Membrane Technology
ISSN (online): 1873-4049

IoT-based Underground Pipeline Intelligent Operation and Maintenance System

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Abstract:
The underground pipeline network, as a crucial component of urban infrastructure, is essential for public services such as water supply, drainage, and natural gas. With the continuous development of urbanization, the scale and complexity of underground pipeline networks are also rapidly increasing. Nevertheless, the operation and maintenance methods for traditional pipeline network are inefficient and lack safety, making it urgent to introduce advanced technology to improve the management level. In this regard, an intelligent operation and maintenance system for underground pipeline networks based on the Internet of Things, which realizes real-time cyclic monitoring of pipeline operation status and data collection, is proposed in this study. The advantage of this system lies in the optimized utilization of resources, helping operations and maintenance personnel to allocate maintenance resources reasonably and reduce unnecessary maintenance costs through accurate data analysis. Meanwhile, its predictive maintenance function helps to prevent potential failures, improve the stability and reliability of the pipeline network, and timely discover safety hazards through real-time monitoring and predictive maintenance, reduce accidents, and improve the safety level of pipeline operation and maintenance.

Keywords: internet of things (IoT), underground pipeline network, intelligent operation and maintenance, circular system

INTRODUCTION

With the accelerated progress of urbanization and the rapid growth of population, the sustainable development of urban infrastructure has become an urgent issue that needs to be addressed in today's society. The underground pipeline network is crucial to the development of cities, the living standards of residents, and the operational quality of enterprises. However, the most widely used method for detecting water pipe leaks at the current stage is “listening and locating”, which involves using special listening headphones to pick up the sound of the leak and determine the location and amount of the leak. However, this traditional underground pipeline data management method can no longer meet the needs of smart city development in terms of real-time, reliability, visibility, etc[1]. In order to improve the management level of underground pipeline network, it is imperative to introduce advanced technological means. The rapid development of Internet of Things technology provides technical support for solving this problem. The Internet of Things (IoT), characterized by realizing information sharing, real-time monitoring, and remote control between devices, is widely used in various fields, providing strong support for the intelligent level of urban infrastructure and is the lifeline of urban development. Strengthening the visualization research of urban underground pipeline network is of great significance for the safety and development of urban areas[2]. In this connection, with an aim to explore a smart operation and maintenance system for underground pipeline networks based on the Internet of Things (IoT), this study delves into the application of IoT technology in the operation and maintenance of underground pipeline networks, analyzing the functional design and working principles of the system. Through the study of this smart operation and maintenance system, innovative solutions are provided for the sustainable development and safe operation of urban underground pipeline networks.

RESEARCH ON THE FOUNDATION OF IOT-BASED UNDERGROUND PIPELINE INTELLIGENT OPERATION AND MAINTENANCE SYSTEM

The current mature method for monitoring water pipe leakage is “listening and locating”. By this traditional maintenance method, one pressurizes the leaking water pipe, checks whether the instrument panel is leaking, then inserts the listening headphones into the leak detector and the shock sensor to listen to the wall, and then adjusts the gain knob to amplify the signal, and finally locates the specific leak position. Refer to Figure 1 for details. However, there are still some issues with it in terms of monitoring technology, data collection, and data analysis. The specific problems are as follows:

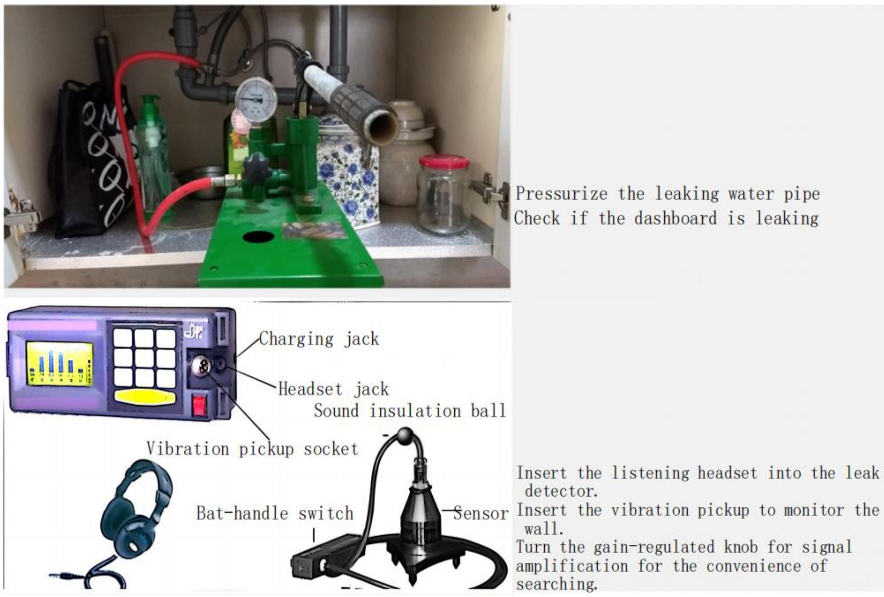

Figure 1. Traditional pipeline inspection system

Single Monitoring Technology

Traditional pipeline monitoring mainly relies on manual inspection and manual data recording, which is inefficient and prone to errors. Meanwhile, traditional monitoring methods are unable to obtain real-time operational data of the pipeline network, making it difficult to respond and address pipeline issues in a timely manner.

Difficulty in Data Collection

The pipeline network is usually distributed underground, making it more difficult for collecting monitoring data. For instance, the monitoring of underground pipeline networks such as water pipelines and gas pipelines requires ground excavation or the use of non-intrusive detection methods, which are inconvenient and costly to operate.

Lack of Timeliness in Data Analysis

The pipeline network monitoring data is vast and complex, requiring effective analysis and processing to draw useful conclusions. However, traditional data analysis methods are unable to fully utilize the data, and the analysis process takes a long time, resulting in poor timeliness of monitoring results.

Poor Coordination in Monitoring Process

Most regions have relatively scattered network monitoring and lack comprehensive monitoring systems. The lack of data sharing among various departments and institutions leads to information silos and inconsistent monitoring results, making it difficult to conduct comprehensive pipeline health assessment and management.

RESEARCH METHODS FOR IOT-BASED UNDERGROUND PIPELINE INTELLIGENT OPERATION AND MAINTENANCE SYSTEM

Due to the many problems with traditional methods of monitoring underground pipe networks, in order to improve the stability, reliability, and efficiency of pipeline network operation and maintenance, an intelligent operation and maintenance system for underground pipe networks based on the Internet of Things (IoT-based underground pipeline intelligent operation and maintenance system) is proposed in this study, which implements the construction of an intelligent water supply pipe network, establishes an Internet of Things-based intelligent pipe network platform, and improves the level of informationization and intelligence of the water supply pipe network[3,4].

Overview of Internet of Things (IoT) Technology

The Internet of Things (IoT) is a dynamic global network infrastructure based on internet technology, which enables the automatic identification and information exchange of objects through modern intelligent perception technology, wireless communication technology, and other means[5]. IoT, as a new concept of information exchange and communication, has three important features:

intelligence, identification and communication, and interconnection[6]. Based on the characteristics of IoT interconnection and sharing, IoT technology is applied to the underground pipe network intelligent operation and maintenance system, enabling it to achieve real-time monitoring, remote control, intelligent analysis, and intelligent operation and maintenance functions. This improves the operational efficiency and reliability of the underground pipe network, reduces maintenance costs, and provides support for the sustainable development of urban infrastructure[7].

Design Ideas

The underground pipeline intelligent operation and maintenance system is a comprehensive monitoring and operation and maintenance system that uses online monitoring equipment as the core, applies modern Internet of Things technology, timely sends information, and collects, stores, processes, queries, and warns real-time and fast monitoring information such as underground pipeline leakage, pressure, and flow[8]. The system, suitable for leak detection and maintenance of household water and remote water supply pipe networks, can monitor in real time whether the pipe network is in a safe state, quickly discover the precise location of the leaking pipe, ensure that it is repaired and handled in a timely manner, and promptly discover and stop the occurrence of pipe bursting accidents.

The system has been established with a cyclic monitoring system composed of property owners, intelligent pipeline network, wireless data collection terminals, and maintenance parties. Throughout the entire monitoring process, the APP is used as the carrier, and data is collected through wireless data collection terminals. The data is sent to the property owners in the form of SMS and APP push notifications, and then feedback is given to the maintenance party by the property owners, hence ensuring timely monitoring and repair reporting of water pipeline leaks. After the maintenance party accepts the order, they promptly provide feedback on the repair progress to the property owners, ensuring smooth information flow and timely and efficient repairs. See Figure 2 for details.

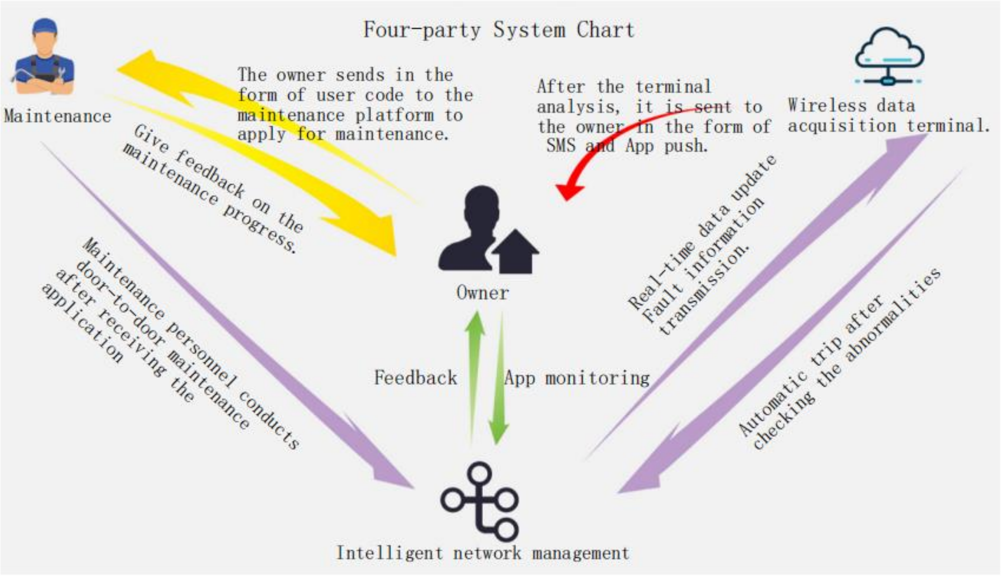

Figure 2. Intelligent operation and maintenance system

Function Analysis

The IoT-based underground pipeline intelligent operation and maintenance system mainly includes three parts: the intelligent perception layer, the information transmission layer, and the intelligent control layer. The three parts of the system are both independent and cooperative, working together to use data as the transmission medium. The three parts are organically combined to build an IoT-based underground pipeline intelligent operation and maintenance system, as shown in Figure 3.

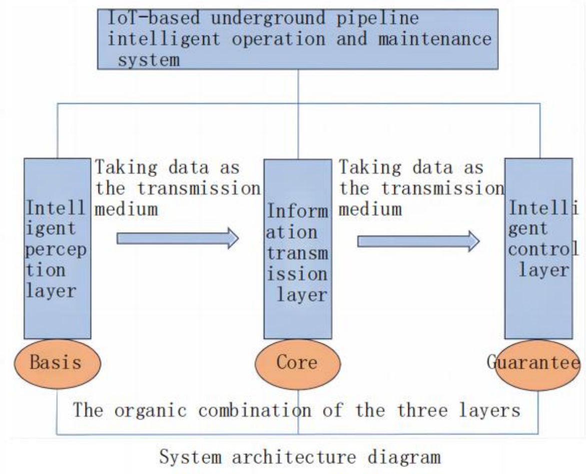

Figure 3. System architecture diagram

Intelligent perception

The perception layer of the system arranges sensors at various key positions in the pipeline system to monitor the real-time operation status, pressure, temperature, flow and other parameters of the pipeline and collect data. These sensors can be pressure sensors, temperature sensors, flow sensors, etc., which transmit real-time underground pipeline data to the perception layer for further processing and analysis.

The perception layer, as the foundation layer, mainly uses various sensors to collect information on the operation status of the pipeline network. The measured analog quantities are converted into electrical signals through preset mechanisms and then converted into corresponding digital quantities, such as current and voltage, to determine whether there are changes in pipe diameter or resistivity in the pipeline network. This information is then transmitted to the monitoring platform for intelligent analysis to determine if there are any faults such as joint detachment, perforation, or rupture in the pipeline. In addition, comparing the monitored signals such as current and voltage, it determines the location and type of the fault, and provides a basis for pipeline maintenance and repair[9].

The sensors of the water supply network mainly include flow meters and pipeline pressure gauges installed on the transmission network, as well as pressure gauges and flow meters installed in water plants and booster stations. The hydraulic monitoring points in the water supply network mainly include pressure monitoring points and flow monitoring points. The urban water supply network perceives the network and utilizes mature sensors to collect real-time flow and pressure information of the pipeline network[10]. Pressure and flow are important indicators for evaluating the quality of urban water supply network operation. The pressure and flow monitoring system of urban water supply network can provide timely information on the operation of the entire network[11], implementing a convenient and efficient pipeline inspection method that integrates monitoring, notification, and maintenance declaration of the underground pipeline intelligent operation and maintenance system.

The main goal of the perception layer is to achieve comprehensive monitoring and data collection of the underground pipe network, providing high-quality data support for data processing, analysis, and decision-making at the upper layer. By reasonably selecting and deploying sensors, collection equipment, and communication technology, the system can ensure timely, accurate, and reliable monitoring of underground pipelines. This provides a reliable data foundation for the intelligent operation and maintenance system, providing support for the efficient operation of the system.

Information transmission

The information transmission layer is a core component of the system, whose main task is to realize the data collection, transmission, and exchange between various nodes of the underground pipeline network (such as sensors, controllers, etc.). These sensors can include pressure sensors, flow sensors, temperature sensors, humidity sensors, etc., which are used to collect the data required for the real-time operation of the pipeline network.

This layer uses various wireless communication technologies to achieve data transmission between sensor nodes and data collection devices, realizing efficient and effective information exchange. Through communication systems (mobile networks, the

Internet, etc.), the basic information obtained by the perception layer is transmitted to various places in a timely, accurate, and efficient manner, achieving long-distance communication between things. The structure design of the underground pipe network intelligent operation and maintenance system relies on the architecture system of the IoT, carries out the structure design of the underground pipe network intelligent operation and maintenance system, constructs an intelligent service platform, and realizes the digital supervision of the underground pipe network infrastructure[12].

The layer implements reliable transmission of data between the perception layer and the application layer, while ensuring the security and integrity of the data. By reasonably selecting and configuring communication networks, protocols, and security mechanisms, the underground pipeline network intelligent operation and maintenance system can efficiently collect, transmit, and process pipeline data, providing a reliable data foundation for the operation and management of the system.

Management control

The intelligent control layer builds a monitoring platform to provide diverse and visual monitoring platforms for different user departments, ensuring the effectiveness and efficiency of information acquisition for user departments. The system achieves monitoring and control functions of pipeline network through network connection and remote technology. Through this method, users can remotely access and manage the pipeline system via the internet or dedicated network anytime and anywhere. They can perform various operations and controls on the underground pipeline intelligent operation and maintenance system through the remote control interface, monitor the running status of the pipeline system in real-time, remotely control equipment, diagnose faults, support decision-making, and promote the safe and efficient operation of the pipeline system.

When the data is transmitted to the monitoring platform, it first goes through the server for time synchronization and source verification, promptly determining whether the data has been marked. Then, the collected data is numbered in chronological order, allocated to address units, and stored in pre-defined database units. If it is recognized that the collected data has been marked, inform the host. When the host receives the information, quickly retrieve similar front-end controller information from the database. The host integrates, analyzes, and processes it to determine the authenticity of the leak. If there is a leak, the host will send an alarm signal and retrieve the alarm site, front-end controller information, and number from the server based on the arranged address. It will then analyze and handle the location, accurately locate the leak point, and finally send a command to the host, requesting the interface to display the “number”, “leak fault”, and “coordinate point” of the alarm site and front-end controller. In the meantime, it will mark the alarm, fault, and other details in the database. If there is no leakage, the host requires the interface to display “time”, “everything is normal”, “no coordinates” in real time, and at the same time, update and display the data of the detection point such as flow rate, pressure, and liquid temperature in real time[13].

SIMULATION EXPERIMENT OF IOT-BASED UNDERGROUND PIPELINE INTELLIGENT OPERATION AND MAINTENANCE SYSTEM

Online Monitoring and Treatment of Pipeline Network

The IoT-based underground pipeline intelligent operation and maintenance system can continuously collect real-time flow and pressure data of the water supply pipeline system, and timely detect anomalies in the pipeline system[14]. After the system is built, the system is tested. For detailed simulation experiments of the system, please refer to Figure 4 and Figure 5.

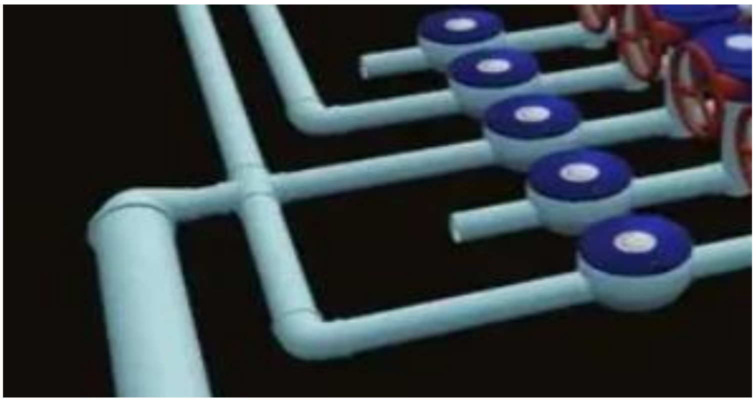

Figure 4. 3D model of the underground pipeline network

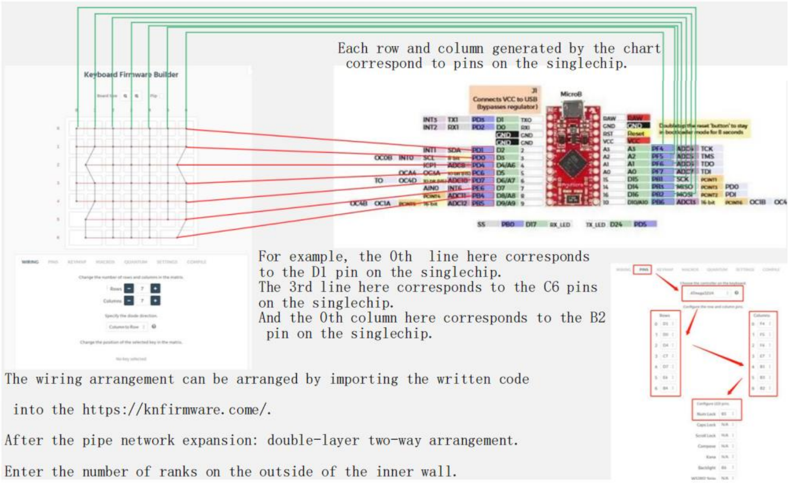

Figure 5. Specific principle system

The system uses weak electrical physical electronic components to detect water leakage points. It uses the triggering principle of MCU and keyboard to lay a weak electrical network with double-layered double-crossed sponge on the outside of the water pipe, and adopts a matrix point-triggering scheme similar to a keyboard. The leakage position will wet the sponge and conduct the upper and lower crossed electrical network to trigger the MCU (microcontroller) pin to generate an electrical signal. Using the principle of the microcontroller matrix keyboard, the row and column wires are connected to the two ends of the microcontroller pin. The row wire is connected to weak electricity through a pull-up resistor. When there is no water leakage, the row wire is in a high-level state and is not connected. See Figure 6 for details. When there is a water leak, the double-layered and bi-directional electric wires distributed between the inner and outer walls of the pipe generate an electrical signal by connecting up and down through the sponge wetted by the leaking point. The wireless transmission module on the microcontroller will transmit the leaking point information to the wireless data acquisition terminal, thereby determining the specific section and specific location of the leaking point on the outer side of the water pipe wall[15]. See Figure 7 for details.

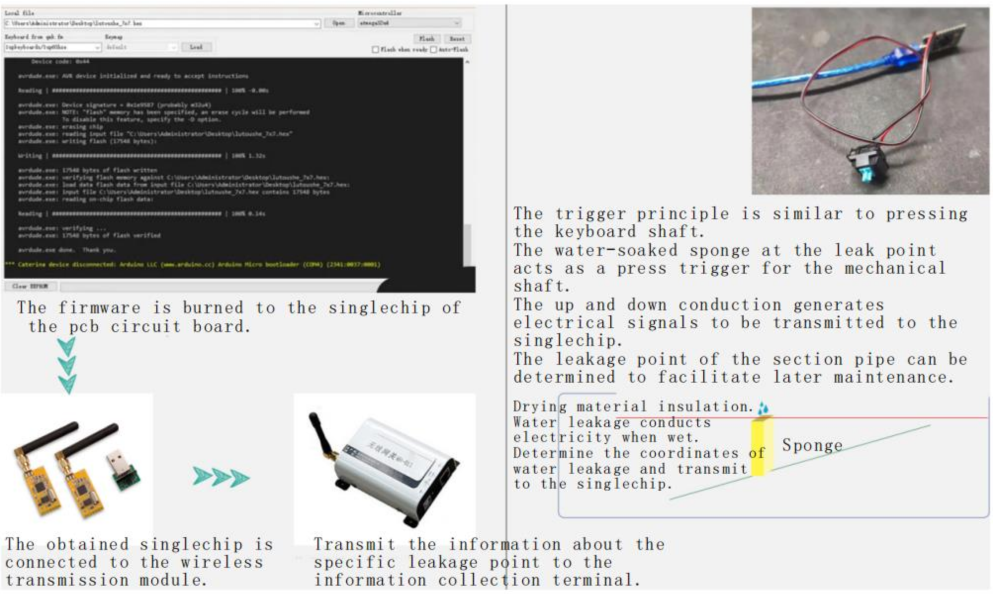

Figure 6. Physical electronic component microcontroller system

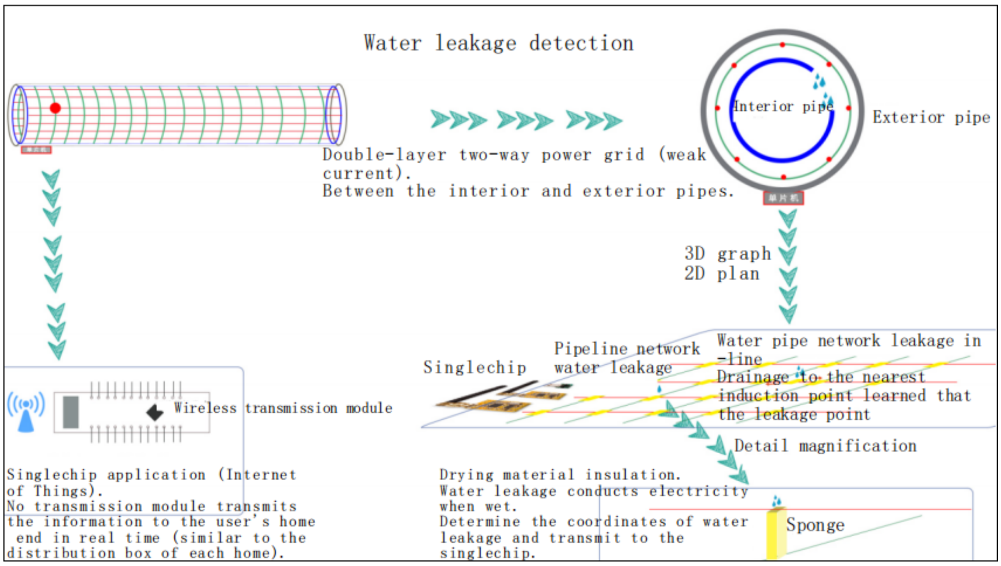

Figure 7. Microcontroller leak detection system

Accurate Positioning and Wireless Data Collection

Wireless data communication transmits the collected data using 4G wireless transmission method through the Comtech TG462 Industrial IoT Gateway. After the microcontroller wireless transmission module is transmitted to the Internet of Things gateway (wireless data acquisition terminal), the gateway uses GPRS wireless transmission to transmit the data to the cloud through the Internet. The cloud analyzes the data and automatically closes the single household water gate, saving a lot of manpower and material resources, achieving convenient and accurate positioning and easy maintenance[16]. See Figure 8 for details.

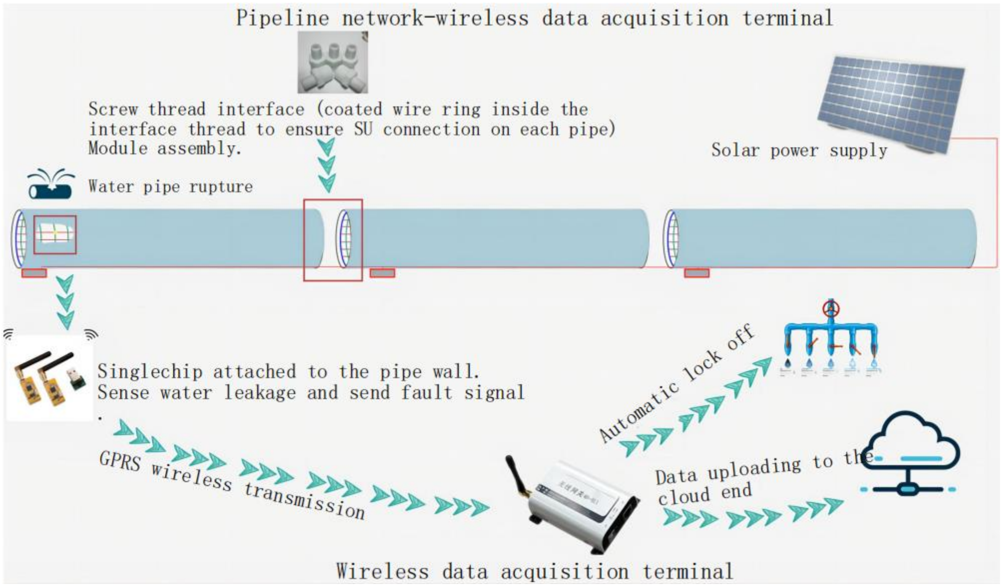

Figure 8. Wireless data acquisition system

Closed-loop System to Achieve Data Sharing

In a closed-loop system, the various modules and components of the underground pipeline network intelligent operation and maintenance system are closely linked and have a data exchange mechanism. Data is collected from different sources (such as sensors, monitoring devices, management systems, etc.) into the intelligent pipe network system, and after processing and analysis, it is passed on to other modules and components for further processing and application. Data is shared in real time between different modules, allowing users to obtain the current pipeline network status and situation, which helps to promptly identify problems and make decisions and take measures quickly.

The closed-loop system integrates and analyzes data from different sources and types, providing comprehensive pipeline information for users to fully understand the operation and management of the pipeline network, in order to better formulate strategies and plans. Data sharing and seamless transmission, more efficient collaboration between modules and components, data collected by sensors can be directly transmitted to monitoring and analysis modules, reducing duplicate input and conversion of data, improving work efficiency. In addition, the closed-loop system can ensure the consistency and accuracy of the data. The data only needs to be transmitted within the system without multiple manual inputs and processing, which improves the credibility and availability of the data.

The closed-loop system migrates the offline mode of “discovering water leakage - closing the water valve - contacting the maintenance personnel by phone - the maintenance personnel coming to the door to inspect the water leakage point - replacing or repairing the water leakage pipe” to the online monitoring platform, namely “homeowner - maintenance party - smart pipe network - wireless data collection terminal”, achieving data sharing.

Analysis of Experimental Data for IoT-based Underground Pipeline Intelligent Operation and Maintenance System

After conducting simulation experiments on the system, all functions can be basically realized. It can not only perform comprehensive analysis on data from multiple monitoring indicators, but also collect and transmit data through high-precision sensors and acquisition devices, thereby improving the system's availability and scalability, and achieving a level of intelligence.

Accurate Monitoring of the Location of Leaks

The underground pipeline intelligent operation and maintenance system can accurately locate the specific location of leakage by comprehensively analyzing the data of multiple monitoring indicators. By comparing data such as pressure changes, abnormal flow rates, and sound characteristics, the system can calculate the approximate range of the leakage location, which helps to quickly locate the problem and timely and accurately report the data of the leakage point location, ensuring no loss of operational data, and the operational information can be processed and traced[17].

Real-time tracking and monitoring

The underground pipeline intelligent operation and maintenance system collects and transmits data through high-precision sensors and collection devices[18]. Once a leakage is detected, the system will promptly issue an alarm signal, notify relevant personnel, and achieve quick response and handling. After registering and logging into the app on their mobile phone or other smart devices, homeowners can visually inspect their own water pipes in three dimensions, and can also view the real-time location of leaks and the progress of pipe maintenance[19].

Strong system scalability

The system adopts the world's most advanced GPRS data network technology and mature and stable intelligent terminals, using unique data processing and control technology. Smart grid systems typically have multi-platform support, allowing them to run and be accessed on different devices such as personal computers, smartphones, and tablets. Users can access the system anytime and anywhere and use its features, which improves the system's availability and scalability[20].

Comparative Analysis of Performance between Traditional Underground Pipeline Network Leakage Monitoring System and IoT-based Underground Pipeline Network Intelligent Operation and Maintenance System (see Table 1)

Analyzing from a macro perspective

Table 1. Comparative analysis of performance between traditional underground pipeline network leakage system and underground pipeline network intelligent operation and maintenance system

Characteristics	Traditional Underground Pipeline Network Leakage System	IoT-based Underground Pipeline Network Intelligent Operation and Maintenance System
Feasible method	√	√
Accurately detect the leakage position	×	√
Data transmission in time	×	√
Real-time tracking monitor	×	√
Strong system function expansion	×	√

Through macro analysis, it is known that the underground pipeline intelligent operation and maintenance system based on the Internet of Things has the characteristics of accurate monitoring of leakage positions, data transmission, real-time tracking and monitoring, and strong system scalability compared to traditional monitoring methods, therefore, the system is feasible.

Analyzing from a micro perspective

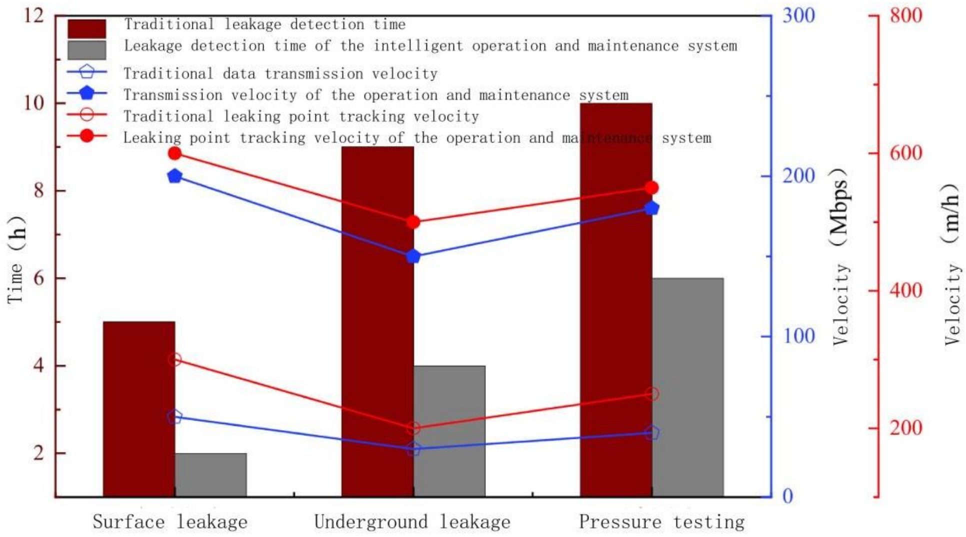

Figure 9. Performance comparison analysis chart

Through microanalysis, it is known that the IoT-based underground pipeline intelligent operation and maintenance system has shorter leak detection time, more timely data transmission, and faster leak tracking speed compared to traditional underground pipeline monitoring methods. Based on these characteristics, the IoT-based underground pipeline operation and maintenance system is more suitable as the core of future underground pipelines. See Figure 9 for details.

CONCLUSION

In the study, the management efficiency, reliability, and sustainability of underground pipeline operation and maintenance is improved by building an IoT-based underground pipeline network intelligent operation and maintenance system. Through comprehensive research on the design, functions, and applications of the system, the network status is monitored in real-time, potential problems are detected in advance, and corresponding measures are taken to effectively reduce network failures. The system can not only quickly identify pipeline anomalies, but also provide strong support for pipeline operation and maintenance decision-making, which provides management personnel with more comprehensive, timely, and accurate information, and helps optimize the decision-making process. The system has significant economic benefits in terms of cost reduction, extending the service life of the pipeline network, and improving resource utilization efficiency, thus improving the public safety emergency capability of the urban underground pipeline network and promoting the healthy and safe development of the city. Finally, with the continuous development of Internet of Things technology, in subsequent research, the intelligence and adaptability of the system will be improved to meet the new requirements of future pipeline network operation and maintenance.

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