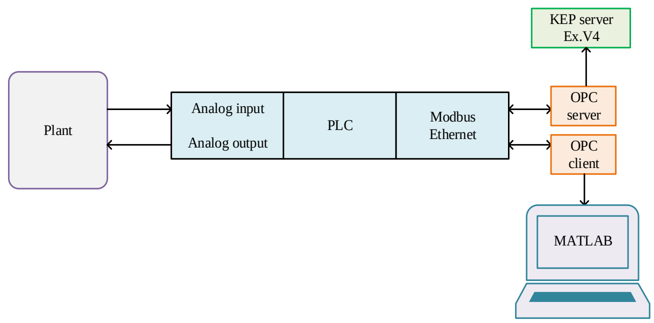

Fig. 13 Communication Flow Diagram with a Neural Network-Based Flow Controller

Table 4. Summary of PLC-based Controllers for Pipeline Monitoring Systems

References	Pipeline	Objective	Controller	Sensors	Advantages	Challenges
Priyanka et al. [54]	Petroleum	Pressure and flow control	PLC-based PID controller	Analog pressure sensor, analog flow sensor	Gives better performance in the disruption rejection test.	Provides high error indices when regulating control valve opening to achieve the specified pipeline system flow rate.
Priyanka et al. [55]	Oil	To control the Flow rate	PLC-based Fuzzy-PID Controller	Pressure and flow sensors	It gives control at a suitable time for preventing the incidence of main risk causes, including crashes / spurts in the long-distance oil transmission pipes	Insufficient system control accuracy
Adityapriatama et al. [57]	Water	Flow Rate Control	PLC Fuzzy Controller	Pressure and flow sensors	The PLC-Fuzzy controller gives good control outputs with respect to time and errors.	Computationally expensive on large-scale systems, the dependability of membership functions is.
Ahmad et al. [58]	Water	Flow rate control	PLC-based neural	-	NN can deal with the plant's unpredictability (noise).	Computationally Expensive

			network controller			
Priyanka et al. [56]	Oil	Pressure and flow control	LQR-PI controller	Pressure and flow sensors	It tunes the transportation system to operate as quickly as feasible toward its target values and delivers control action at the appropriate time.	Intensify overshoot and make the system more unstable.

6.2. Data Integrity of PLC Devices on ICS

PLCs are the fundamental component of ICS for automating the observation control of physical industrial and infrastructure activities, for example, electricity generation, gas pipelines, and water management. PLCs deliver exclusive security risks when compared with the existing computing systems because they are intensely integrated with physical activities and are vulnerable to attacks. Recently, cyber-attacks against PLCs have increased. They may introduce some negative impacts on ICS functioning. As a result, they cause service disruption, apparatus damage, people's safety concerns, and related commercial complications. For example, the Middle Eastern oil and gas petrochemical facility [59] was attacked. Here, the file name of the transported data is faked, and malicious malware is inserted into the control device. Furthermore, the most popular PLC viruses, such as "PLC Blaster" [60] and "PLC Backdoor" [61], can disrupt the execution and communication of PLC devices.

Yang et al. [62] suggested a data recovery method for recovering PLC devices from abnormal conditions with shorter latency. Here, the normal data messages are combined with the malicious packets to disrupt the target devices. For instance, the "Force Signal Off" attack is carried out by creating packets with signal-setting instructions and transferring them to the targeted components. This attack might disrupt the gas pipeline and possibly disrupt the gas delivery. The "Register Attack" is carried out by submitting an alteration appeal to the target PLC to alert the registers to change the higher limit of the water level. As a result, a liquid overflow occurs.

To prevent the gas pipeline from being cut, a resilience mechanism is developed on PLC devices. Here, the attacks are carried out 300 times by randomly injecting them, 284 of which are recognized and blocked during the data authentication step. This system detects the malicious alteration to valves and turns off the malicious execution to "turn the valve off". Also, the measured data is considered "Null" for protecting the gas pipeline and preserving stable pressure. Zubair et al. [63] conducted a real-time study to investigate the control logic attack on a gas pipeline testbed using the Schneider Electric Modicon M221 PLC. Here, the built-in evaluation function of a PLC is hijacked by the attacker. PEM (PLC Memory Extractor) is employed to examine the attack by capturing the memory of the infected PLC. It detected the attack efficiently because it scanned the full memory without necessitating hardware intervention with a suspicious PLC. The doubtful PLC's RAM alone contains the malicious evaluation operation and the changed jump table. The trace of the attack can be removed by rebooting the PLC.

The PLC is widely used in oil and gas platforms due to its extensive control functions and capacity to endure processes in hostile settings such as offshore platforms. SCADA is utilized for regulating the heating and partitioning of volatile hydrocarbons and assuring safe actions through an HMI furnished with emergency shutdown override options. This flooding attack has the ability to disrupt process control, resulting in pipeline outbursts, fatalities, and environmental damage. Mohammed et al. [64] identified and alleviated the field flooding attacks on oil and gas transportation systems utilizing a supervised machine learning model. Robles-Durazno et al. [65] introduced an attack discovery and mitigation strategy for assaults on Programming Logic input memory. Figure 14 depicts the testbed's architecture, which contains the following components: Compact Workstation Rig, Festo MPS PA, 4 sensors, a single actuator, a single solenoid valve, a single proportional valve, SCADA system, PLC (SIMATIC S7-1500), and Human Machine Interface (HMI). Also, the Attacker Machine is running on Kali OS.

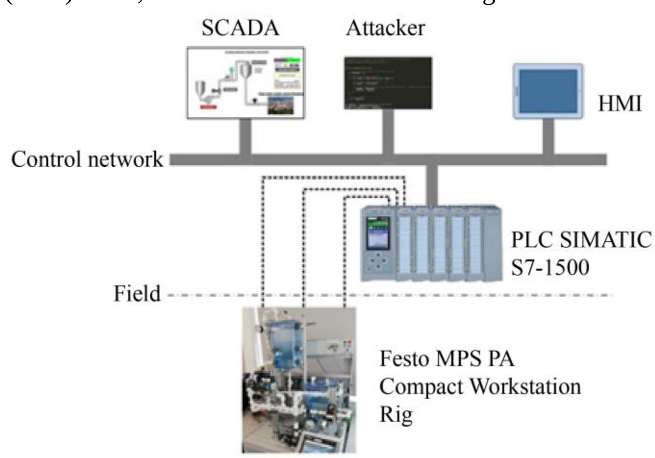

Fig. 14 Architecture of the testbed for attack detection in PLC

The attacker's goal is to overwrite the memory regions of the PLC allocated to the Inputs. The attack detection algorithm is embedded in the PLC itself, which means that no external equipment is needed to detect cyber-attacks. As a result, it reduces the response time and total cost.

The widespread use of SCADA systems in critical infrastructures increases the risk of highly advanced cyber-attacks that could threaten national security. The accurate and timely detection of cyber-attacks in SCADA systems using an artificial intelligence-based approach was presented in a research paper by Mehmet Akif Özgül et al. [66]. The process designed to operate the system was running in perpetuity. Scenarios for attacks such as Man-in-the-Middle (MITM), Denial of Service (DoS), and Command Injection were implemented in addition to the safe regular state. The gathered data was processed using basic machine learning methods, including KNN, Naive Bayes, Decision Trees, and Logistic Regression. Besides that, combinations of these approaches have been attempted.

Mustafa Tahsin Yilmaz et al. [67] proposed a Deep Learning Model named DeepNonLocalNN that combines Convolutional Neural Networks and non-local attention blocks for identifying local patterns and global relationships in an IIoT network traffic. The proposed model was found to outperform NonLocalNN, CNNWithAttention, ResidualAttentionNetwork, and LSTM when the proposed model was evaluated using the WUSTL-IIoT-2021 dataset. The proposed model had an accuracy of 0.9999, an ROC-AUC of 1.0000, and a macro F1-score of 0.93. Long Short-Term Memory (LSTM) and residual attention networks. It excelled at detecting minority types of attacks, such as Command Injection (CommInj, F1: 0.92) and Backdoor (F1: 0.73), which dealt with class imbalance issues. The scalability of the model provides a high-performance SCADA security solution for IIoT using regularization and non-local attention.

The Grey Wolf Optimization Method is improved by Zhenshan Chen et al. [68] by increasing the local search ability and population diversity with the addition of a microecological evolutionary mechanism and a nonlinear convergence factor. Using this improved grey wolf optimization method, the key hyperparameters of the long Short-Term Memory Neural Network are tuned, leading to an efficient and precise scenario prediction method. It is found that, from the experimental results, the mean square error of the proposed method is less than that of other models by 78.33%, 65.79%, and 53.57%, respectively. In comparison with other conventional methods of situational evaluation, it is found that the system developed by the authors has a false positive rate of 52.33% and a false alert rate of 53.33%. Table 5 provides a quick summary of attack detection models on PLC.

Table 5. Summary of Attack Detection Models on PLC

References	Pipeline	Attack type	Device	Method	Challenges
Yang et al. [62]	Gas	Force Signal Off Register Attack	Siemens S7 300	Intrusion-resilient mechanism	Undertaking forensic analysis is a time-consuming and labour-intensive task because of heterogeneous hardware architectures and unique firmware/communication protocols.
Zubair et al. [63]	Gas	Control-logic attack	Modicon M221 PLC	PLC memory extractor and firmware analysis	Even though firmware analysis can offer valuable forensic artifacts, it cannot reveal the present condition of the PLC, including input/output data conditions.
Mohammed et al. [64]	Oil and Gas	field flooding attacks	-	Supervised machine learning	Circumstances that exhibit how field flooding assaults could spread inside an industrial network with several brands of PLCs and protocols are not included.
Robles-Durazno et al. [65]	Water	Memory attack	SIMATIC S7-1500	Sensor reading-based detection algorithm	Getting the sensor data straight from the analogue channel permits reducing the influence of attacks on the input memory; nevertheless, it adds a little delay in the operation of the control system.
Mehmet Akif Özgül et al., [66]	Gas	DoS, MITM, and Command Injection	-	machine learning	Setting up their own test environment and creating original datasets for analysis are more limited.

7. Challenges and Future Research Direction

The pipeline infrastructure that is primarily built underground to detect structural flaws such as leaks, bursts, and joint loosening cannot be monitored continuously in a short period of time. Commercially accessible technologies (hardware-based) and methods currently in the research phase (software-based) have varied benefits and limits when it comes to diverse pipe systems and ecological conditions.

- Hardware-based devices are frequently incapable of providing constant surveillance, and their testing times are longer than those of software-based techniques. Exterior aspects such as seasonality, ambient temperature, soil qualities, and mobility can all create variances in the accuracy of the data, which must be considered before applying hardware-based devices. These approaches necessitate several professional personnel to deal with heavy equipment during leakage inspection. The majority of hardware-driven approaches determine and localize the leak with greater accuracy. However, they do not quantify the leakage rate.
- In general, software-based approaches are less expensive, labour-intensive, and time-efficient than hardware solutions. The sub-optimal model-based approaches can detect leaks with fewer data points, but estimating the factors for such models is problematic. The data-dependent approaches perform well in leak detection; however, they depend primarily on the quantity and quality of accessible data. Consequently, its fundamental weakness is the inability to gather sufficient high-quality data. Alternatively, internal/computational-based approaches produce a high percentage of false-positive alerts while the fluid flow rate is modest or there are several leakages.
- In recent days, machine learning approaches have been preferred to predict the position of leaks in oil and gas pipelines since they robotically analyze and screen data while avoiding the intrinsic subjectivity of manual pipeline state evaluation. As a result, these strategies might not apply to real pipeline processes due to discrepancies between simulated and actual data.
- To overcome these limitations, a pipelining monitoring system based on a PLC and SCADA has been developed for oil/gas pipelines. However, it has some disadvantages when compared to PC programming. The conventional PLC architecture always sequentially conducts the scan cycle activities; a longer program results in a longer scan time. As a result, they reduce the performance and reaction time of the system.
- External parameters, including frequency intervention and power outages, can erase a PLC's memory. If this occurs, the code within the PLC might turn out to be unreadable, or the PLC might not be read appropriately after an unintentional shutdown.
- PLC components must be continuously communicated with neighbouring components, such as peripherals, HMI, and other smart gadgets, to function correctly. This transmission session is enabled by Ethernet connections and necessitates a secure, robust, and reliable connection. If this connection fails, the associated equipment will be unable to perform its activities as planned, causing facility downtime.
- Some PLC-based systems, for example, the gas detection system proposed by Ayaz et al. [50], measured the gas level of each region at specific intervals because of the consideration of a single sensor unit. The distance between the evaluation points and the sensor unit will impact the delay of the measurement process.
- The labor expenses of maintaining wired sensors in Aziz's remote pipeline monitoring system [27] are often higher than those of wireless sensors.
- In PLC-based Fuzzy Logic Control, diffuse Membership Functions (MFs) are challenging to find. In this setting, the tuning of MF is a time-consuming process and a frequently ineffective activity.

Based on the comprehensive literature analysis conducted in this study, the following research pathways are indicated as future opportunities:

- Aziz's remote pipeline monitoring system [27] can be expanded by adding wireless sensors to implement the same leakage detection system. This will improve the system's reliability and minimize the wire maintenance costs.
- The time period and pipeline lengths should be correctly identified during the design process to avoid or remove the shortcomings of the gas detection system provided by Ayaz et al. [50].
- Some metaheuristic strategies can be employed to automate the tuning process of MFs in PLC-based Fuzzy Logic Control.
- The usage of optimized data blocks in PLC can decrease attacks on the input memory. Hence, designers are recommended to employ function blocks as much as possible in their designs to reduce sensitivity to input memory attacks. Furthermore, the hardware design must include redundant sensor architecture with the goal of switching control techniques if an attack is noticed.

7.1. Strategies for Dealing with Limitations of a PLC System

Although PLC systems are commonly used in remote pipeline control, they have significant limitations that might impair their performance, reliability, and scalability. Here are some techniques for dealing with these constraints:

- The initial step in overcoming PLC constraints is to select the appropriate PLC model for the application. Every PLC model has distinct features, including memory size, processing speed, input/output capacity, communication protocols, and expansion options. It is recommended to choose a PLC model based on environmental conditions such as temperature, humidity, vibration, and noise.

- Another approach for dealing with PLC constraints is to improve the program logic that runs on the PLC.
- A third approach to dealing with PLC restrictions is to leverage modular and distributed architectures, which can boost PLC flexibility and scalability.
- A fourth approach to overcoming PLC constraints is to combine the PLC with other systems and devices that can improve the PLC's abilities and performance. For instance, the PLC can be connected with a Human-Machine Interface (HMI) to provide a graphical and interactive interface for PLC operation and monitoring. PLC can also be connected with a SCADA system for collecting, storing, analyzing, and displaying PLC data and controlling the PLC remotely. PLC can also be connected with other devices like sensors, actuators, cameras, or robots to give the PLC extra inputs and outputs.

8. Conclusion

In this study, a systematic cataloguing of current leakage discovery technologies, a comparative analysis of hardware and software-driven approaches, and a detailed background study of PLC-based pipe management solutions are presented. The current review discovered that combining PLC with different control approaches, such as PID, fuzzy, or PI, delivers better performance in terms of accuracy and reduced error in terms of false alarms. PLCs can have limitations, but data show they offer more benefits than weaknesses. System programming with a ladder diagram is more valuable than other types of programming languages because even an electrician with inadequate programming expertise can comprehend and program a PLC based on his awareness of electrical systems. However, a normal PLC architecture repeats the scan cycle execution uninterruptedly. In the future, the researchers will be expected to change the PLC architectures for scan time reduction and utilize them as the primary controller for remote pipeline monitoring.

Conflict of Interest Statement

The authors have no conflict of interest to declare.

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