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Title

IoT Based Real Time Monitoring and Control of Level II Digital Twin Of Pipeline Systems Using Arduino and LabVieW

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Abstract:

Pipeline transportation is a fundamental phase in the oil and gas chain, responsible for the efficient and continuous transfer of fluids over long distances. However, this infrastructure faces critical challenges such as pressure fluctuations, flow irregularities, and vibration problems, which can lead to operational disruptions and environmental hazards. To address these issues, this thesis proposes a smart pipeline monitoring system based on Arduino, LabVIEW, and IoT technologies.

The system is built using an Arduino UNO microcontroller in conjunction with a NodeMCU ESP8266 module for wireless data transmission. A G1/4 0–1.2 MPa hydraulic pressure sensor and a YF-S201 flow sensor are integrated to measure key parameters in the pipeline. Local alerts are triggered using LEDs and a buzzer in the event of abnormal readings. Calibration data is stored in EEPROM to maintain measurement consistency, and a manual calibration trigger is implemented to enhance long-term accuracy.

Monitoring is achieved through a dual-interface approach : real-time sensor data is transmitted to the ThingSpeak IoT platform for cloud-based visualization and remote access, while LabVIEW is used locally to create a dynamic graphical user interface (GUI). The LabVIEW interface provides live data plotting, digital gauges for pressure and flow, system status indicators, and manual control buttons. Additionally, the GUI offers real-time alarms and logging capabilities for localized supervision.

This hybrid system demonstrates a cost-effective and scalable solution that integrates embedded systems, graphical programming, and IoT to enhance the reliability, transparency, and safety of pipeline infrastructure in the oil and gas industry.

Résumé

Le transport par canalisation constitue une phase fondamentale dans la chaîne pétrolière et gazière, assurant le transfert efficace et continu des fluides sur de longues distances. Cependant, cette infrastructure est confrontée à des défis critiques tels que les fluctuations de pression, les irrégularités de débit et les problèmes de vibration, pouvant entraîner des interruptions opérationnelles et des risques environnementaux. Pour répondre à ces problématiques, ce mémoire propose un système intelligent de surveillance de pipeline basé sur Arduino, LabVIEW et les technologies IoT.

Le système est conçu à l'aide d'un microcontrôleur Arduino UNO, associé à un module NodeMCU ESP8266 pour la transmission de données sans fil. Un capteur de pression hydraulique G1/4 0–1,2 MPa et un capteur de débit YF-S201 sont intégrés pour mesurer les paramètres clés dans le pipeline. Des alertes locales sont déclenchées à l'aide de LEDs et d'un buzzer en cas de lectures anormales. Les données d'étalonnage sont stockées dans la mémoire EEPROM afin de garantir la cohérence des mesures, et un bouton de calibration manuelle est mis en place pour améliorer la précision à long terme.

La surveillance est assurée par une approche à double interface : les données des capteurs sont transmises en temps réel à la plateforme IoT ThingSpeak pour une visualisation cloud et un accès à distance, tandis que LabVIEW est utilisé localement pour créer une interface graphique dynamique (GUI). L'interface LabVIEW offre des graphiques en temps réel, des jauges numériques pour la pression et le débit, des indicateurs d'état du système ainsi que des boutons de contrôle manuel. De plus, elle propose des alarmes en temps réel et des fonctions d'enregistrement pour une supervision localisée.

Ce système hybride démontre une solution évolutive et économique intégrant les systèmes embarqués, la programmation graphique et l'Internet des objets (IoT), afin d'améliorer la fiabilité, la transparence et la sécurité des infrastructures de transport par pipeline dans l'industrie pétrolière et gazière.

الملخص

يُعدّ النقل عبر الأنابيب مرحلة أساسية في سلسلة إنتاج النفط والغاز، حيث يساهم في نقل السوائل بكفاءة واستمرارية عبر مسافات طويلة .إلا أن هذا النوع من البنى التحتية يواجه تحديات حرجة مثل تقلبات الضغط، وعدم انتظام التدفق، ومشاكل الاهتزاز، والتي قد تؤدي إلى تعطّل العمليات وتهديدات بيئية .لمواجهة هذه التحديات، يقترح هذا البحث نظاماً ذكياً لمراقبة خطوط الأنابيب يعتمد على Arduino و LabVIEW وتقنيات إنترنت الأشياء.(IoT)

تم بناء النظام باستخدام متـحكم Arduino UNO إلى جانب وحدة NodeMCU ESP8266 لنقل البيانات لاسلكياً . كما تم دمج حساس ضغط هيدروليكي G1/4 بمدى 0–1.2 ميغاباسكال مع حساس تدفق من نوع YF-S201 لقياس المعايير الأساسية داخل خط الأنابيب .يتم تشغيل تنبيهات محلية باستخدام مصابيح LED وصفّارة إنذار (Buzzer) عند اكتشاف قراءات غير طبيعية .تُخزَّن بيانات المعايرة في ذاكرة EEPROM للحفاظ على اتساق القياسات، مع إمكانية تشغيل المعايرة اليدوية لتحسين الدقة على المدى الطويل.

يتم تنفيذ عملية المراقبة من خلال واجهتين متكاملتين :تُرسل بيانات الحساسات في الزمن الحقيقي إلى منصة ThingSpeakالسحابية لعرضها والوصول إليها عن بُعد، بينما تُستخدم واجهة LabVIEW محلياً لإنشاء واجهة رسومية ديناميكية .(GUI) تتيح هذه الواجهة رسم البيانات مباشرة، وعرض المقاييس الرقمية للضغط والتدفق، ومؤشرات حالة النظام، وأزرار للتحكم اليدوي .كما توفر تنبيهات فورية ووظائف تسجيل لمراقبة محلية فعالة.

يثبت هذا النظام الهجين فعاليته كحل منخفض التكلفة وقابل للتوسع، من خلال دمج الأنظمة المدمجة، والبرمجة الرسومية، وتقنيات إنترنت الأشياء، مما يُحسّن من موثوقية وشفافية وأمان البنية التحتية لأنابيب النفط والغاز.

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Dedication

I dedicate this Master's thesis with deep gratitude and appreciation to my loving mother, father, and siblings, whose unwavering support, love, and encouragement have been the foundation of my academic journey. Your belief in my abilities and sacrifices made for my education have shaped me into the individual I am today. This achievement would not have been possible without you

To my friends, thank you for standing by my side throughout the writing process. Your words of encouragement and belief in my capabilities have provided me with the strength to overcome challenges and persevere. Lastly, I express my sincere gratitude to all those who have offered their assistance and support, whether through providing resources, proofreading, or lending a listening ear.

Your contributions have lightened my burdens and enriched my work.

Acknowledgment:

I would like to extend my heartfelt gratitude and appreciation to all those who have contributed to the successful completion of my Master's thesis. First and foremost, I am profoundly grateful to the almighty ALLAH for granting me the strength and ability to comprehend, learn, and accomplish this thesis.

I would like to express my deepest thanks to my supervisor, Dr. FERTAS.N, *for his exceptional guidance, expertise, and unwavering support throughout the entire research process. His invaluable insights and constructive feedback have been pivotal in shaping this thesis.*

My gratitude extends to the faculty members and mentors who have provided me with their valuable help and profound knowledge during my academic journey, especially Souhil Sid for his time and efforts. Their dedication to my growth and development has pushed me to new intellectual heights and expanded my horizons.

I am also immensely grateful to my colleagues and friends who have continuously served as a source of inspiration, motivation, and intellectual exchange. Their engaging discussions, innovative ideas, and constant encouragement have played a significant role in shaping my thesis.

Lastly, I would like to acknowledge the unwavering support of my family and loved ones throughout this journey. Their boundless love, understanding, and encouragement have been my source of strength during the most challenging times.

Once again, I express my sincerest appreciation to all those who have contributed to the completion of my Master's thesis.

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List of Abbreviations

GUI	Graphical User Interface
IoT	Internet Of Things
ANN	Artificial Neural Network
ML	Machine Learning
RMS	Root Mean Square
SCADA	Supervisory Control and Data Aquisition
FFT	Fast Fourier Transform
ESD	Emergency Shut Down
BRN	Bir Rebaa Nord

General Introduction

Pipeline transportation is one of the most efficient and widely used methods for transferring fluids such as oil, gas, and water over long distances. It forms the backbone of energy distribution in many countries, enabling the continuous and reliable supply of petroleum products from extraction sites to processing facilities and end-users. Despite its strategic importance, pipeline systems are exposed to numerous challenges that can compromise safety, efficiency, and environmental integrity [1], [2].

Key issues in pipeline infrastructure include pressure fluctuations, leakage, blockage, flow inconsistencies, and vibrations due to mechanical or operational faults. These problems, if not detected early, may lead to severe accidents, economic losses, and environmental disasters [3], [4]. Therefore, ensuring real-time monitoring and early fault detection is critical in modern pipeline systems, especially in the oil and gas sector.

Traditional monitoring systems often rely on manual inspection or expensive industrial SCADA systems, which may not be feasible for small-scale installations or educational research. With the rise of low-cost microcontrollers, wireless communication modules, and cloud-based IoT platforms, it is now possible to develop smart, affordable, and scalable monitoring systems that offer real-time supervision and remote accessibility [5],[6].

This thesis presents the design and implementation of a smart pipeline monitoring system based on Arduino and Internet of Things (IoT) technologies. The core of the system includes an Arduino UNO microcontroller connected to pressure and flow sensors that measure fluid conditions within the pipeline. A NodeMCU ESP8266 module is used to wirelessly transmit sensor data to the ThingSpeak cloud platform, where users can remotely view and analyze the system status in real time.

To enhance local monitoring capabilities, LabVIEW software is used to develop a graphical user interface (GUI) that displays live sensor data through digital gauges, real-time plots, and system status indicators. The LabVIEW interface also integrates alarm functions and manual control features, providing a user-friendly visualization and control environment.

Additional functionalities include local alerts through LEDs and a buzzer in case of abnormal conditions, as well as the use of EEPROM memory for saving calibration parameters. A manual calibration trigger has been implemented to allow flexible recalibration of the sensors as needed.

The integration of Arduino, LabVIEW, and IoT technologies offers a robust and accessible solution for real-time pipeline supervision. This system can be applied not only in educational and research settings but also as a prototype model for industrial applications where cost-effective monitoring is essential.

This work gains further value when viewed in the context of Algeria's extensive hydrocarbon infrastructure. SONATRACH, the national oil and gas company, operates over 21,000 km of pipelines across 22 canalisation transport systems, with the Bir Rebaa Nord (BRN) site being a key node in the Southern Network. The total actual transmission capacity across the national network for 2024 is 404.935 MTOE, with 255.501 MTOE already reserved [7]. These figures highlight the critical importance of ensuring operational safety and early anomaly detection in national pipeline systems, making the proposed monitoring system particularly relevant.

Through this work, we aim to demonstrate how embedded systems and IoT platforms can be leveraged to improve safety, reliability, and operational transparency in fluid transportation networks. The thesis also highlights the importance of combining local and cloud-based monitoring for effective decision-making and early fault detection in pipeline management.

This thesis is organized into three chapters:

Chapter 1: introduces the fundamental concepts of oil and gas pipeline transportation, with a focus on the common challenges encountered in fluid transport systems such as pressure drops, leakages, and vibrations. It also presents the principles of measuring key parameters like flow rate and pressure, as well as the importance of real-time monitoring in ensuring pipeline safety and efficiency.

Chapter 2: presents the hardware and software components used in the proposed smart pipeline monitoring system. It details the architecture and functionality of devices such as the Arduino UNO, NodeMCU ESP8266, pressure and flow sensors, and the ThingSpeak IoT platform. This chapter also includes the wiring diagram, sensor integration, and the development of the LabVIEW interface used for local visualization and control.

Chapter 3: covers the implementation, coding, calibration, testing, and results of the smart monitoring system. It includes the system's performance evaluation under different operational scenarios, screenshots of the ThingSpeak cloud dashboard and LabVIEW GUI, and a discussion of the strengths and limitations of the design. It also highlights possible improvements and potential extensions for industrial applications.

Chapter 01:

Pipeline Transportation and Monitoring Fundamentals

1.1.Introduction

Pipeline transportation represents one of the most efficient and economical methods for transporting fluids, gases, and even mud over long distances. The global pipeline infrastructure spans millions of kilometers, carrying essential resources including crude oil, natural gas, refined petroleum products, water, and various chemicals .According to the International Energy Agency, pipelines transport approximately 65% of the world's crude oil and 85% of natural gas, making them critical components of global energy infrastructure .

The strategic importance of pipeline systems extends beyond mere transportation efficiency. These systems enable the connection of remote production sites to processing facilities and end consumers, facilitating economic development and energy security. However, the extensive nature of pipeline networks, often traversing challenging terrains and operating under extreme conditions, presents significant monitoring and maintenance challenges.

1.2.The importance of pipeline transportation in Algeria

SONATRACH exploits a transport system via hydrocarbures (Petroleum gas, Condensate, natural gas and gas petroleum liquid) consisting of 22 transport systems via canalisation (STC) with a total length of 21 190 km. The actual, reserved, and available transmission capacities of the various Pipeline Transmission Systems declared for 2024 are as follows:

- The total actual capacity is 404.935 MTOE, including 263.244 MTOE for the Northern Network and 141.692 MTOE for the Southern Network;
- The total reserved capacity for 2024 is 255.501 MTOE, or 63% of the total actual capacity;
- The total available capacity is 149.435 MTOE. [1]

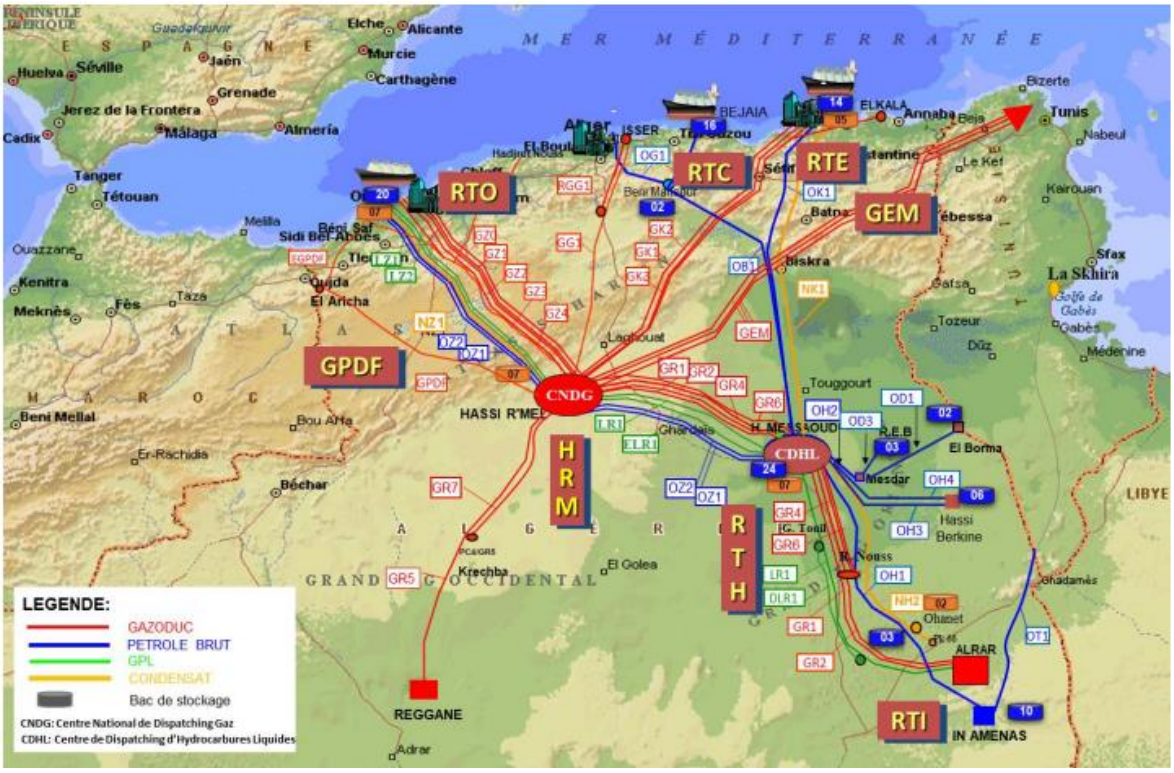


Figure 1. 1: Current Mapping of the pipeline Transport Network

1.3.Pipeline System Fundamentals

1.3.1.Types of Pipeline Systems

Pipelines can be divided into three main categories which focus on the extraction of materials, long term transport and final delivery [9]

1.4.2.1.Gathering pipelines:

They take the resources between the point of extraction and the relevant processing location to minimize the time between extraction and initial processing. This type tends to be short in length, small in diameter and they work in a variable pressure .

1.4.2.2.Transmission pipelines :

They are designed to transport materials over long distances, they can be found running between countries and across continents. This type is made with the largest pipes, and works at high pressure levels.

1.4.2.3.Distribution pipelines :

This line is the one that delivers resources to their final industrial, commercial or residential destinations after they arrive from the initial production site to the treatment facilty and toward the final city where it will be used. These pipelines come small in diameter and short in length compared to transportation lines. [9]

1.3.2.Pipeline Components and Infrastructure

Modern pipeline systems comprise several interconnected components : [4]

1.4.2.1.Primary Components:

- Pipe segments (steel, plastic, or composite materials)
- Pumping/compression stations for pressure maintenance
- Valve stations for flow control and isolation
- Metering stations for flow measurement and custody transfer
- Storage facilities and terminals

1.4.2.2.Secondary Infrastructure:

- Cathodic protection systems for corrosion prevention
- Communication systems for operational control
- Supervisory Control and Data Acquisition (SCADA) systems
- Emergency shutdown systems
- Pipeline markers and right-of-way maintenance facilities [10]

1.4.Critical Parameters in Pipeline Monitoring

Effective pipeline monitoring requires continuous surveillance of multiple parameters that indicates system health, operational efficiency, and safety status. The three most critical parameters are pressure, flow, and vibration, each providing unique insights into pipeline condition and performance [11].

1.4.1.Pressure Monitoring and Detection

Pressure monitoring forms the backbone of pipeline safety and operational control systems. Pressure variations can indicate numerous conditions, from routine operational changes to critical failures requiring immediate attention.

1.4.2.1.Fundamentals of Pressure in Pipeline Systems

Pressure in pipeline systems results from multiple factors including elevation changes, friction losses, pump/compressor operation, and downstream demand variations. The fundamental pressure relationships in pipelines are governed by the Darcy-Weisbach equation for friction losses and the continuity equation for mass conservation.

For steady state flow in horizontal pipelines, the pressure drop due to friction is expressed as :

$$\boxed{\Delta P = f \times (L/D) \times (\rho V^2/2)}$$

Where :

- **ΔP** = pressure drop
- **f** = friction factor
- **L** = pipe length
- **D** = pipe diameter
- **ρ** = fluid density
- **V** = flow velocity

1.4.2.2.Pressure Anomaly Detection

Pressure monitoring systems must distinguish between normal operational variations and abnormal conditions that may indicate numerous cases such as :

- **Leak Detection :**

Sudden pressure drops often indicate pipeline breaches. The magnitude and rate of pressure decline can help estimate leak size and location [3]. Research by Zhang et al. demonstrated that pressure-based leak detection algorithms can identify leaks as small as 0.5% of normal flow rate when properly calibrated [12].

- **Blockage Detection :**

Gradual pressure increases upstream combined with pressure decreases downstream typically indicate partial or complete blockages. The pressure signature varies depending on blockage type (solid deposits, hydrate formation, or external damage).

- **Equipment Malfunction :**

Pump or compressor failures result in characteristic pressure patterns that can be distinguished from other anomalies through pattern recognition algorithms.

1.4.2.3.Advanced Pressure Monitoring Technologies

Modern pressure monitoring systems employ various sensor technologies such as :

- **Strain Gauge Pressure Transmitters :**

These devices convert mechanical strain caused by pressure into electrical signals [5]. They offer high accuracy (±0.1% of full scale) and excellent long-term stability, making them suitable for custody transfer applications [12].

Figure 1. 2: Strain gauge transmetter

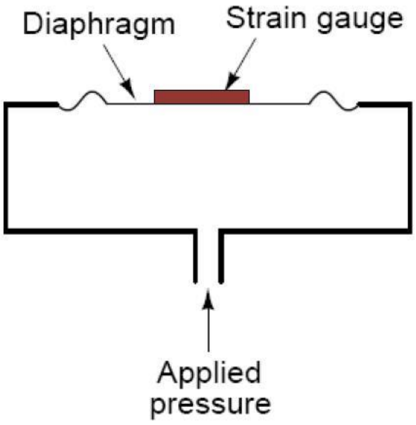


Figure 1. 3: Strain gauge working diagram

- **Piezoelectric Pressure Sensors :**

Utilizing the piezoelectric effect, these sensors provide rapid response times and high sensitivity, particularly valuable for detecting transient pressure events and water hammer conditions [13].

The next two figures presents real piezoelectric pressure sensor and its internal structure :

Figure 1. 4: Piezoelectric pressure sensor CP103

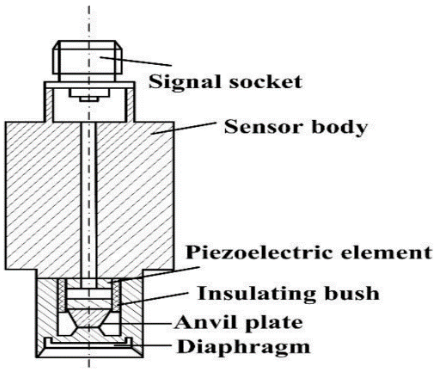


Figure 1. 5: structure of piezoelectric sensor

Now here is the working principle of piezoelectric sensor :

A piezoelectric sensor sends a signal when it sustains a physical force, which might be pressing, pushing, or changing temperature. Piezoelectric sensors generate an output signal directly from applied stress, requiring no external voltage.

The piezoelectric effect is the process that enables a signal output. This effect is how materials such as certain engineered ceramics, synthetics and select naturally-forming crystals generate an electric charge when they sustain mechanical stress like squeezing or pushing.

Here's a brief example of how a piezoelectric pressure sensor works:

- A piezoelectric material attaches to a metal diaphragm that sustains the pressure to be measured.

- Mechanical force applies to the metal diaphragm via pressure, deforming it slightly. This stress generates an electrical charge across the piezo material.
- The resulting electrical charges can be measured as a voltage, and professionals process them using signal processing. Professionals can then interpret them to collect useful data.

Voltage can also cause the piezoelectric material to change shape or make the crystal shrink or expand. This shape or size change is known as an inverse piezoelectric effect. The inverse piezoelectric effect can occur in many daily applications, creating and detecting high-pitch sounds and vibrations. It’s useful in siren applications such as smoke detectors and lower frequency applications such as sonar or underwater imaging.

A typical inverse piezoelectric effect application example is playing music on your smartphone or a doctor performing therapeutic ultrasound treatments. Piezoelectric crystals in speakers and ultrasonic equipment oscillate when alternating voltage is applied, creating sound waves or varying power levels and frequencies. [13]

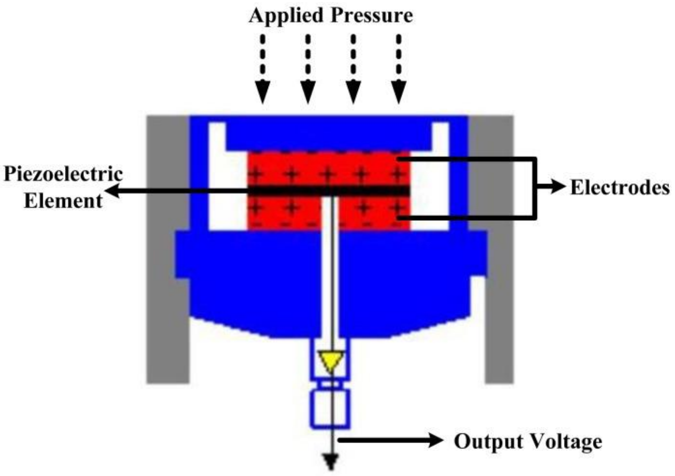


Figure 1. 6: Working principle of piezoelectric PT

- **Optical Pressure Sensors :**

Fiber-optic pressure sensors offer advantages in harsh environments, providing immunity to electromagnetic interference and the ability to operate in explosive atmospheres without additional safety barriers .

The next two figures illustrates real world deployement and sensor structure diagram :

Figure 1. 7: optical fiber sensor installed on an actual pipeline

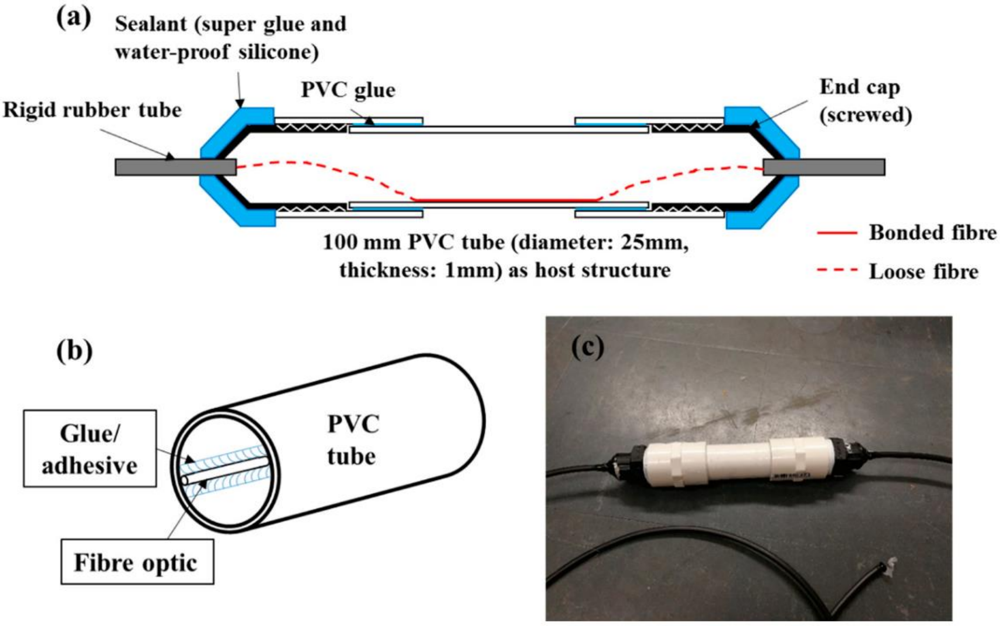


Figure 1. 8: schematic drawing of a prototype in-pipe fiber-optic pressure sensor

1.4.2.Flow Monitoring and Measurement

Flow measurement serves multiple purposes in pipeline operations, including custody transfer, leak detection, operational optimization, and regulatory compliance. Accurate flow measurement is essential for material balance calculations and detecting unauthorized product removal.

1.4.2.1.Flow Measurement Principles

Flow measurement in pipelines employs various physical principles, each with specific advantages and limitations.

- **Differential Pressure Flow Meters :**

Based on Bernoulli's principle, these meters create a pressure drop across flow restriction (orifice plate, venturi, or flow nozzle). The flow rate is proportional to the square root of the differential pressure :

$$\boxed{Q = C_d \times A \times \sqrt{2\Delta P/\rho}}$$

Where:

- **Q** = volumetric flow rate
- **Cd** = discharge coefficient
- **A** = effective area of restriction
- **ΔP** = differential pressure
- **ρ** = fluid density

- **Ultrasonic Flow Meters :**

Ultrasonic flow meters use high-frequency sound waves to measure the velocity of a fluid. The **transit-time** type relies on two piezoelectric transducers placed on opposite sides of a pipe. One sends ultrasonic pulses downstream (with the flow), while the other sends them upstream (against the flow). The difference in time taken by the pulses to travel through the fluid is directly proportional to the flow velocity. This method is accurate for clean fluids. These meters are popular in water treatment and oil pipelines due to their non-invasive nature and absence of moving parts.[13]

Here is a diagram of the operation of ultrasonic flow meter :

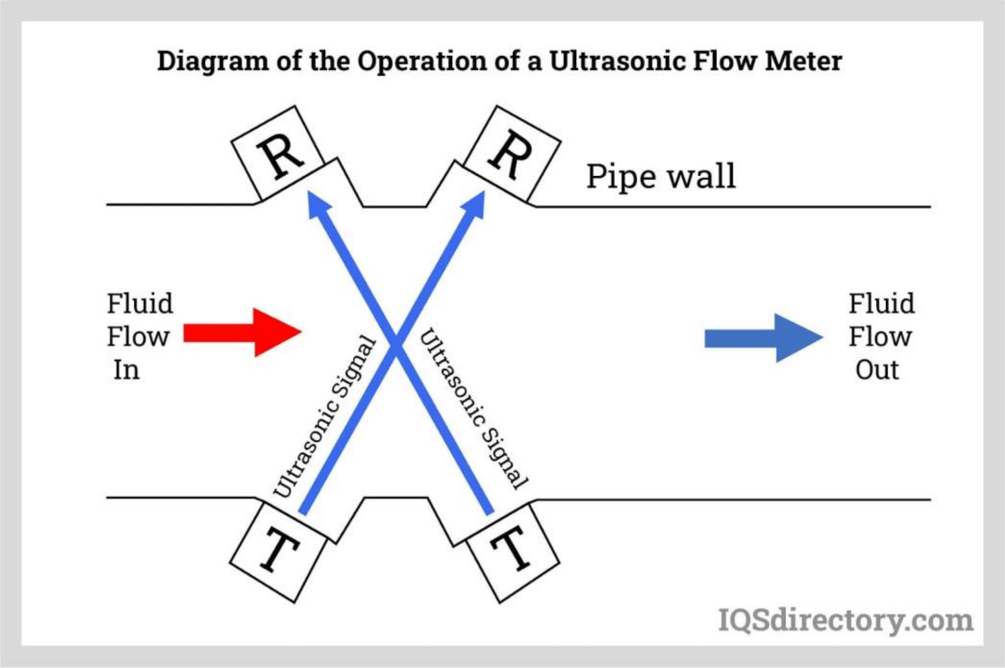


Figure 1. 9: Diagram of the operation of ultrasonic flow meter

- **Turbine Flow Meters :**

  Turbine flow meters operate mechanically. As the fluid passes through the meter, it strikes a rotor (turbine), causing it to spin. The rotational speed is proportional to the flow velocity. Magnetic or optical sensors detect the movement of the blades, and the resulting pulses are converted into volumetric flow rate. Turbine meters are highly accurate and reliable in clean, steady-flow environments but can be affected by particulates, which may damage internal components.[13]

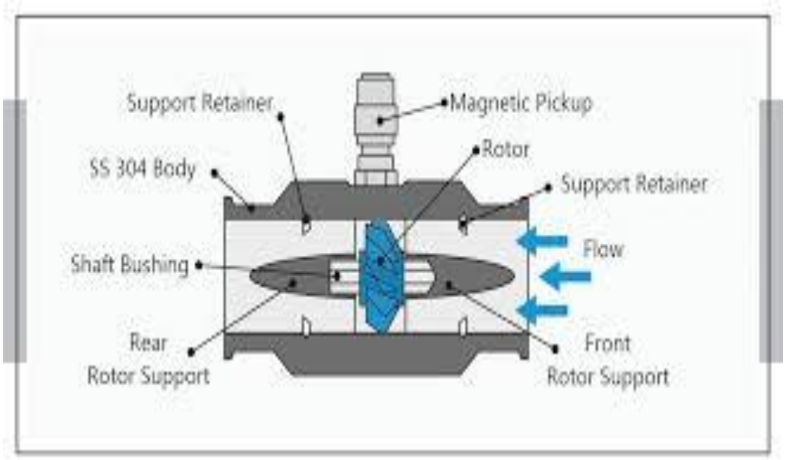


Figure 1. 10: Turbine flow meter structure diagram

- **Coriolis Flow Meters :**

Coriolis flow meters directly measure mass flow using the Coriolis effect. The meter contains one or more tubes that are set to vibrate. As the fluid flows through the vibrating tubes, Coriolis forces cause a twisting or phase shift in the vibration pattern. The degree of this twist is proportional to the mass flow rate. In addition to mass, these meters can also measure fluid density and temperature. Coriolis meters are extremely accurate, suitable for a wide range of fluids including hydrocarbons, and are commonly used in oil and gas applications for custody transfer and high-precision measurement flow anomaly detection. [14]

Figure 1. 11: real world coriolis Flow meter

Here is a figure showing working principle of the Coriolis flow meter:

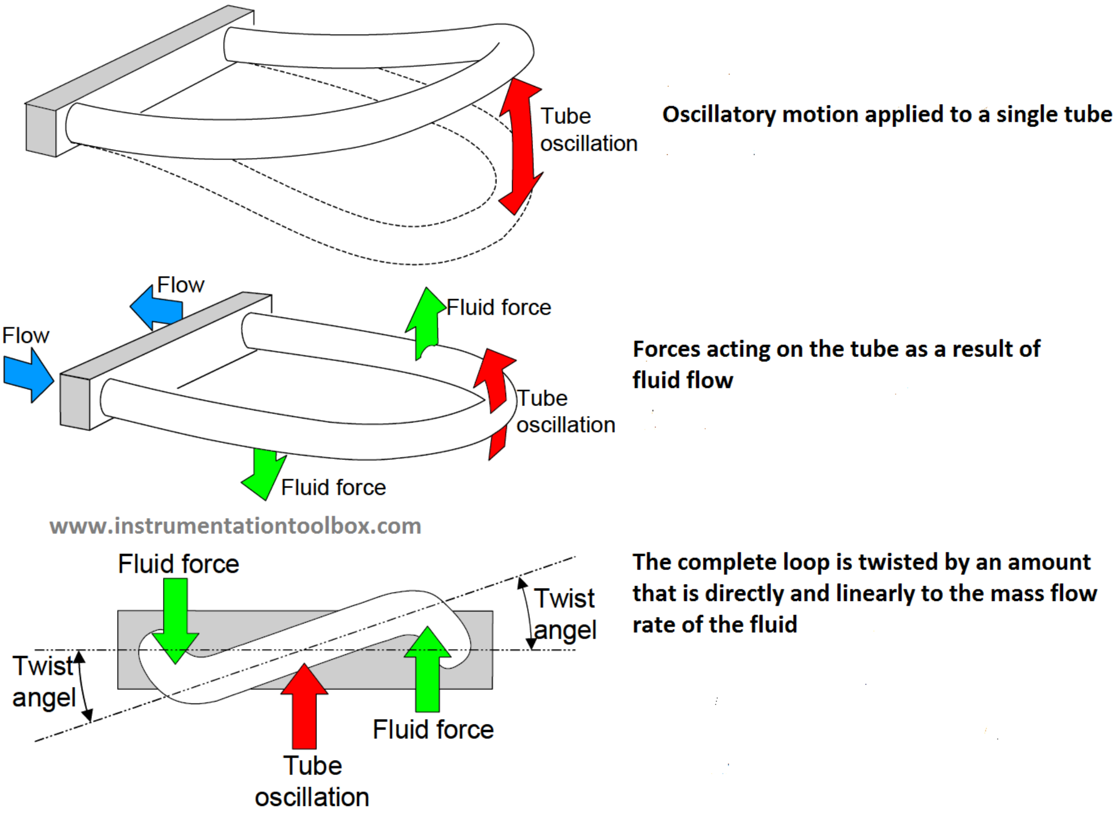


Figure 1. 12: Illustration of coriolis flow meter working principle

Heres a diagram showing the location of inlet and outlet sensors in coriolis flow meter :

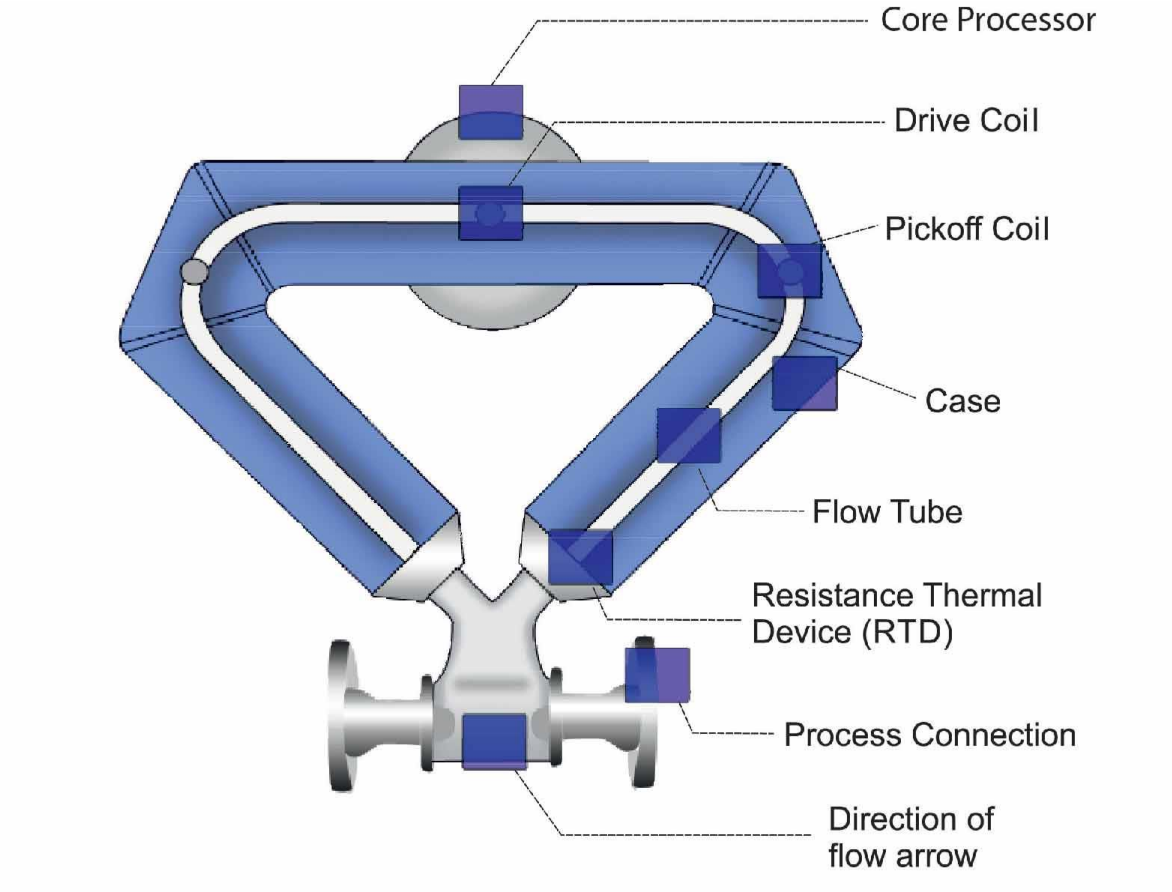


Figure 1. 13: Inlet & Outlet sensor location

Flow monitoring systems analyze various parameters to detect abnormal conditions :

- **Mass Balance Analysis**

Continuous comparison of inlet and outlet flows helps identify leaks or unauthorized withdrawals. The sensitivity of mass balance methods depends on measurement accuracy and system hold-up characteristics.

- **Flow Pattern Analysis**

Normal flow patterns in pipeline systems follow predictable trends based on seasonal demand, operational schedules, and system characteristics. Deviations from expected patterns can indicate various problems including leaks, equipment malfunctions, or operational errors.

- **Statistical Process Control**

Application of statistical methods to flow data helps distinguish between normal process variations and significant anomalies. Control charts and trend analysis provide operators with tools for early problem detection.

1.4.3.Vibration Monitoring and Analysis

Vibration monitoring has emerged as a powerful tool for pipeline condition assessment, particularly for detecting mechanical problems, flow-induced vibrations, and external interference. Pipeline vibrations result from various sources including fluid flow turbulence, pump/compressor operation, external forces, and structural resonances.

1.4.2.1.Sources of Pipeline Vibration

- **Flow-Induced Vibrations**

Turbulent flow creates pressure fluctuations that can excite pipeline vibrations .The intensity of flow-induced vibrations depends on flow velocity, fluid properties, and pipeline geometry .Research by Liu and Wang showed that flow-induced vibrations increase exponentially with Reynolds number above the critical threshold for turbulent flow .

- **Mechanical Vibrations**

Rotating equipment such as pumps and compressors transmit vibrations through the pipeline system. These vibrations typically occur at specific frequencies related to equipment operating speeds and can propagate considerable distances through the pipeline.

- **External Vibrations**

Construction activities, seismic events, and vehicular traffic near pipelines can induce vibrations that may affect pipeline integrity. Monitoring these vibrations helps assess potential threats to pipeline safety.

1.4.2.2.Vibration Measurement Technologies

- **Accelerometers**

Piezoelectric accelerometers are highly sensitive, offering a BFR from 1 Hz to 20 Hz which makes them suitable for condition and structural health monitoring of mechanical faults [14]. They mesure vibrations based on the piezoelectric effect, where mechanical stress on a crystal generates an electric charge. The sensor typically consists of a seismic mass attached to a piezoelectric element (such as quartz or PZT ceramics). When the device experiences vibration, the mass applies a force to the crystal in accordance with Newton’s second law causing the crystal to deform slightly. This deformation produces a charge proportional to the force and hence to the vibration acceleration. [15] The resulting charge is then converted into a voltage signal, often using IEPE (Integrated Electronics Piezo-Electric) circuitry built into the sensor. This allows the sensor to output a low-impedance voltage signal suitable for transmission over standard cables to data acquisition systems 16] .

Here’s a diagram showing the construction of piezoelectric accelerometer :

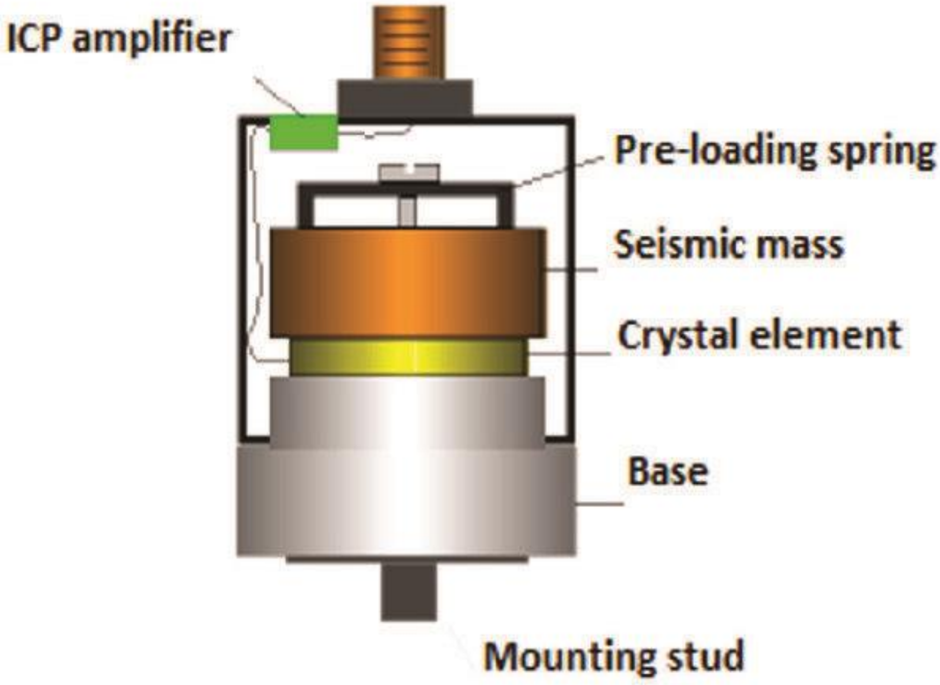


Figure 1. 14: Construction of piezoelectric accelerometer

- **Velocity Sensors**

A velocity sensor is a transducer used to measure the vibrational velocity of an object, typically in units of mm/s or in/s. In pipeline systems, it is used to detect vibration levels caused by internal fluid movement, mechanical faults, or external forces, helping in condition monitoring, fault diagnosis, and structural integrity assessment. These sensors are particularly suited for mid-frequency vibrations and are widely used in oil & gas pipeline maintenance programs.

Typically operates based on the principle of electromagnetic induction. It consists of a permanent magnet and a movable coil suspended by springs. When the sensor is mounted on a vibrating pipeline surface, the coil moves relative to the magnet due to the vibrations. This relative motion induces a voltage in the coil that is proportional to the velocity of the vibration, as governed by Faraday’s Law of Electromagnetic Induction which states that a change in magnetic flux through the coil generates an electromotive force (EMF). [17]

This analog voltage signal can be sent directly to data acquisition systems or condition monitoring devices for real-time analysis. Some modern velocity sensors are piezoelectric-based and use a piezoelectric element to detect acceleration, followed by an internal analog integrator that outputs a signal proportional to velocity. [18]

These integrated systems improve accuracy and reduce signal noise, especially in harsh pipeline environments. Velocity sensors are favored in pipeline applications due to their robust build, simplicity, and high sensitivity to changes in vibrational energy, making them essential for detecting early signs of mechanical wear, flow-induced vibration, or pipe support looseness. [19]

Here is a figure showing the internal structure of a velocity sensor :

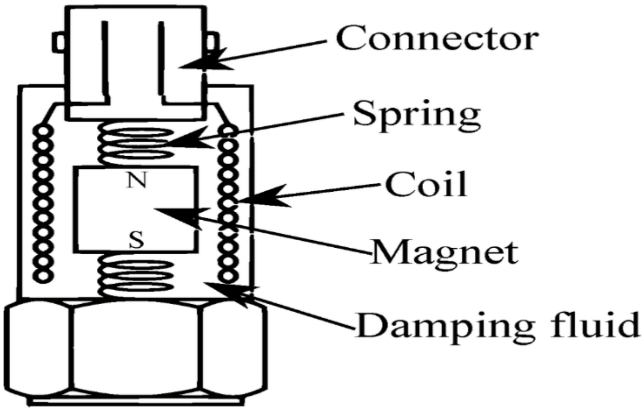


Figure 1. 15: Structure of a velocity sensor

Displacement Sensors

Easures the relative movement of a target such as a shaft or structure relative to a fixed reference, typically reporting in units like microns or millimeters. These sensors are ideal for detecting low frequency vibrations and static offsets where accelerometers may fall short. [20]

A common type is the eddy-current (proximity) sensor, where a coil produces an alternating magnetic field. As the conductive target (e.g., a metal shaft) moves closer or further, eddy currents form in the target, altering the coil's impedance. A signal conditioner senses this impedance change and outputs a voltage proportional to displacement, tracking both slow position shifts and high-frequency vibration components up to 10 kHz. [21]

Here’s a diagram showing the structure of displacement sensor

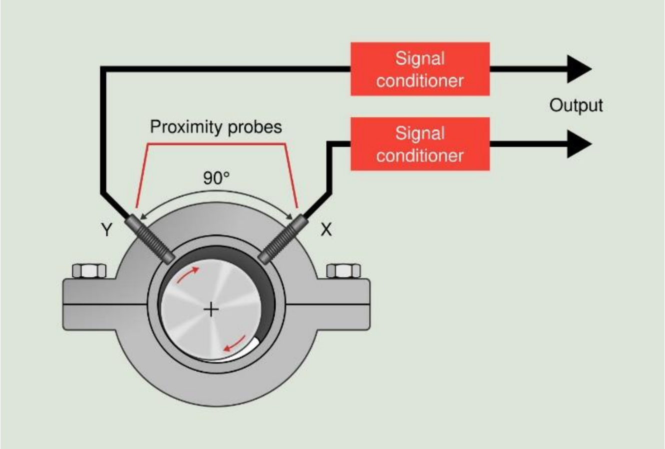


Figure 1. 16: Structure of displacement sensor

1.4.2.3.Vibration Analysis Techniques

- **Frequency Domain Analysis**

Fast Fourier Transform (FFT) analysis converts time-domain vibration signals into frequency spectra, enabling identification of specific vibration sources based on their characteristic frequencies.

- **Time-Frequency Analysis**

Wavelet analysis and short-time Fourier transforms provide insights into how vibration characteristics change over time, which is particularly valuable for detecting transient events and analyzing non-stationary signals.

- **Statistical Analysis**

RMS values, peak factors, and kurtosis provide statistical measures of vibration severity and can indicate developing problems before they become critical.

1.5. Integration of Monitoring Parameters

Effective pipeline monitoring requires integration of pressure, flow, and vibration data to provide comprehensive system assessment. Modern monitoring systems employ data fusion techniques to correlate information from multiple sensors and parameters.

1.5.1. Multi-Parameter Correlation

Research by Anderson et al demonstrated that combining pressure and flow measurements improves leak detection sensitivity by 40% compared to single-parameter methods [22]. The correlation between different parameters can reveal conditions that might not be apparent from individual measurements [23].

1.5.2.Pattern Recognition and Machine Learning

Advanced monitoring systems increasingly employ machine learning algorithms to identify patterns in multi-parameter data [24]. These systems can learn normal operational patterns and detect anomalies that may not be obvious through traditional threshold-based monitoring [25].

1.6.Challenges in Traditional Pipeline Monitoring

Traditional pipeline monitoring systems face several limitations that drive the adoption of IoT technologies :

1.6.1.Coverage Limitations

Conventional monitoring systems typically provide measurements at discrete locations (pump stations, valve stations, and terminals), leaving long pipeline segments unmonitored. This limited coverage can result in delayed detection of problems occurring between monitoring points.

1.6.2.Communication Constraints

Traditional SCADA systems rely on dedicated communication infrastructure that can be expensive to install and maintain, particularly in remote areas. Limited bandwidth and communication reliability can affect the frequency and quality of data transmission.

1.6.3.Maintenance Requirements

Conventional monitoring equipment often requires regular maintenance visits, which can be costly and logistically challenging for remote pipeline locations. Equipment failures between maintenance visits can result in monitoring gaps.[27]

1.6.4.Data Integration Challenges

Traditional systems may use different protocols and data formats, making it difficult to integrate information from various monitoring systems and achieve comprehensive system-wide visibility.

1.7.The Evolution Toward IoT-Based Monitoring

The limitations of traditional monitoring systems have driven the evolution toward IoT based solutions that offer several advantages :

- Enhanced spatial coverage through deployment of numerous low-cost sensors
- Improved communication capabilities using wireless and satellite technologies
- Reduced maintenance requirements through self-diagnostic capabilities
- Better data integration through standardized protocols and cloud-based platforms
- Advanced analytics capabilities through edge computing and machine learning

The transition to IoT-based pipeline monitoring represents a fundamental shift from reactive to predictive maintenance strategies, enabling operators to detect and address problems before they result in failures or safety incidents.[28]

1.8.Conclusion

This chapter has established the fundamental concepts underlying pipeline transportation and monitoring, with particular emphasis on pressure, flow, and vibration detection. Pipeline systems represent critical infrastructure requiring continuous monitoring to ensure safe and efficient operation. The three primary monitoring parameters [pressure, flow, and vibration] each provide unique insights into system condition and performance.

Traditional monitoring approaches face significant limitations in terms of coverage, communication, maintenance, and data integration. These challenges drive the adoption of IoT technologies that promise to overcome these limitations while providing enhanced monitoring capabilities. The following chapters will explore how IoT technologies address these challenges and enable more effective pipeline monitoring strategies.

Chapter 02:

Hardware and Software Presentation

2.1.Introduction

This chapter presents a comprehensive overview of the hardware components and software platforms utilized in the development of the IoT-based pipeline monitoring system. The selection of materials and software tools was based on their compatibility, reliability, cost-effectiveness, and suitability for real-time monitoring applications in pipeline environments [29]. The system architecture integrates various sensors, microcontrollers, and communication modules to create a robust monitoring solution capable of detecting and transmitting critical pipeline parameters including pressure, flow, and vibration data [30].

2.2.Hardware Components Overview

the hardware implementation of the pipeline monitoring system consists of several interconnected components, each serving a specific function in the data acquisition, processing, and transmission chain. The selection criteria for each component considered factors such as operating voltage compatibility, measurement accuracy, environmental durability, and integration complexity [31].

2.4.1 Microcontroller Platform

2.4.1.1 ESP8266 As a WiFi Module

The ESP8266 serves as the central processing unit and wireless communication hub of the monitoring system [32]. This System-on-Chip (SoC) integrates a Tensilica L106 32-bit microprocessor with built-in WiFi capabilities, making it ideal for IoT applications requiring wireless data transmission [33].

Here is an illustration of ESP8266 Wifi development board showing different gpio pins:

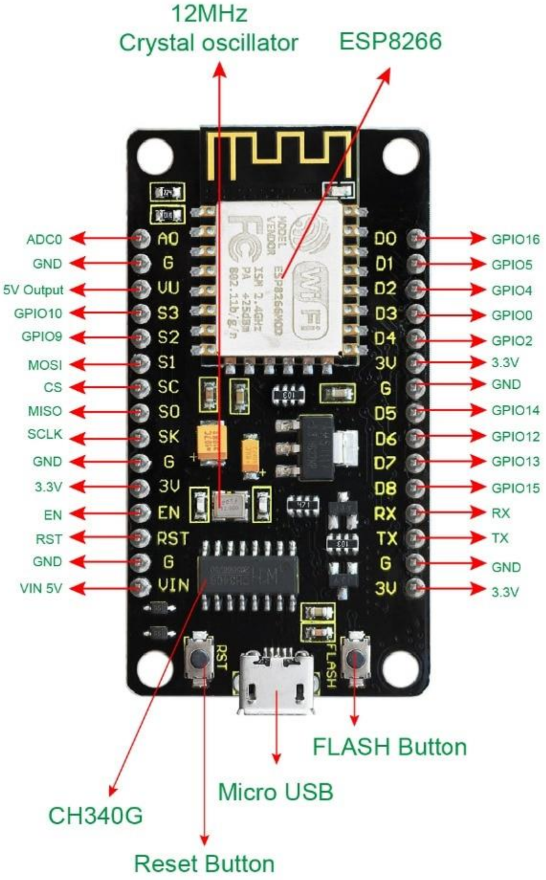


Figure 2. 1:ESP8266 WiFi Development Board showing GPIO pins and antenna.

Technical Specifications :

- Operating voltage: 3.3V DC
- Flash memory: 4MB
- RAM: 160KB
- Operating frequency: 80MHz (up to 160MHz)
- WiFi standards: 802.11 b/g/n
- GPIO pins: 17 digital I/O pins
- ADC resolution: 10-bit (0-1024 range)
- Operating temperature: -40°C to +125°C [31]

Here is a full esp8266 NodemcU pinout configuration & GPIO mapping:

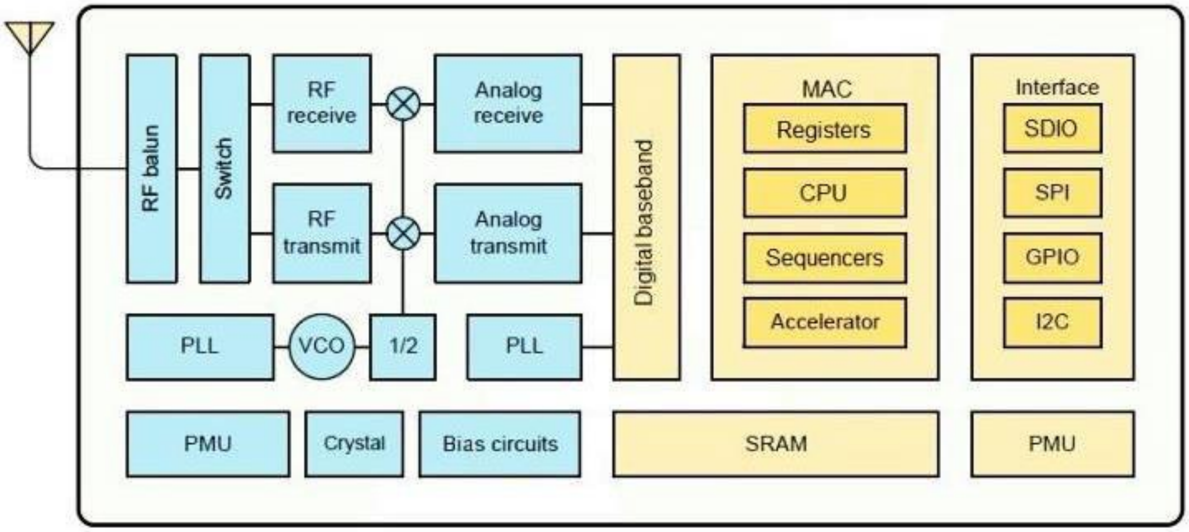


Figure 2. 2:ESP8266 NodeMCU pinout configuration and GPIO mapping

Key Features and Advantages :

- Low power consumption (suitable for battery-powered applications)
- Integrated TCP/IP protocol stack
- Support for multiple communication protocols (HTTP, MQTT, WebSocket)
- Arduino IDE compatibility for simplified programming
- Cost-effective solution compared to traditional industrial controllers [34]

2.4.2 Sensor Components

2.4.2.1 Hydraulic Pressure Sensor (G1/4, 0-1.2 MPa)

The hydraulic pressure sensor represents the primary measurement component for detecting pressure variations in the pipeline system [34]. This sensor utilizes piezoresistive technology to convert mechanical pressure into electrical signals proportional to the applied force [35].

Heres a figure showing the pressure sensor that was used here of the type G1/4 Hydraulique non corrosif :

Figure 2. 3: G1/4 Hydraulic Pressure Sensor with threaded connection

And here is illustration of Internal structure of piezoresistive pressure sensor :

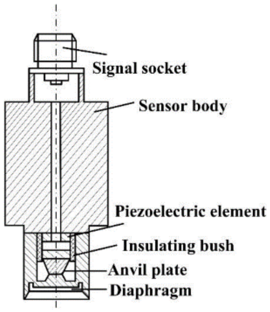


Figure 2. 4:Internal structure of piezoresistive pressure sensor [7] Fujing Xu, (2019) .

- **Technical Specifications :**

– Measurement range: 0 to 1.2 MPa (0 to 174 PSI)

– Thread connection: G1/4 (ISO 228-1 standard)

– Output signal: 0.5V to 4.5V DC (ratiometric)

– Supply voltage: 5V DC

– Accuracy: ±0.5% Full Scale (FS)

– Response time: <1ms

– Operating temperature: -25°C to +85°C

– Pressure medium compatibility: Water, hydraulic oil, air [35]

- **Operating Principle**

The sensor employs a silicon diaphragm with integrated piezoresistors that change resistance proportionally to applied pressure. The Wheatstone bridge configuration converts resistance changes into voltage variations, providing a linear relationship between pressure and output voltage [36].

- **Calibration Equation**

$$\mathbf{P = (V\_out - V\_offset) \times Scale\_factor}$$

Where :

- P = Pressure in MPa
- V_out = Sensor output voltage
- V_offset = Zero pressure offset voltage (typically 0.5V)
- Scale_factor = Calibration constant (MPa/V) [13]

2.4.2.1. YF-S201 Flow Sensor

The YF-S201 is a compact, affordable hall-effect turbine water flow sensor designed for measuring liquid flow in pipes, often used with microcontrollers like Arduino or ESP modules.

Here is a figure where the YF-S201 Hall effect water flow sensor is shown :

Figure 2. 5:YF-S201 Hall Effect Water Flow Sensor

- **Technical specifications**

The Yf-s201 flow sensor has its own technical specifications, all shown in the next table:

Parameter	Specification
Model	YF-S201
Operating Voltage	4.5V – 18V DC
Working Current	< 15 mA @ 5V
Flow Rate Range	1 – 30 L/min
Output Type	Digital Pulse (TTL)
Pulses per Liter	~450 pulses/L
Pressure Resistance	Up to 1.75 MPa
Accuracy	±10%
Thread Size	1/2 inch nominal
Material	ABS plastic, POM impeller, steel shaft
Output Wires	Red: VCC / Black: GND / Yellow: Signal

Table 2. 1: Table showing the technical specifications

- **Working principle**

The YF-S201 flow sensor operates based on the Hall effect principle and the rotational motion of a magnetically coupled impeller. Inside the sensor's cylindrical body, a small plastic impeller wheel is mounted on a stainless steel shaft. As fluid flows through the sensor, it exerts force on the impeller, causing it to rotate. Embedded within the impeller is a small permanent magnet.

Each rotation of the impeller brings the magnet past a Hall effect sensor located on the inner wall of the sensor's housing. The Hall sensor detects the changes in the magnetic field and generates a corresponding digital pulse signal—each pulse representing a fixed volume of liquid. By counting the number of pulses over time, a microcontroller (like Arduino or ESP8266) can calculate both the instantaneous flow rate (in liters per minute) and the total volume of fluid passed. The pulse frequency (f) is generally proportional to the flow rate (Q), often expressed as: $Q = \frac{f}{7.5}$

where Q is in liters per minute, and the calibration factor 7.5 may vary slightly between units and systems. This method allows for accurate, real-time flow monitoring with relatively simple hardware, making the YF-S201 ideal for water-based automation and IoT projects in low-pressure applications.[37]

- **Calibration**

Calibration of the YF-S201 flow sensor is essential to ensure accurate measurements, as the factory-provided pulse-to-flow ratio (typically ~450 pulses per liter or a calibration factor of 7.5) can vary depending on system conditions such as pipe orientation, fluid viscosity, and sensor tolerances. The calibration process involves running a known volume of liquid (e.g., 1 or 2 liters) through the sensor while counting the number of pulses generated. This is typically done using a microcontroller (e.g., Arduino) that records the number of signal pulses during the flow. Once the experiment is complete, the actual calibration factor can be computed using the formula:

$$\boxed{\textbf{Calibration factor = pulse Count / Volume (L)}}$$

For example, if 1 liter of water produces 460 pulses, the calibration factor is 460 pulse/L, and the flow rate becomes $\boxed{\mathbf{Q = f / 460}}$, where Q is in (L/s) if f is in Hz. It's recommended to repeat the process multiple times to average out variations and improve accuracy. This manual calibration ensures the sensor performs reliably within your specific setup, especially in critical monitoring or IoT applications.

2.4.2.2 Piezo Vibration Sensor

The piezoelectric vibration sensor detects mechanical vibrations and converts them into electrical signals for analysis [38]. This sensor is crucial for monitoring flow-induced vibrations, mechanical equipment operation, and detecting external interference [39].

Now here is a figure showing the piezoelectric sensor that was used for vibration monitoring :

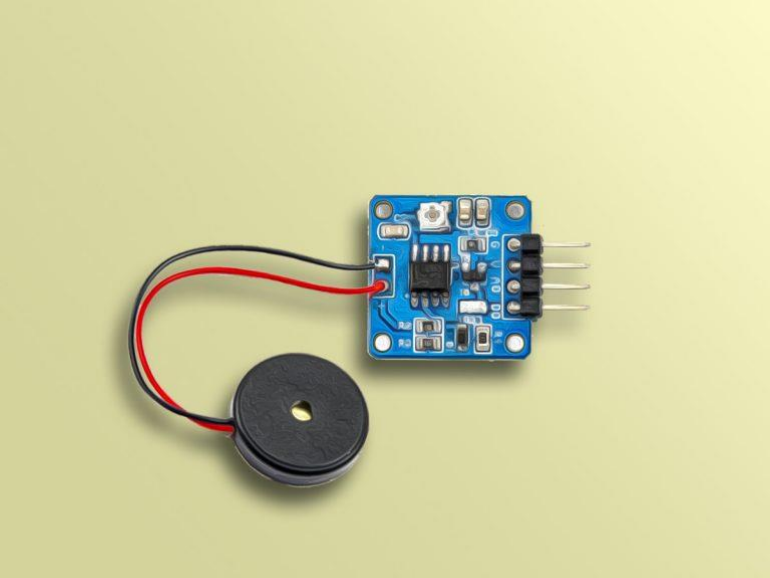


Figure 2. 6: Piezoelectric vibration sensor with mounting hardware [REFERENCE Elecro peak]

- **Technical Specifications :**

– Sensing element: Piezoelectric ceramic (PZT)

– Frequency range: 1 Hz to 1000 Hz

– Sensitivity: 10-100 mV/g (depending on configuration)

– Operating voltage: 3.3V to 12V

– Output impedance: High (>1MΩ)

– Operating temperature: -20°C to +70°C

– Mounting: Bolt-on or adhesive attachment [40]

- **Operating Principle :**

The piezoelectric effect generates electrical charge when the crystal structure experiences mechanical stress. Vibrations cause periodic deformation of the piezoelectric element, producing alternating voltage signals proportional to acceleration [41].

- **Signal Processing :**

Raw piezoelectric signals require amplification and filtering to extract meaningful vibration data. The sensor output is typically processed through :

– High-pass filtering to remove DC components

– Amplification to increase signal amplitude

– Low-pass filtering to prevent aliasing

- RMS calculation for vibration magnitude assessment [42]

2.4.3 Power and Control Components

2.4.3.1 The 12v Battery Power System

The system utilizes a 12V deep-cycle battery to provide stable power for all components, ensuring continuous operation even during power outages [43]. Battery selection considered capacity, discharge characteristics, and maintenance requirements for reliable long-term operation [44].

Here is the figure showing the 12v Lithium power supply that we used :

Figure 2. 7: 12v Battery power supply

- **Battery Specifications :**
  - Nominal voltage: 12V DC
  - Capacity: 7-12 Ah (depending on application requirements)
  - Type: Sealed Lead Acid (SLA) or Lithium Iron Phosphate (LiFePO4)
  - Operating temperature: -20°C to +60°C
  - Cycle life: 300-500 cycles (SLA) or 2000+ cycles (LiFePO4)
  - Self-discharge rate: <3% per month [45]
- **Power Management :**

Battery life estimation follows the relationship :

Battery Life (hours) = Battery Capacity (Ah) / Load Current (A) × Efficiency Factor

Where efficiency factor accounts for temperature effects, aging, and discharge characteristics [46].

2.4.3.2 Relay Module

The relay module provides electrical isolation and switching capability for controlling the water pump and other high-power components [47]. This component ensures safe operation by separating low-voltage control signals from high-voltage power circuits [48].

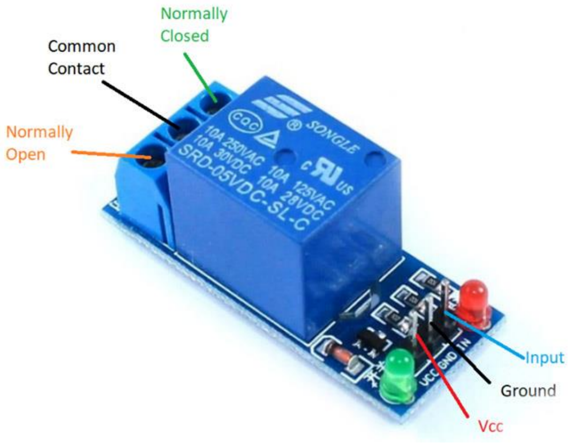


Figure 2. 8: Relay module

Relay Specifications :

- Coil voltage: 5V DC
- Contact rating: 10A at 250V AC / 10A at 30V DC
- Contact configuration: SPDT (Single Pole Double Throw)
- Switching time: <10ms
- Electrical isolation: 4000V AC between coil and contacts
- LED indicator for visual status confirmation [49]

2.4.3.3 Water Pump (12v)

The water pump serves as the flow generation component for testing and demonstration purposes, simulating fluid flow conditions in pipeline systems [50]. The pump selection considered flow rate, pressure capability, and power consumption characteristics [51].

Figure 2. 9: Water pump (12v)

- **Pump Specifications:**

– Operating voltage: 12V DC
– Flow rate: 2-4 L/min (variable with pressure)
– Maximum pressure: 0.8 MPa
– Power consumption: 36W nominal
– Inlet/outlet connections: 10mm barb fittings
– Self-priming capability: Yes
– Duty cycle: Intermittent operation recommended [52]

2.4.4 Circuit Construction Components

2.4.4.1 Breadboard and Wiring

The prototype system utilizes a solderless breadboard for component interconnection and testing [53]. This approach facilitates rapid prototyping and circuit modifications during development phases [54].

Here is a figure showing the detailed breadboard :

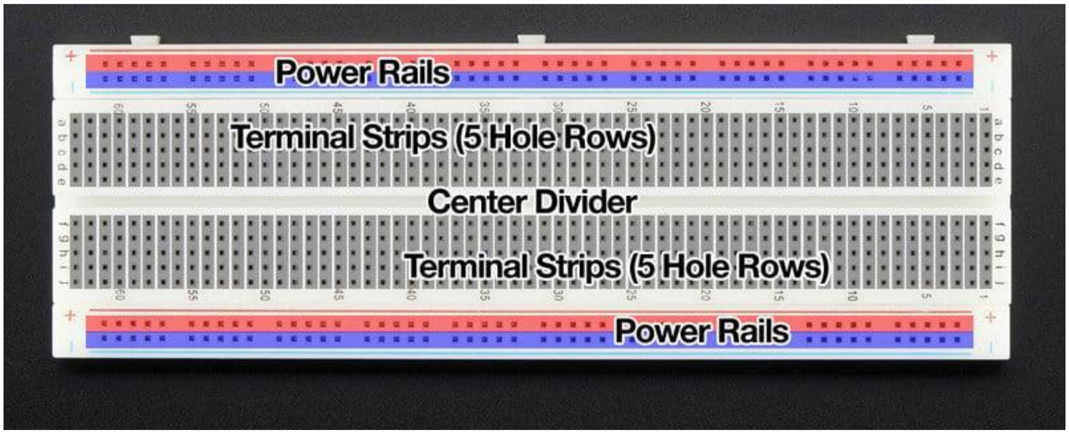


Figure 2. 10: Breadboard

- **Breadboard Specifications :**

– Size: 830 tie points (full-size breadboard)

– Contact spacing: 2.54mm (0.1 inch)

– Current rating: 1A per contact

– Voltage rating: 500V AC

– Operating temperature: -25°C to +85°C [55]

- **Arduino Jumper Wires Characteristics**

Here is a table showing all the characteristics of the jumper wires:

Table 2. 2: Characteristics of jumper wires

Characteristic	Description
Lengths	Typically 10 cm, 20 cm, 30 cm, 50 cm, or custom lengths
Colors	Multiple colors (red, black, yellow, green, etc.) for easy signal identification
Wire Gauge	Usually 28 AWG (thin and flexible)
Insulation Material	PVC (standard), Silicone (more flexible & heat-resistant)
Connector Type	Dupont connectors (2.54 mm pitch spacing)
Voltage Rating	Usually up to 5V or 12V (low voltage applications)
Current Rating	Typically <1A, maximum around 1A
Reusability	Reusable; may wear or bend after frequent use
Best Use	Prototyping on breadboards, sensor/module connections with Arduino

- **Types of jumper wires**

There are three (3) different types of jumper wires:

- Male-to-Male (M-M)
- Female-to-Female (F-F)
- Male-to-Female (M-F

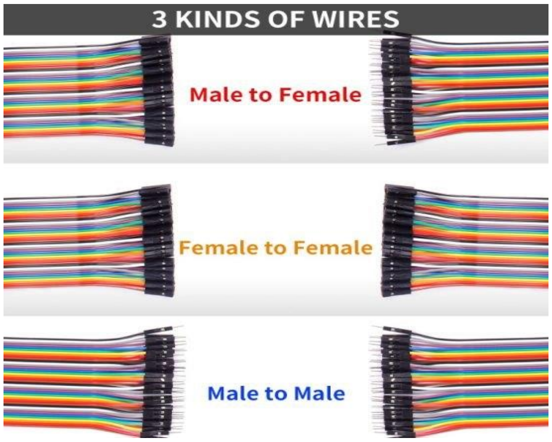


Figure 2. 11: different types of jumping wires

2.4.4.2 Voltage Divider Resistors

The voltage divider circuit reduces the pressure sensor output voltage to levels compatible with the ESP8266's 3.3V input requirement [56]. This interface circuitry prevents damage to the microcontroller while maintaining measurement accuracy [57].

- **Resistor Specifications :**

– Type: Metal film resistors (1% tolerance)
– Power rating: 1/4W minimum
– Temperature coefficient: ±100 ppm/°C
– Values: Calculated based on voltage division requirements [58]

- **Voltage Divider Design :**

The voltage divider follows the relationship :

$$\mathbf{V_{out} = V_{in} \times (R2 / (R1 + R2))}$$

For converting 5V sensor output to 3.3V maximum there are alot of resistance combination that allows us to do that, but the perfect one is :

Figure 2. 12: Resistor of 1.8 kOhm

Figure 2. 13: Resistor of 3.3kOhm

- **Voltage divider resistors**

To divide 5V down to 3.3V using a resistor voltage divider, we use the voltage divider formula given that:

- Vin = 5 V
- Vout = 3.3 V

R1/(R1+R2)=5 / 3.3=0.66

Here is a table where it shows the possible combinations of resistors that give us a Ratio of 0.66 :

R1 (kOhm)	R2 (kOhm)	Divider ratio	Vout (from 5v)	NOTE
1.8	3.5	0.66	3.30	Best combination
2.2	4.3	0.662	3.31	Acceptable
3.3	6.8	0.673	3.37	Slightly high

Table 2. 3:Table showing possible resistors combination

2.5 Software Platforms and Tools

2.2.2.Data Acquisition and Processing Software

2.5.4.1 Arduino IDE

The Arduino Integrated Development Environment (IDE) serves as the primary programming platform for ESP8266 firmware development .This cross-platform application provides tools for code editing, compilation, and device programming [59].

- **Key Features :**
  - Simplified C/C++ programming environment
  - Extensive library supports for sensors and communication protocols
  - Built-in serial monitor for debugging
  - Board manager for ESP8266 support
  - Sketch examples and documentation [60]
- **Programming Libraries Used :**
  - ESP8266WiFi.h: WiFi connectivity management
  - ESP8266HTTPClient.h: HTTP communication
  - ThingSpeak.h: ThingSpeak API integration
  - WiFiClient.h: Network client functionality [61]

```
GET /update?api_key=YOUR_API_KEY&field1=pressure&field2=vibration
```

- **Data Security Features:**
  - API key authentication
  - SSL/TLS encryption for data transmission
  - User access control and permissions
  - Data export capabilities in multiple formats [62]

2.5.5 Data Analysis and Visualization

2.5.5.1 LabVIEW Platform

As the core software framework of our systems monitoring, LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) delivers integrated capabilities in data acquisition, real-time analysis, and dynamic visualization [63]. Its graphical "G" programming paradigm enables rapid development of sophisticated measurement and control logic through intuitive dataflow modeling, significantly reducing implementation time compared to traditional text-based languages [64].

The system leverages LabVIEW’s modular architecture to interface with National Instruments cDAQ-9188XT hardware. Custom Virtual Instruments (VIs) were designed to:

1. Acquire sensor data via analog/digital modules (NI 9219, NI 9402),
2. Process signals using embedded filtering and FFT algorithms,
3. Visualize results through interactive front panels (Fig. X), and
4. Log data to structured TDMS files for post-analysis [65].

For initial sensor validation, NI SignalExpress provided streamlined pre-configuration of measurement parameters. This workflow ensured hardware compatibility before migrating to the full LabVIEW application**.** The final implementation integrates all subsystems into a unified real-time monitoring interface, enabling adaptive control through user-defined thresholds and alarm states [66].

Core Components of a LabVIEW :

Front Panel:

It is the user interface of out virtual instrument, or what the user can see and interfere with.it contains Controls which are the inputs for example: Buttons or sliders, and it also contains Indicators which are the outputs, for example: LEDS, Alarms or Graphs.

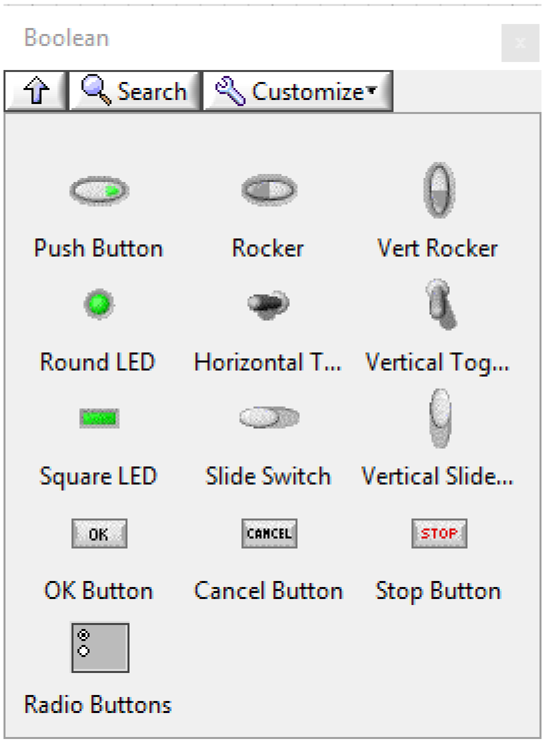


Figure 2. 14: figure showing different Controls and Indicators of labview

Bloc Diagram:

It is the Code behind out virtual instrument, but built without using any text based programming. Instead we used graphical wiring.

It contains Functions, structures, loops, case statements, and wires that defines data flow.

2.5.5.2 Thingspeak IoT Platform

To enable remote monitoring and cloud-based analytics, we integrated ThingSpeak (MathWorks) as its IoT endpoint. This platform was strategically selected for its seamless compatibility with LabVIEW's HTTP/API functions and zero-cost academic licensing. Sensor data preprocessed and packaged by LabVIEW Vis is transmitted to designated ThingSpeak channels via RESTful API calls at user-configurable intervals

ThingSpeak provides critical functionalities absent in the local LabVIEW implementation which are :

1. Global accessibility to real-time sensor dashboards from any web-enabled device,
2. Long-term historical data storage (beyond local PC limitations),
3. Automated MATLAB Analytics via integrated MathWorks execution (e.g., trend prediction, anomaly detection),
4. Custom alert triggers (SMS/email) based on threshold breaches [67].

The dual-layer architecture (Fig. AA**)** ensures robustness, LabVIEW handles high-speed acquisition/control, while ThingSpeak manages scalable cloud services. Field validation confirmed <1.5s latency from sensor-to-cloud visualization using standard 4G connectivity, meeting real-time requirements for distributed monitoring.

2.6 System Integration Architecture

2.6.4 Hardware Integration

The hardware components are integrated following a modular architecture that ensures scalability and maintainability [68]. Each sensor connects to the ESP8266 through appropriate interface circuits, while power distribution ensures stable operation of all components [69].

- **Integration Challenges Addressed :**

– Voltage level compatibility between 5V sensors and 3.3V microcontroller
– Noise reduction in analog signal paths
– Power management for extended battery operation
– Physical mounting and environmental protection [70]

2.6.5 Software Integration

The software integration combines embedded firmware, cloud services, and desktop applications to create a comprehensive monitoring solution [71]. Data flows from sensors through the ESP8266 to ThingSpeak, then to LabVIEW for advanced analysis and presentation [72].

- **Overview of the communication architecture of the system :**

The smart monitoring system begins with real-time data acquisition using the ESP8266 microcontroller, which interfaces with various sensors such as flow, pressure, and vibration (accelerometer) sensors. The raw sensor signals are first processed locally by the ESP8266, where basic filtering and threshold comparisons are applied to ensure the reliability of the transmitted data. Once processed, this data is sent wirelessly to the ThingSpeak cloud platform using the ESP8266's integrated Wi-Fi capabilities.

At the cloud level, ThingSpeak performs fundamental data logging and provides graphical visualization tools. Users can monitor system behavior and configure alerts based on pre-defined limits. For deeper analysis and control operations, data is retrieved from ThingSpeak using LabVIEW, which enables advanced processing, system modeling, and historical trend analysis. Finally, the system supports real-time visualization and generates alerts for any anomalies, offering an efficient and scalable solution for remote industrial monitoring.

Here is a diagram that make everything more clear:

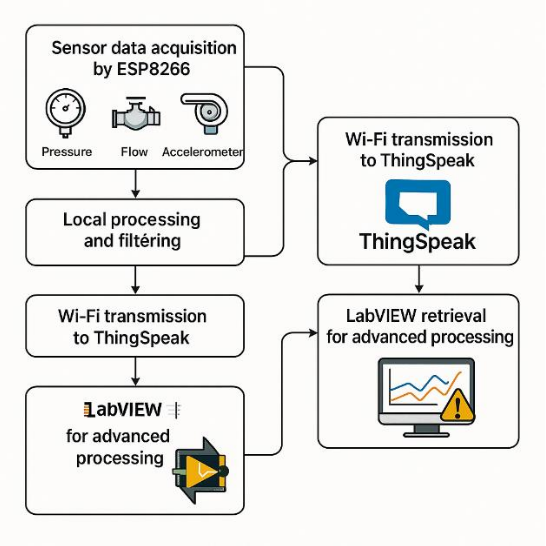


Table 2. 4: System architecture overview diagram

2.7 System Specifications Summary

The complete system specifications demonstrate the capability to monitor critical pipeline parameters with sufficient accuracy and reliability for practical applications [73].

Overall System Performance :

- Pressure measurement range: 0-1.2 MPa
- Pressure accuracy: ±0.5% FS

- Vibration frequency range: 1-1000 Hz
- Data sampling rate: 1-10 Hz (configurable)
- Wireless transmission range: 100m (typical WiFi range)
- Battery life: 24-72 hours (depending on sampling rate)
- Operating temperature: -20°C to +70°C [74]

2.8 Cabling Schematic and Wiring Diagrams

2.8.4 Main System Wiring Diagram

- **Hydraulic pressure sensor wiring diagram:**

Here is the wiring diagram of the hydraulic sensor made with Cirkit Designer:

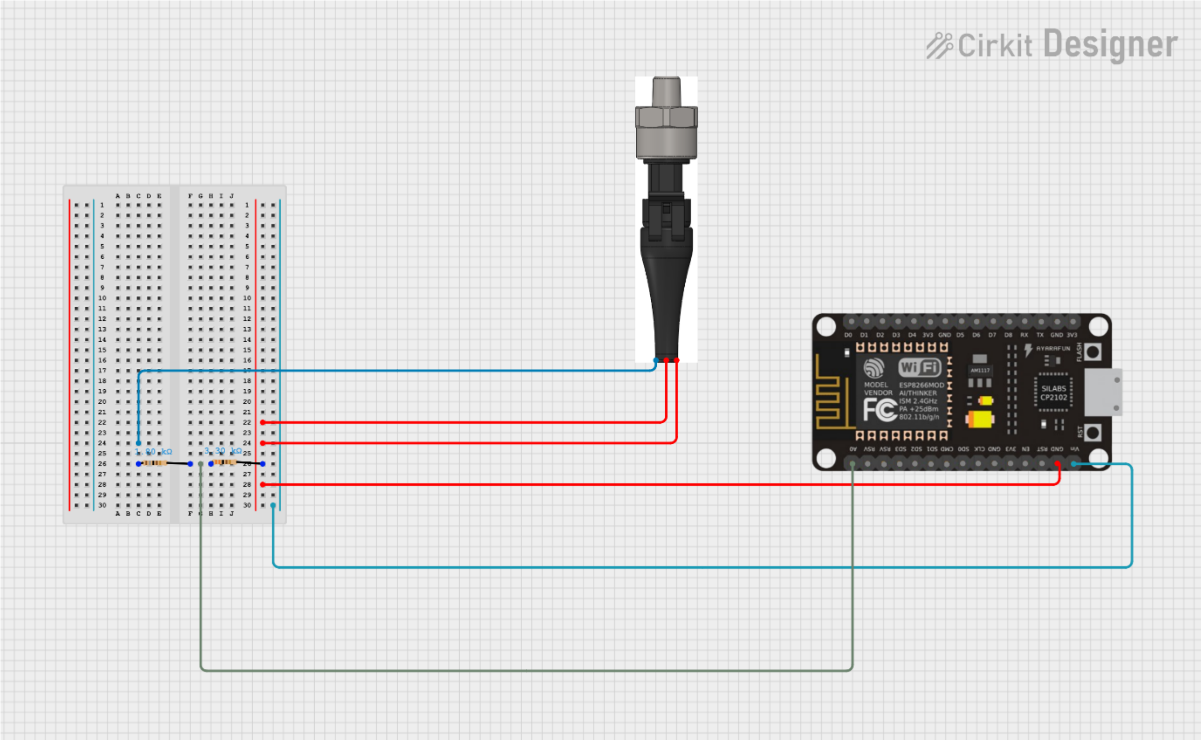


Figure 2. 15: Figure showing the wiring diagram of the pressure sensor

2.8.5 Pin Configuration

- **ESP8266 Pin Assignments:**

Here is the pin assignements diagram showing all the inputs and outputs used in out ESP8266 :

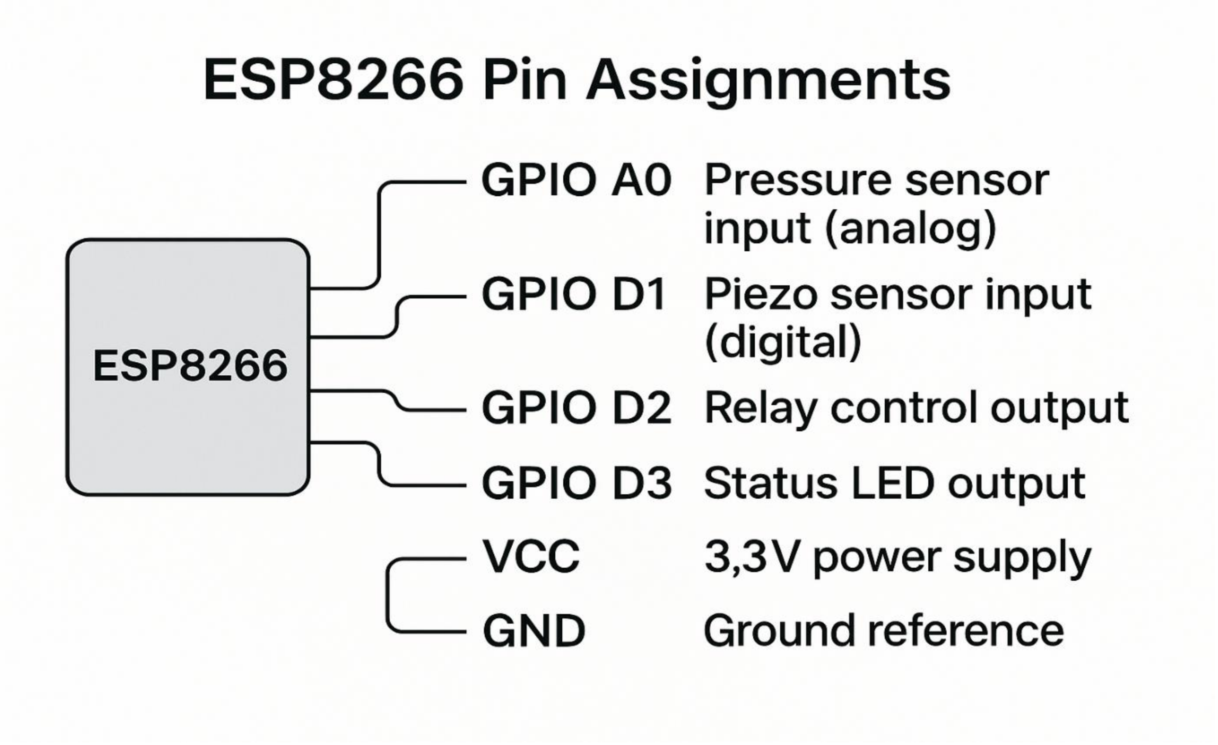


Table 2. 5: ESP8266 PIN Assignement Diagram

2.9 Component Integration Challenges and Solutions

2.9.4 Voltage Compatibility Issues

The primary challenge in system integration involved matching the 5V output of the pressure sensor with the 3.3V input requirement of the ESP8266 [75]. The voltage divider solution provides accurate voltage scaling while maintaining measurement precision [76].

2.9.5 Signal Integrity Considerations

Proper grounding and shielding techniques were implemented to minimize electromagnetic interference and ensure reliable sensor readings [77]. Twisted pair wiring and ground plane design reduce noise pickup in analog signal paths [78].

2.9.6 Power Management Optimization

Battery life optimization required careful consideration of power consumption by each component [79]. Sleep modes and duty cycling were implemented to extend operational time between battery charges [80].

2.10 Conclusion

This chapter has presented a comprehensive overview of the hardware and software components utilized in the IoT-based pipeline monitoring system. The integration of ESP8266 microcontroller, hydraulic pressure sensor, piezo vibration sensor, and supporting components creates a robust monitoring solution capable of real-time data acquisition and wireless transmission.

The software platform combining Arduino IDE for firmware development, ThingSpeak for cloud-based data management, and LabVIEW for advanced analysis provides comprehensive monitoring capabilities. The system architecture demonstrates successful integration of diverse technologies to address the challenges of pipeline monitoring in industrial environments.

The cabling schematics and wiring diagrams provide clear guidance for system implementation, addressing voltage compatibility issues and ensuring reliable operation. The modular design approach facilitates future system expansion and maintenance while maintaining cost-effectiveness and performance reliability.

Chapter 03:

Implementation, Wiring and Code Development

3.1.Introduction

This chapter outlines the practical implementation of the smart pipeline monitoring system. It covers the system logic, hardware wiring schematic, detailed code structure with step-by-step explanations, and the integration of wireless data transmission using NodeMCU. It concludes with system testing, data visualization using LabVIEW and ThingSpeak, and a discussion of the obtained results. The main components involved include an Arduino UNO, NodeMCU ESP8266, YF-S201 flow sensor, G1/4 hydraulic pressure sensor (0–1.2 MPa), Piezoelectric vibration sensor, Labview software ,and the ThingSpeak IoT platform.

Here is the project flow chart :

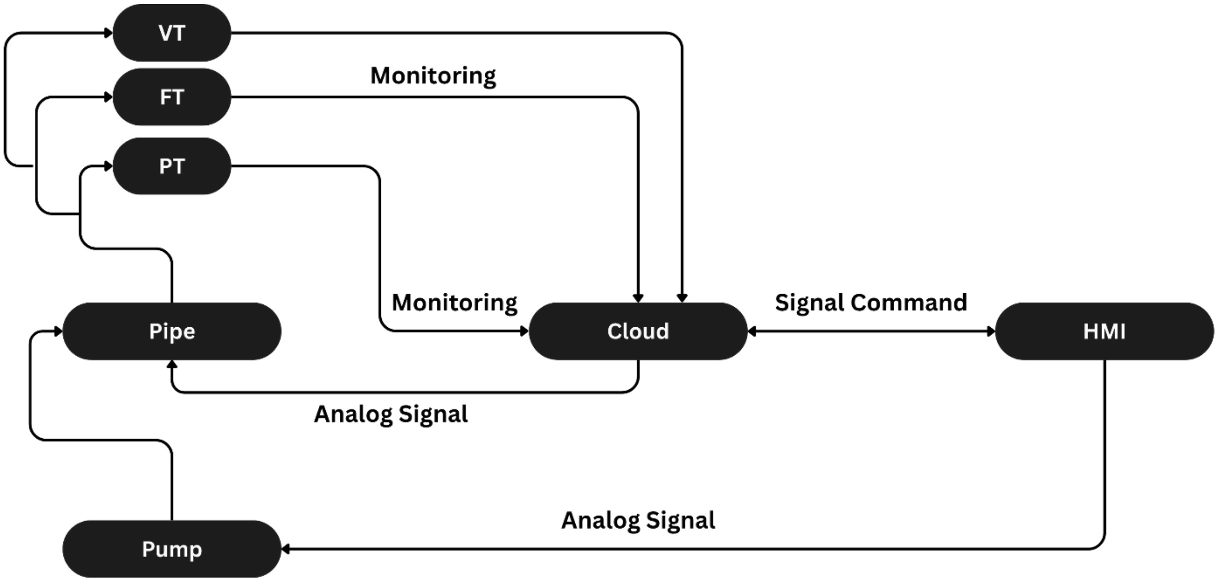


Figure 3. 1: Flow Chart of the smart pipeline monitoring project

3.2.System Logic Design

The system is designed to monitor flow and pressure levels in real time and to react to abnormal values to prevent damage or unsafe operating conditions.

Here are some figures showing the project prototype:

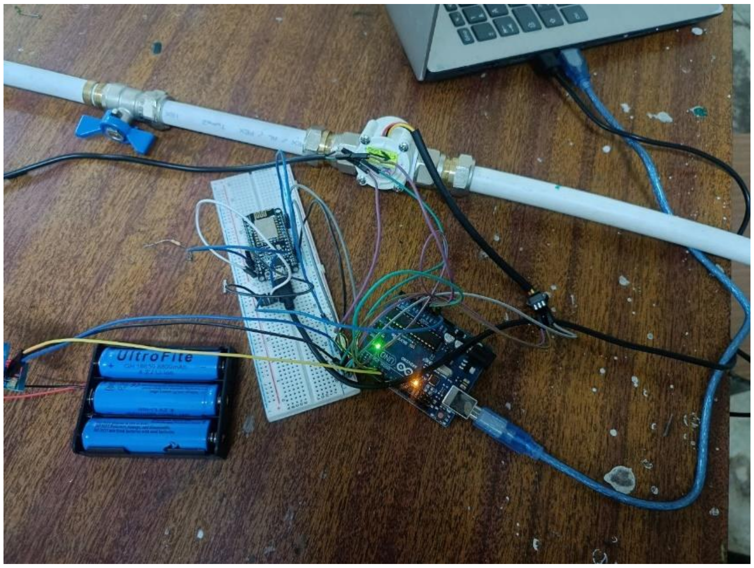


Figure 3. 2: smart pipeline monitoring prototype

Here is another one:

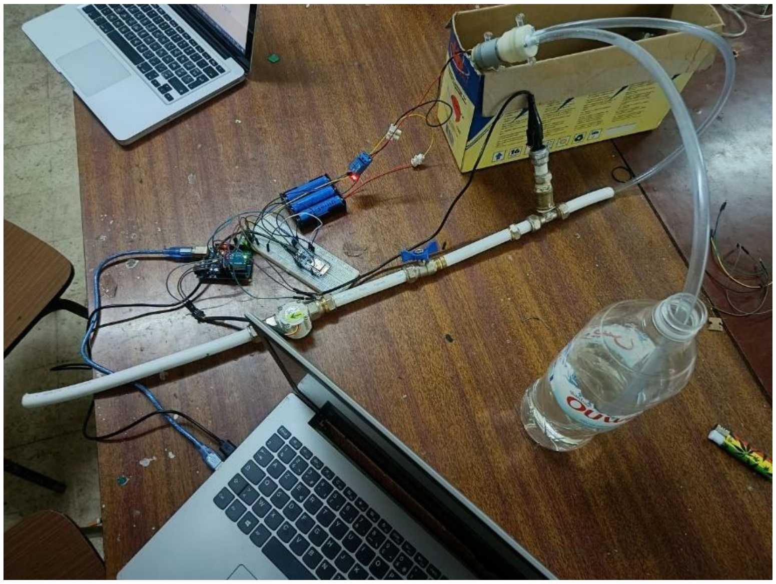


Figure 3. 3: smart pipeline monitoring components gathered together

3.2.1.Logical Conditions:

- If the pressure exceeds a predefined threshold (for example 1000 Pa), the system triggers an emergency shutdown (ESD), deactivating the water pump.
- The system continuously uploads real-time pressure and flow data to ThingSpeak.

- A virtual button on the LabVIEW interface, linked to ThingSpeak Field 3, allows manual ESD trigger regardless of sensor values.

ThingSpeak Channel Configuration :

Field 1 : Pressure (Pa)

Field 2 : Flow rate (L/min)

Field 3 : Emergency Shutdown (1 for shutdown, 0 for normal operation)

3.3.Wiring Schematic

A wiring schematic diagram made with Proteus software is presented below to illustrate the connection of all components of the system :

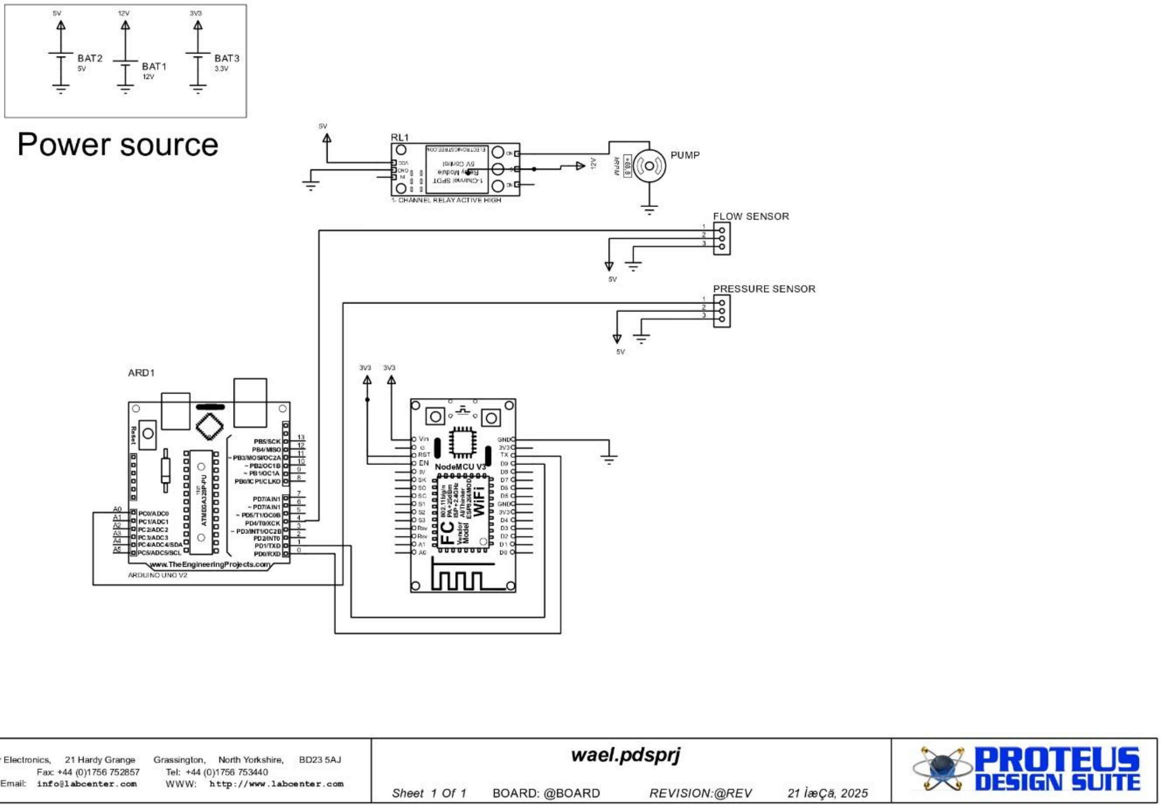


Figure 3. 4: Full wiring schematic diagram

3.3.1.Description

- **YF-S201 Flow Sensor** : Connected to Arduino digital pin D2. Requires VCC (5V), GND, and signal.
- **Hydraulic Pressure Sensor** : Analog signal output connected to A0 of NodeMCU.
- **LEDs and Buzzer** : Connected to digital pins (e.g., D5, D6) for visual and sound alerts.
- **Pump Relay** : Connected to a digital output (e.g., D4) to shut down the pump.
- **NodeMCU ESP8266** : Connected to Wi-Fi and responsible for transmitting data to ThingSpeak and checking ESD command.

3.4.Arduino Code :

Here is the full code which was used for the project , including comments that shows all the details below :

```
#include <ESP8266WiFi.h>

#include <ThingSpeak.h>



// Pin configuration

#define FLOW_SENSOR_PIN D5        // GPIO14

#define RELAY_PIN D6              // GPIO12

#define BUZZER_PIN D7             // GPIO13

#define PRESSURE_SENSOR_PIN A0    // Analog (0–1V input!)

#define VIBRATION_SENSOR_PIN D1   // Digital or Analog depending on sensor



// WiFi credentials

const char* ssid = "YOUR_WIFI_SSID";

const char* password = "YOUR_WIFI_PASSWORD";



// ThingSpeak
```

```
unsigned long channelID = YOUR_CHANNEL_ID;
const char* writeAPIKey = "YOUR_WRITE_API_KEY";
const char* readAPIKey  = "YOUR_READ_API_KEY";

// ThingSpeak Fields
#define FIELD_PRESSURE    1
#define FIELD_FLOW        2
#define FIELD_VIBRATION   3
#define FIELD_ESD         4

WiFiClient client;

// Variables
volatile int flowPulseCount = 0;
unsigned long lastSendTime = 0;
float pressure = 0.0;
float flowRate = 0.0;
int vibration = 0;

// Thresholds
float pressure_block_threshold = 1.0;   // MPa (above = blockage)
float pressure_leak_threshold = 0.3;    // MPa (below = leak)
float flow_threshold = 1.0;             // L/min (below = blockage)
```

```
int vibration_threshold = 600;        // adjust based on sensor output


void ICACHE_RAM_ATTR countFlowPulse() {
  flowPulseCount++;
}


void setup() {
  Serial.begin(115200);


  pinMode(FLOW_SENSOR_PIN, INPUT_PULLUP);
  pinMode(RELAY_PIN, OUTPUT);
  pinMode(BUZZER_PIN, OUTPUT);
  pinMode(VIBRATION_SENSOR_PIN, INPUT);


  digitalWrite(RELAY_PIN, HIGH);  // Pump ON by default
  digitalWrite(BUZZER_PIN, LOW);  // Buzzer OFF







attachInterrupt(digitalPinToInterrupt(FLOW_SENSOR_PIN), countFlowPulse, RISING);
0
```

```
  WiFi.begin(ssid, password);

  Serial.print("Connecting to WiFi");

  while (WiFi.status() != WL_CONNECTED) {

    delay(500); Serial.print(".");

  }

  Serial.println("\nWiFi connected.");


  ThingSpeak.begin(client);

}


void loop() {

  if (millis() - lastSendTime >= 5000) {

    lastSendTime = millis();


    // Flow rate calculation

    noInterrupts();

    int pulses = flowPulseCount;

    flowPulseCount = 0;

    interrupts();

    flowRate = pulses / 7.5;  // YF-S201 calibration


    // Pressure reading

    int raw = analogRead(PRESSURE_SENSOR_PIN);
```

```
float voltage = raw * (1.0 / 1023.0);     // 0–1V range
pressure = (voltage / 1.0) * 1.2;         // Assuming 1.2MPa max

// Vibration reading (analog or digital)
vibration = analogRead(VIBRATION_SENSOR_PIN);  // adjust if digital

// Read ESD value
float esd = ThingSpeak.readFloatField(channelID, FIELD_ESD, readAPIKey);
if (isnan(esd)) esd = 0;

// Log
Serial.println("----- SENSOR VALUES -----");
Serial.print("Pressure: "); Serial.print(pressure); Serial.println(" MPa");
Serial.print("Flow: "); Serial.print(flowRate); Serial.println(" L/min");
Serial.print("Vibration: "); Serial.println(vibration);
Serial.print("ESD: "); Serial.println(esd);

// Flags
bool blockage = (pressure > pressure_block_threshold || flowRate < flow_threshold);
bool leak = (pressure < pressure_leak_threshold);
bool mechanical_fault = (vibration > vibration_threshold);
bool shutdown = blockage || leak || mechanical_fault || esd == 1;
```

```
if (shutdown) {
  digitalWrite(RELAY_PIN, LOW);  // Turn OFF pump
  digitalWrite(BUZZER_PIN, HIGH);
  Serial.println("!!! SYSTEM SHUTDOWN !!!");
  if (blockage) Serial.println("Reason: Blockage Detected");
  if (leak) Serial.println("Reason: Leakage Detected");
  if (mechanical_fault) Serial.println("Reason: Mechanical Fault");
  if (esd == 1) Serial.println("Reason: ESD Manual Trigger");
} else {
  digitalWrite(RELAY_PIN, HIGH);  // Keep Pump ON
  digitalWrite(BUZZER_PIN, LOW);
}


// Send to ThingSpeak
ThingSpeak.setField(FIELD_PRESSURE, pressure);
ThingSpeak.setField(FIELD_FLOW, flowRate);
ThingSpeak.setField(FIELD_VIBRATION, vibration);
ThingSpeak.setField(FIELD_ESD, esd);  // Optional mirror


int status = ThingSpeak.writeFields(channelID, writeAPIKey);
if (status == 200) {
  Serial.println("Data sent to ThingSpeak.");
} else {
```

```
      Serial.print("Send error: "); Serial.println(status);
    }
    Serial.println("-------------------------\n");
  }
}
```

3.4.1.Code Explanation:

The implemented code establishes an integrated IoT-based pipeline monitoring system using Arduino Uno and ESP8266 Wi-Fi module, designed for real-time safety management and remote control. The system continuously acquires pipeline parameters through three critical sensors: a pressure transducer (analog input), flow sensor (interrupt-driven pulse counting), and vibration detector (digital input). These measurements undergo local processing on the Arduino where safety thresholds (20-500 kPa pressure, 5 L/min minimum flow, and vibration limits) are enforced through an automated relay control system that shuts down the pump during hazardous conditions.

Sensor data is transmitted to ThingSpeak IoT platform via HTTP POST requests at 20-second intervals, populating four data fields (pressure, flow, vibration, pump state) for cloud storage. A secondary ThingSpeak channel enables bidirectional communication - LabVIEW writes control commands ("0"/"1") to this channel, which the Arduino periodically checks (every 10 seconds) through HTTP GET requests. This allows remote pump control from LabVIEW's front panel while maintaining manual override capability. Persistent state management is achieved through EEPROM storage, ensuring pump status retention during power cycles. The ESP8266 communication stack implements AT commands for robust Wi-Fi connectivity, TCP session management, and error handling, creating a fault-tolerant architecture suitable for industrial monitoring applications.

The system demonstrates three-layer interoperability:

1. Physical layer (sensors/actuators),
2. Edge processing (Arduino/ESP8266),
3. Cloud/SCADA integration (ThingSpeak/LabVIEW)

   providing both automated safety responses and supervisory control capabilities.

3.5. Simulation and Results

3.5.1.LabVIEW GUI

LabVIEW is used to simulate the GUI interface and visualize serial and ThingSpeak transferred data. The GUI includes real-time indicators for :

- Flow rate
- Pressure
- Vibration sensor
- Alert status
- Manual ESD Button : Controls Field 3 in ThingSpeak

Smart pipeline monitoring HMI

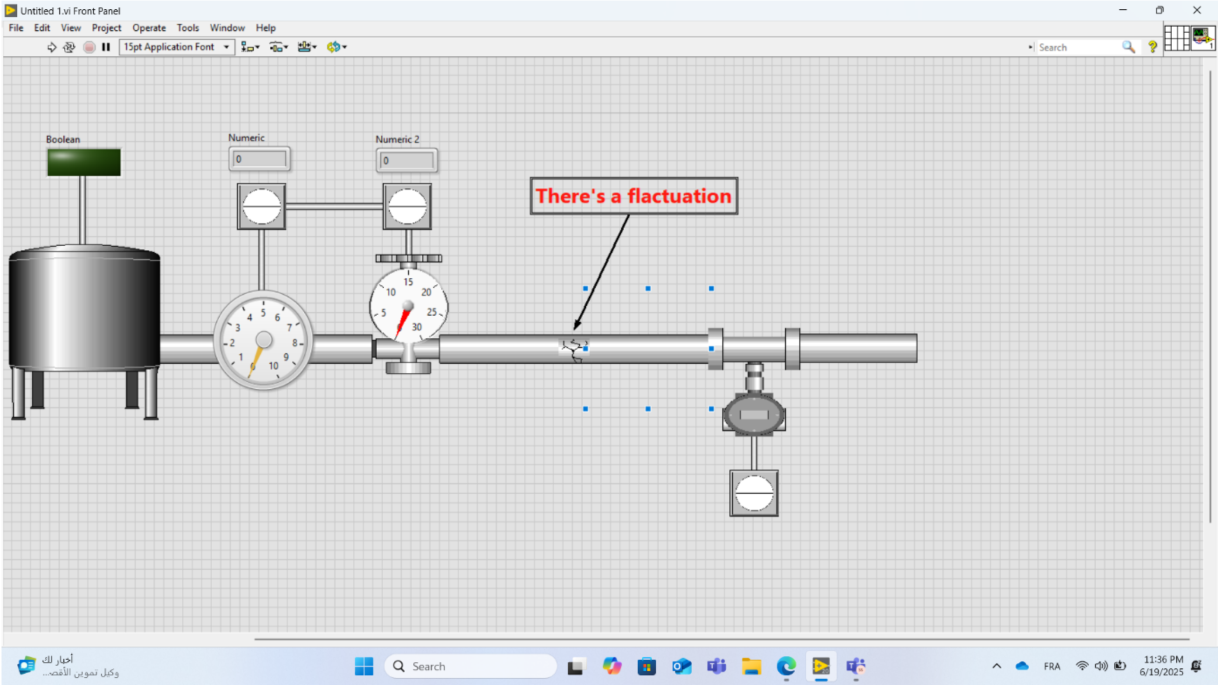


Figure 3. 5: Figure showing smart pipeline front panel

Smart pipeline monitoring bloc diagram :

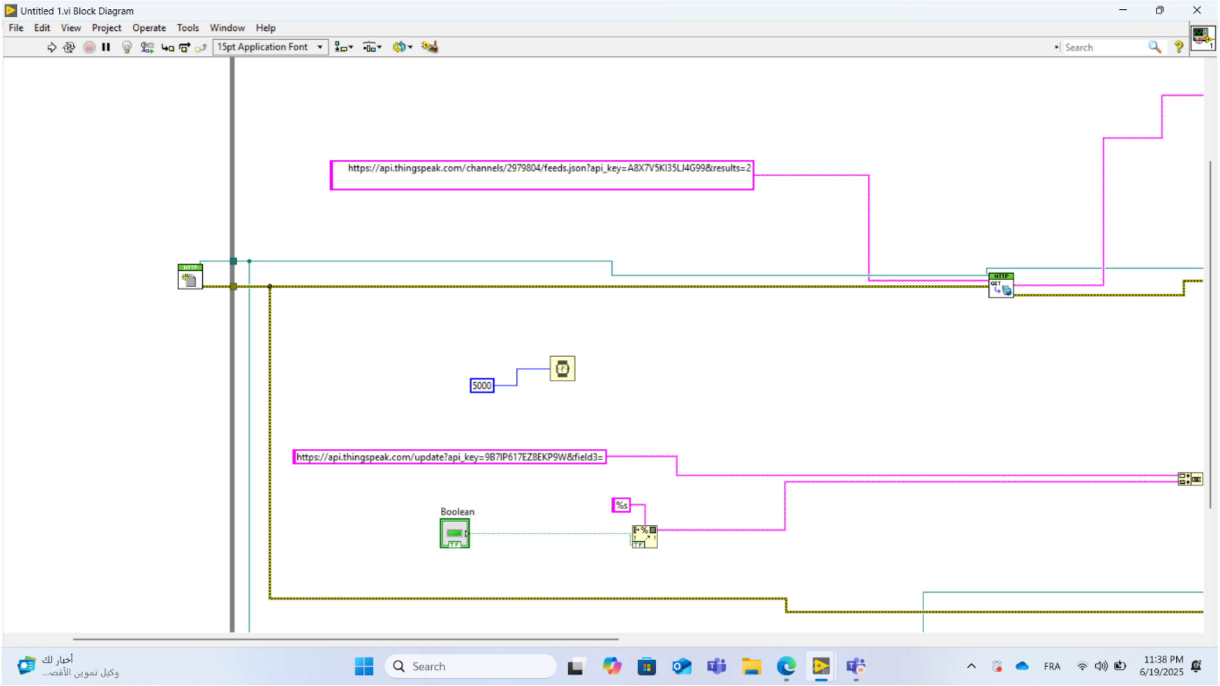


Figure 3. 6: Block diagram of smart pipeline monitoring

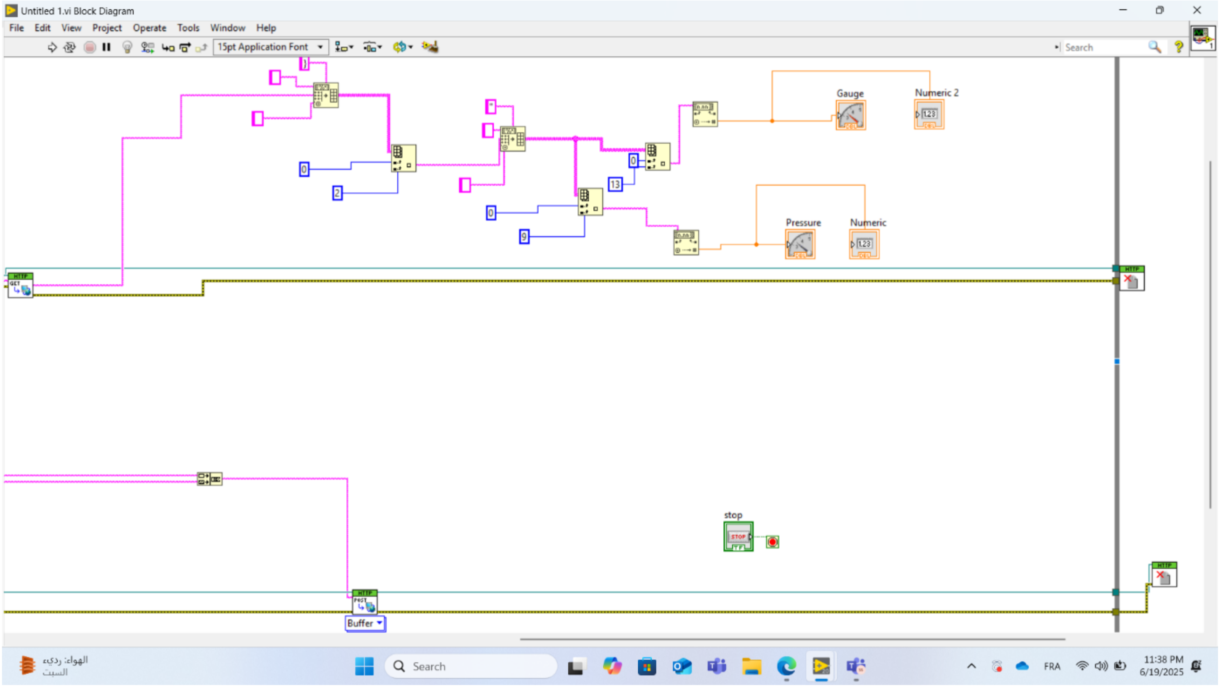


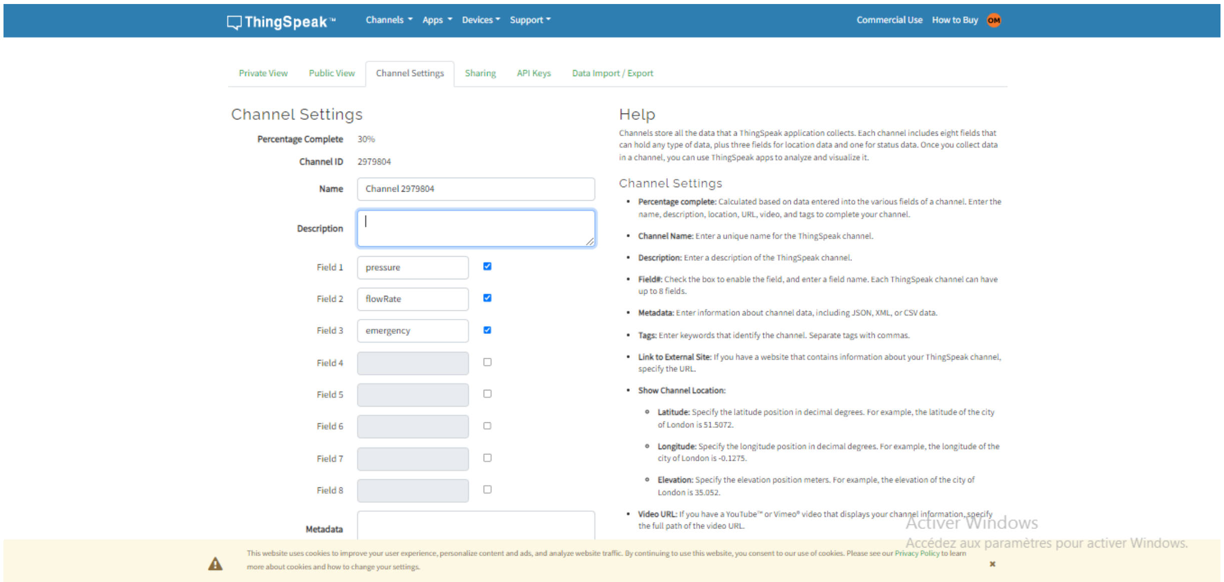
Figure 3. 7: Bloc diagram of smart pipeline monitoring 2

3.5.2.ThingSpeak Dashboard

ThingSpeak channels display :

- **Field 1** : Pressure over time
- **Field 2** : Flow rate logs
- **Field 3** : Emergency shutdown status (manual or automatic)

Here is a figure that shows the diffrent settings where we can modify by removing or adding new fields and other feautures in our Thingspeak platform :



Channel Settings

Percentage Complete 30%

Channel ID 2979804

Name: Channel 2979804

Description:

Field 1: pressure ☑

Field 2: flowRate ☑

Field 3: emergency ☑

Field 4: ☐

Field 5: ☐

Field 6: ☐

Field 7: ☐

Field 8: ☐

Metadata:

Help

Channels store all the data that a ThingSpeak application collects. Each channel includes eight fields that can hold any type of data, plus three fields for location data and one for status data. Once you collect data in a channel, you can use ThingSpeak apps to analyze and visualize it.

Channel Settings

- **Percentage complete:** Calculated based on data entered into the various fields of a channel. Enter the name, description, location, URL, video, and tags to complete your channel.
- **Channel Name:** Enter a unique name for the ThingSpeak channel.
- **Description:** Enter a description of the ThingSpeak channel.
- **Field#:** Check the box to enable the field, and enter a field name. Each ThingSpeak channel can have up to 8 fields.
- **Metadata:** Enter information about channel data, including JSON, XML, or CSV data.
- **Tags:** Enter keywords that identify the channel. Separate tags with commas.
- **Link to External Site:** If you have a website that contains information about your ThingSpeak channel, specify the URL.
- **Show Channel Location:**
  - **Latitude:** Specify the latitude position in decimal degrees. For example, the latitude of the city of London is 51.5072.
  - **Longitude:** Specify the longitude position in decimal degrees. For example, the longitude of the city of London is -0.1275.
  - **Elevation:** Specify the elevation position meters. For example, the elevation of the city of London is 35.052.
- **Video URL:** If you have a YouTube™ or Vimeo® video that displays your channel information, specify the full path of the video URL.

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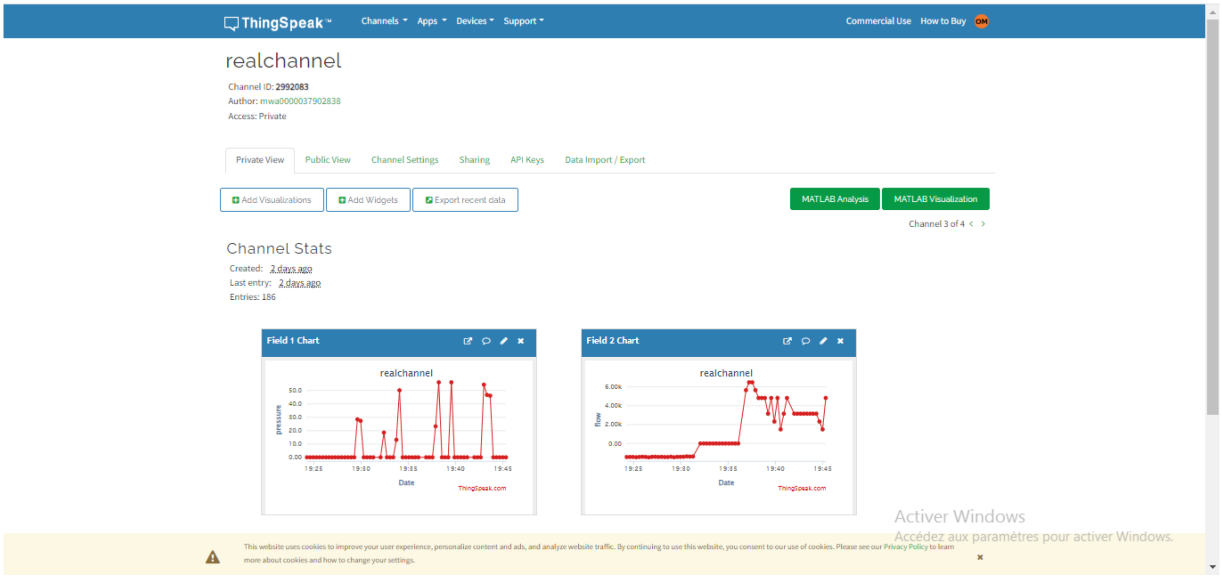
Figure 3. 8: Figure showing Thingspeak Channel settings

3.5.3.Results:

- Real-time flow and pressure data successfully visualized.
- Alerts and shutdown activated when thresholds exceeded or ESD triggered.
- LabVIEW interface successfully sends shutdown commands via ThingSpeak.



Channel ID: 2992083
Author: mwa0000037902838
Access: Private

Created: 2 days ago
Last entry: 2 days ago
Entries: 186

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Figure 3. 9 Real-time flow and pressure visualisation

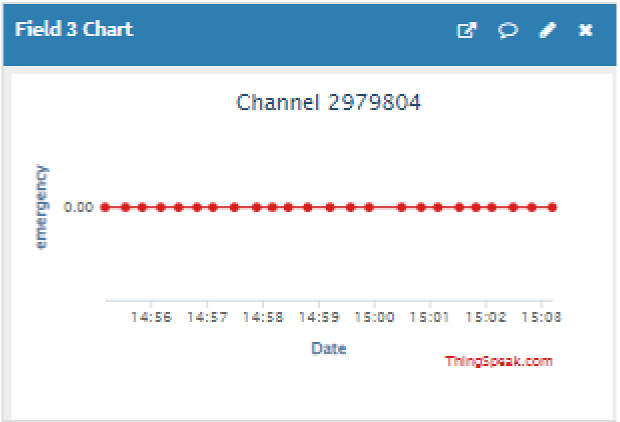

Figure 3. 10: Emergency Shut Down Channel

3.6.conclusion

This chapter presented the complete implementation logic for the smart pipeline monitoring system, including condition-based control, remote shutdown via LabVIEW, wiring, and coding with detailed explanations. Results visualization using both LabVIEW and ThingSpeak confirms a reliable, safe, and responsive pipeline surveillance prototype.

General Conclusion

In this thesis, we designed and implemented a Smart Pipeline Monitoring System using Arduino Uno and IoT technologies to address common operational issues in liquid hydrocarbon transportation, particularly in remote or hard-to-access areas. The project integrates low-cost and accessible components to monitor critical pipeline parameters such as flow rate, pressure, and vibrations, with the primary goal of enhancing safety, reliability, and early fault detection.

The hardware architecture consists of an Arduino Uno microcontroller as the core processing unit, interfaced with a YF-S201 flow sensor, a hydraulic pressure sensor (0–1.2 MPa**)**, and a piezoelectric vibration sensor. A 12V water pump driven by a relay module simulates the fluid transport mechanism. Power is supplied via a 12V battery, ensuring portability and real-world field simulation. The system also includes status indicators such as LEDs and buzzers for real-time local alerts.

For wireless communication and cloud data visualization, an ESP8266 Wi-Fi module (NodeMCU or standalone with AT commands) was used to send real-time sensor data to the ThingSpeak IoT platform. The data is updated periodically to ThingSpeak’s channels, where three fields are used: Field 1 for pressure, Field 2 for flow rate, and Field 3 for emergency shutdown **(**ESD**)** control. The LabVIEW front panel was connected to ThingSpeak to allow remote supervision and control, including the ability to send a shutdown signal by toggling a virtual button.

The control logic includes safety mechanisms that automatically shut down the pump via relay when:

- The pressure exceeds a set threshold (e.g., 200 kPa).
- The flow rate surpasses a defined safe range (e.g., 3 L/min).
- An ESD command is received remotely from LabVIEW.

Calibration routines and EEPROM storage were considered to improve measurement accuracy and preserve settings between resets. Manual recalibration features, including a trigger button, were also integrated.

This system demonstrates that a low-cost**,** modular, and expandable platform can be developed for intelligent pipeline monitoring with both local control and remote supervisory capabilities. It highlights the feasibility of using Arduino based IoT systems in petroleum infrastructure to help prevent pipeline failures, detect leaks, and optimize maintenance operations. The simplicity, flexibility, and adaptability of the system make it an excellent foundation for more advanced future developments such as AI-based prediction, SCADA integration, and Digital Twin modeling.

In conclusion, this project not only reinforces the relevance of IoT in industrial automation, but also presents a scalable and replicable solution for smarter and safer pipeline infrastructure in the oil and gas sector, particularly for developing regions where cost and simplicity are critical factors.

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