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DESIGN OF WATER PIPELINE MONITORING SYSTEM BASED ON MULTI-SOURCE INFORMATION FUSION

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Abstract: Water pipelines are generally buried in the ground, as a typical underground hidden engineering, their structural damages such as pipe burst, leakage, seepage and uneven settlement are characterized by strong concealment and long disaster-causing chain, which not only cause a large amount of waste of water resources, but also lead to safety accidents such as pavement collapse, which seriously threaten public safety. This study aims to propose a multi-dimensional monitoring system that integrates distributed fiber optic sensing and IoT technologies. Through in-depth analysis of the formation principle of pipe burst, leakage, seepage, uneven settlement and other problems, we utilize the deployment of Φ-OTDR fiber optic arrays (spatial resolution of 0.5m) to integrate high-precision pressure transmitters (accuracy ±0.1%FS) and electromagnetic flow meters (accuracy ±0.5%) to construct a multi-physical field synchronous sensing network, and to achieve the monitoring of pipeline pressure transient (sampling rate ≥100Hz), flow rate (sampling rate ≥100Hz), flow rate abnormality (detection sensitivity ≤0.1L/s), temperature gradient (resolution 0.1℃), negative pressure wave, stress and strain distribution (με level) holographic monitoring, and early warning and precise positioning. Engineering validation shows that this system helps to detect pipeline problems in time, reduce accident losses, guarantee the reliable operation of water pipelines, provide strong support for the stability and safety of the water transmission system, and provide key technical support for the construction of a resilient urban water transmission system.
Keywords: Pipeline health monitoring; Water pipeline; Sensor; Multi-physical field coupling

1 INTRODUCTION

As the core component of modern municipal infrastructure, urban water pipeline is the key link to ensure the stable supply of water for residential life and industrial production, and its safe operation is directly related to the protection of people's livelihood and economic development. However, affected by multiple factors such as geological environment variability, material aging, and third-party construction disturbance, pipeline systems frequently suffer from structural failure accidents such as pipe bursts, leaks, and uneven settlement, which bring huge losses to society and the economy, for example, in 2017, the continuous bursting of the DN1600 water supply main pipe in the west line of the city of Linyi led to two large-scale water shutdowns in the main urban area, and the direct economic loss amounted to 3,552,800 yuan.7 Such accidents not only cause waste of water and direct economic losses, but also lead to a loss of water resources and a decrease in water consumption and water supply costs. Such accidents not only cause water waste and direct economic losses, but also may trigger chain reactions in the industrial chain - the indirect economic losses incurred by industrial enterprises due to the interruption of water supply leading to production stagnation can be up to 3-5 times of the direct losses.

The current monitoring technology is facing a double challenge: on the one hand, the traditional point sensors (such as pressure/flowmeter) have low spatial resolution, weak anti-interference ability and other shortcomings, it is difficult to realize the long-distance buried pipeline monitoring of the whole area coverage; on the other hand, a single-parameter monitoring system is unable to effectively characterize the multi-physical coupling of the pipeline damage mechanism. In recent years, academics have made breakthroughs through technology integration: distributed fiber optic sensing technology (BOTDR/OFDR) can realize strain-temperature-vibration multi-parameter simultaneous sensing[1-2], with a spatial resolution of meters, and detection sensitivity exceeding that of traditional sensors by two orders of magnitude; flexible piezoelectric vibration sensing network can accurately identify leakage aperture and positioning error <0.5m through acoustic signal feature extraction; smart ball (SmartBall) can accurately identify leakage aperture and positioning error <0.5m; and smart ball (SmartBall) can be used to detect the damage of the pipeline. The detection rate of small leakage (<1L/min) is increased to 92% by combining machine learning algorithms with mobile detection devices such as SmartBall.

Based on the above background and the shortcomings of previous studies, this study aims to design a comprehensive, efficient and accurate design for pipe burst/leakage monitoring, third-party disturbance/leakage monitoring, and settlement/stress monitoring of water pipelines. The design will comprehensively consider a variety of factors affecting pipeline safety, optimize the sensor selection and installation layout, and improve the monitoring accuracy and early warning capability for various failure states of pipelines. Through this study, it is expected to provide a more reliable guarantee for the safe operation of pipelines, reduce the economic losses and social impacts caused by pipeline accidents, and promote the further development of pipeline monitoring technology.

2 OMNI-DIRECTIONAL MONITORING SYSTEM ARCHITECTURE

The purpose of this paper is to use distributed fiber optic sensing technology, combined with conventional manometers and flow meters to monitor the pipeline in real time, mainly to achieve three aspects of the function: burst/leakage monitoring, third-party disturbance/leakage monitoring, and settlement/stress monitoring. The omni-directional monitoring system of water pipeline status adopts a layered data communication network architecture, which is divided into field equipment layer, control layer and information management layer.

Measurement data is collected by various sensors in the field equipment layer, then transmitted to the data acquisition instruments in the control layer via fiber optic data network to obtain multiple types of monitoring quantities, and finally transmitted remotely from the control layer to the information management layer via data transmission equipment. The data transmission equipment is compatible with many types of fiber optic and electrical acquisition instruments, and the remote transmission of massive monitoring data is realized by means of Internet/wireless Internet. Pressure sensors and flow sensors adopt 485 bus instruments. The structural schematic diagram of the omni-directional monitoring system of water pipeline status is shown in Figure 1. The selection and arrangement of sensors for all-round monitoring of water pipeline status are shown in Table 1.

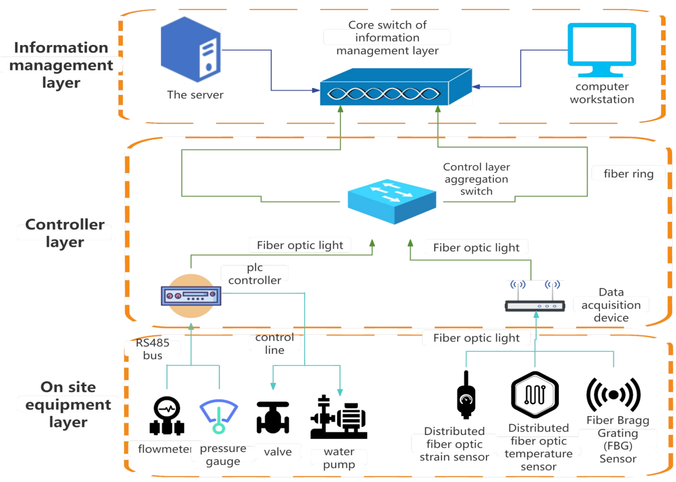

Figure 1 Structural Schematic Diagram of an All-Round Monitoring System for the Condition of Water Pipelines

Table 1 Omni-Directional Monitoring of the Condition of Water Pipelines Sensor Selection and Arrangement Methods

Monitoring content	transducers	Sensor arrangement	Data acquisition instruments (control level equipment)
Pipe burst/ leakage monitoring	Fiber Optic Grating FBG Sensors	Laying inside the bottom of the pipe along the axis of the pipe	Distributed Fiber Optic Collector
	Manometers and flow meters	Water main and branch pipelines at various intersections	PLC controller
Third-party disturbance/leakage monitoring	Distributed Fiber Optic Temperature Sensors	Parallel to the bottom of the pipe in the direction of the pipe axis	Distributed Fiber Optic Temperature Collector
Settlement/stress monitoring	Distributed Fiber Optic Strain Sensors	Three distributed fiber optic strain sensors placed in parallel along the axis of the pipeline	Distributed Fiber Optic Strain Gauge

2.1 Information Management System Architecture and Functions

In the all-round monitoring system of water pipeline status, the information management layer contains core switches, servers, workstations and other equipment. Deploying industrial-grade Layer 3 ring switch (H3C S6850-56HF, backplane bandwidth 5.76Tbps) to build the backbone network, and realizing the fusion of heterogeneous data from multiple sources through Kafka stream processing platform. The information management layer plays a crucial role, and it has multiple functions:

(1) Data collection and integration function: the information management layer collects data from each control layer data collection instrument of the water pipeline, and the data format produced by different data collection instruments may vary, and the information management layer standardizes and stores the collected data. This enables subsequent data processing and analysis to be carried out on a standardized basis and improves data availability.

(2) Data storage and management function: Considering the continuity and mass of water pipeline monitoring data, the information management system adopts appropriate data storage technology.

(3) Information sharing and visualization function: The information management system provides the processed

monitoring information to different departments, such as pipeline maintenance department, water supply dispatching department and emergency management department. At the same time, it makes complex data easier to understand and use through charts, maps and three-dimensional models, etc., and visualizes the pipeline's operation status, fault location and historical data trends. It allows managers to quickly grasp the key information of pipelines and make accurate decisions.

2.2 Control Layer Architecture and Functions

In the omni-directional monitoring system of water pipeline status, the control layer contains convergence switches, programmable logic controllers (PLCs), fiber optic data collectors, communication equipment and other equipment. These devices are uniformly installed in the field control cabinet and distributed in various key positions of the water pipeline. The control layer plays the key role of the top and bottom, which is the key link to realize the safe and stable operation of the pipeline. The core functions of the control layer include:
(1) Multi-source data fusion: through the IEEE 1588 accurate clock synchronization (error <1μs), integrating PLC process parameters (pressure, flow), fiber optic strain data (100Hz sampling), vibration spectrum (0-20kHz) and other multi-dimensional information, to build a spatio-temporally aligned data cube.
(2) Intelligent decision-making control: Model predictive control (MPC) algorithm is adopted to optimize the regulation strategy in real time based on the pipeline hydraulics model.
(3) Pressure closed-loop control: drive the motorized control valve (Fisher DVC6200) through the PID algorithm to maintain the pressure fluctuation <±0.05MPa
Equipment deployment follows the IEC 61499 standard, the control cabinet to meet the IP54 protection level, environmental adaptability indicators: operating temperature -40 ℃ ~ +70 ℃, humidity 0-95% RH. Through the TSN time-sensitive network (IEEE 802.1Qbv) to ensure that the control command transmission delay <2ms, jitter <50μs. programmable logic controller (PLC) as shown in Figure 2, the The distributed fiber-optic temperature data collector is shown in Figure 3, and the aqueduct control cabinet architecture is shown in Figure 4.

Figure 2 Programmable Logic Controller (PLC)

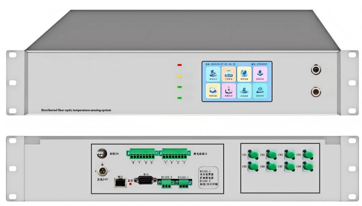

Figure 3 Distributed Fiber Optic Temperature Data Collector

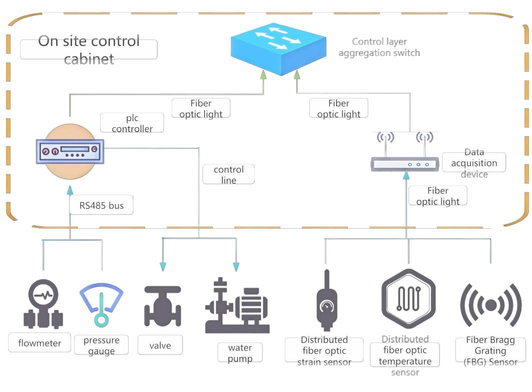

Figure 4 Aqueduct Control Cabinet Architecture Diagram

2.3 Field Device Layer Architecture and Functionality

In the omni-directional monitoring system for the condition of the water pipeline, the field equipment layer equipment contains various types of sensors such as flow sensors, pressure sensors, high-sensitivity fiber grating FBG sensors, distributed fiber optic temperature sensors, distributed fiber optic strain sensors, and so on. These sensors are distributed in key locations of the water pipeline to form a sensor network. The field device layer is the foundation of the entire system and plays an indispensable and critical role. The pressure transmitter is shown in Figure 5, the electromagnetic flow meter is shown in Figure 6, the distributed fiber optic strain sensor is shown in Figure 7, the distributed fiber optic temperature sensor is shown in Figure 8, and the fiber grating FBG sensor is shown in Figure 9.

Figure 5 Pressure Transmitter

Figure 6 Electromagnetic Flow Meter

Figure 7 Distributed Fiber Optic Strain Sensors

Figure 8 Distributed Fiber Optic Temperature Sensors

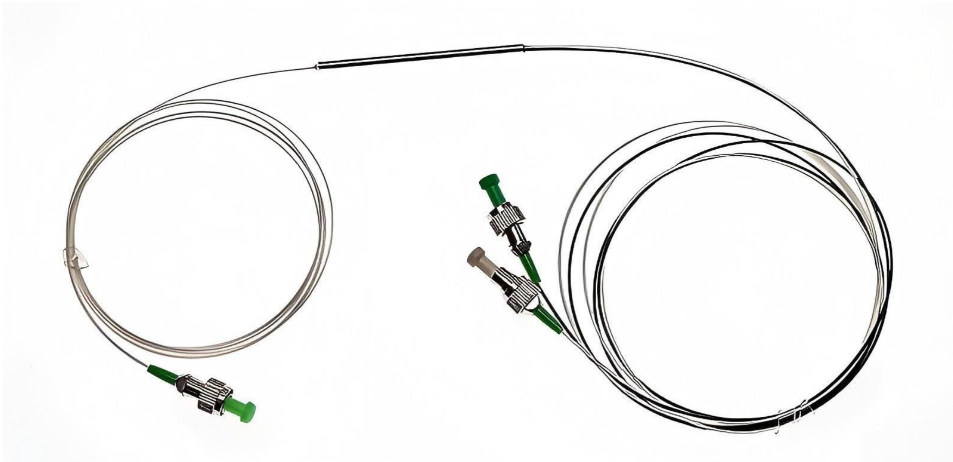

Figure 9 Fiber Optic Grating FBG Sensors

3 EQUIPMENT SELECTION AND INSTALLATION

3.1 PLC Selection and Hardware Configuration

Based on the control requirements of the water transmission system and the scale of the project, this study adopts Siemens S7-1200 series PLC as the core controller. This series PLC has complete input and output interfaces, efficient data processing capability and reliable communication function, which can meet the technical requirements of the system in data acquisition, control operation and remote communication.
The core configuration of PLC includes CPU module, power supply module, digital input/output module (DI/DO) and analog input/output module (AI/AO). Among them, the CPU module selects S7-1214C, which integrates 6 digital input points and 2 digital output points, which is sufficient to meet the basic switching signal acquisition and control requirements. For the acquisition of flow, pressure and other analog signals, the configuration of a dedicated analog input module SM1231, the module can receive 0-10V or 4-20mA standard industrial signals, and convert them into digital for PLC data processing.PLC programmable controller I / O point allocation is shown in Table 2.

Table 2 PLC Programmable Controller I/O Points Table

Equipment/Instrument Name	Name of measurement point	Signal form			
		DI	DO	AI	AO
Electromagnetic flow meter				1	
Pressure Transmitter				1	
Motorized valves	Auto/Manual position	1			
	Valve open states	1			
	Valve closed status	1			
	fault state	1			
	Open Valve Command		1		
	Shutdown command		1		
add up the total		4	2	2	

3.2 Pipe Burst/Leakage Monitoring Design and Equipment Installation

When a pipe burst or leak occurs, the stress waves (including negative pressure waves and acoustic waves) propagating in the fluid medium inside the pipe can be effectively detected by high-sensitivity fiber Bragg grating (FBG) sensors. Through the cooperative pressure and flow multi-parameter monitoring means, the system can realize real-time monitoring and diagnosis of leakage events, and achieve sub-kilometer high-precision positioning.FBG as a wavelength-selective reflective grating, its detection system through the laying of special fiber optic cables inside the pipeline[3-4], the use of grating sensors to collect the pipeline axial stress distribution signals, and based on the stress anomalies to achieve leakage detection.
The research team carried out distributed FBG leakage detection simulation experiments, the results show that the grating reflection wavelength offset can be effectively used as a leakage criterion, combined with optical time-domain reflectance (OTDR) addressing technology can be realized leakage spatial localization, the localization error is controlled within the range of ± 0.5% of the length of the pipe section. The sensor is fixed on the inner wall of the pipeline by embedded installation, and the signal is led out to the outside of the pipeline by armored guide cable, and finally the monitoring data is transmitted to the data acquisition instrument in the field control cabinet through industrial bus. The system adopts IP65 protection level chassis, which meets GB3836 explosion-proof requirements and ensures reliable operation in hazardous environments such as oil and gas pipelines. The fiber grating sensor arrangement

structure is shown in Figure 10, and its sectional installation schematic is shown in Figure 11, demonstrating the integration scheme of the grating array with the pipeline structure.

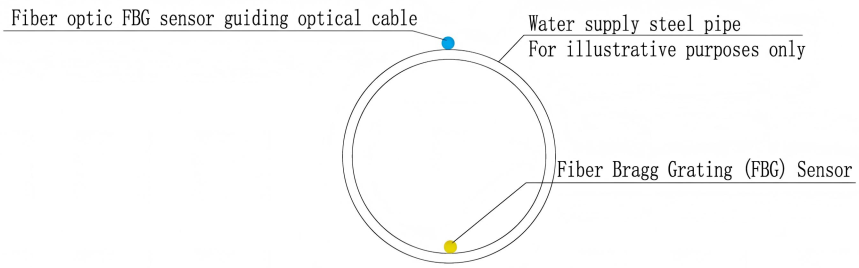

Figure 10 Fiber Optic Grating FBG Sensor Layout

3.3 Third-Party Disturbance/Leakage Monitoring Design and Equipment Installation

Third-party construction activities and working conditions such as pipeline leakage will lead to abnormal changes in the temperature field distribution along the pipeline. Based on the thermodynamic temperature tracing principle, when a leak occurs, the leaking medium will form a localized temperature gradient along the direction of gravity due to the liquid gravity effect[5-6]. By monitoring the heat transfer effect between the leaking liquid and the surrounding soil, the third-party disturbance/leakage monitoring problem can be transformed into a real-time monitoring problem of the temperature field along the pipeline.

Distributed fiber-optic temperature sensing network (DTS) is laid along the bottom axis of the pipeline in the direction of the design spacing to achieve quantitative assessment of the degree of leakage through continuous monitoring of the dynamic characteristics of the temperature field around the pipeline. In order to meet the site construction requirements and long-term service reliability, the sensor adopts a double-layer stainless steel armored structure (in line with GB/T7424.2-2008 standard), in order to provide mechanical protection, at the same time, through the pre-set stress relaxation margin to ensure that the optical fiber is only on the thermal excitation response to avoid the mechanical strain interference[7-8]. Distributed fiber-optic temperature sensor typical arrangement scheme shown in Figure 12, its spatial resolution of up to 1m, temperature measurement accuracy of ± 0.5 ℃.

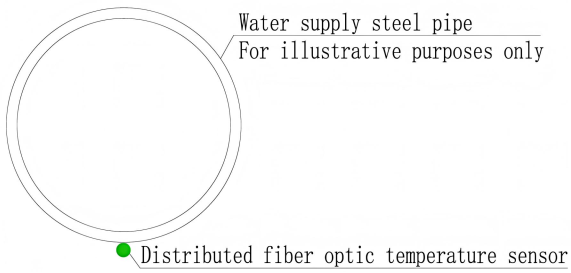

Figure 11 Distributed Fiber Optic Temperature Sensor Layout

3.4 Settlement/Stress Monitoring Design and Equipment Installation

Subject to the uneven settlement of soil and environmental loads, the pipeline structure will produce complex stress redistribution. In order to monitor the characteristics of the soil displacement field distribution around the pipeline, the optimized structural design of strand-encapsulated distributed fiber-optic strain sensor is used in this study. The sensor enhances the mechanical protection through multi-strand galvanized steel strand (in accordance with GB/T5224-2014 standard), which improves the fiber shear strength to ≥200MPa and ensures the long-term stability under complex geological conditions.

The monitoring system is symmetrically laid with 3 distributed fiber optic sensing arrays along the pipeline axis at an angle of ±120°, constituting an axial continuous monitoring section, which can synchronously obtain multi-dimensional mechanical parameters such as pipeline bending strain (range ±1500 με), axial compression strain (precision ±0.1% F.S.), and neutral plane position strain (spatial resolution of 1m), etc. The sensing cables are connected to the outer wall of the pipeline, and are connected to the outer wall of the pipeline with the fiber optic cable[9-10]. The sensing fiber optic cable is cured and connected with the outer wall of the pipeline by epoxy resin adhesive (elastic modulus of 2.5GPa), and the external HDPE armored protective layer (thickness ≥ 2mm) is overlaid to form a monitoring system with strain transfer efficiency of 96%. The system realizes the dynamic monitoring of 10Hz sampling frequency through BOTDA technology, and the data is transmitted to the cloud platform for real-time analysis and early warning through 4G wireless transmission. The typical layout of distributed fiber optic strain sensors is shown in Figure 13, with a strain sensitivity of 1με and a temperature compensation accuracy of ±0.5℃.

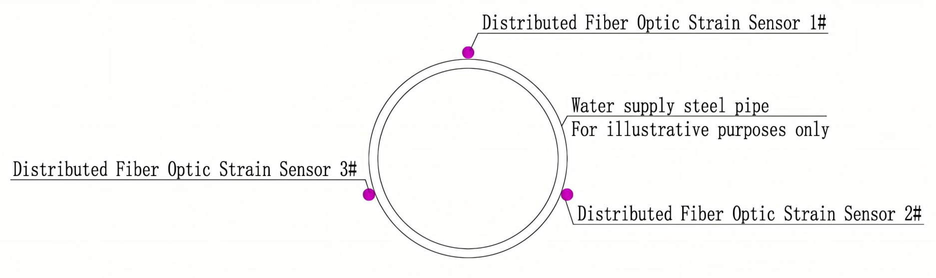

Figure 11 Distributed Fiber Optic Strain Sensor Layout

4 CONCLUSION

In this study, a multi-parameter fusion water pipeline safety monitoring system was developed to realize all-round monitoring of pipe burst/leakage, third-party disturbance/leakage and structural stress/settlement. In terms of sensing network design, the system integrates a multi-physical field sensing array consisting of flow meters (accuracy ±0.5%), pressure sensors (range 0-1.6MPa), distributed fiber optic sensors, etc., and constructs a fault diagnosis model based on multi-parameter coupling analysis. The data acquisition network adopts industrial-grade Modbus RTU protocol, and ensures the reliability of data transmission (packet loss rate <0.1%) through the hybrid networking method of 4G wireless communication (transmission interval ≤5s) and fiber optic communication (bandwidth ≥100Mbps).

Compared with the existing monitoring system, the innovation of this system is reflected in the completeness of the monitoring dimension, and the existing system is mostly limited to the monitoring of a single failure mode with obvious differences and advantages. The system through the integration of pressure (sampling rate of 10Hz), flow (accuracy of 0.5 level), temperature (resolution of 0.1 ℃), acoustic (frequency response of 20-20kHz) and strain (sensitivity of 1 με) and other multi-dimensional information, so that the burst pipe positioning accuracy is increased to ± 50m (conventional methods ± 200m), the false alarm rate is reduced to <0.5 times / month. Compared with the conventional inspection method (cycle ≥ 7 days), this system realizes real-time monitoring response at the minute level, which shortens the fault discovery time by more than 85%.

Statistics show that water loss due to pipe burst and leakage accounts for about 3-5% of the total urban water supply. The application of this system can reduce the leakage rate by more than 40%, and reduce the economic loss of about 1.2 million yuan/km per year (calculated according to the industrial water price). Through preventive maintenance, the system improves the reliability of water supply to 99.9%, which effectively guarantees the safety of urban water supply and the continuity of industrial production, and has significant social and economic benefits.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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