Research on Smart Pipeline Network Architecture Based on Pipeline Lifecycle Integrity Management

Xixiang Zhang, Yufeng Yang, Shaohui Jia, Qiang Zhang, and Ranran Wei

Abstract With the increasing maturity of information technology, the research of oil and gas pipelines in smart pipeline networks is becoming more and more mature. At the same time, the construction of an smart pipeline network is also an important part of China's smart energy construction. The establishment of smart pipeline network systems, the use of big data analysis, cloud computing, and other advanced technologies do a good job in data mining, mobile application, comprehensive decision-making, emergency disaster prevention and other support work, which promotes the integration of pipeline management and intelligence, serving as an effective means and inevitable choice to improve the level of oil and gas pipeline management and promote the development of the industry. This paper analyzes the practical needs of China's smart pipeline network, puts forward a smart pipeline network architecture guided by the pipeline lifecycle integrity management, and discusses some problems of China's smart pipeline network.

Keywords Pipeline · Integrity · Life cycle · Smart pipeline network · Big data · Artificial intelligence

1 Introduction

Since 2016, China successively issued documents such as *Guiding Opinions on Promoting the Development of 'Internet + Smart Energy,'* etc., proposing the direction of 'Internet + smartization' for future energy exploration. Under this context, the construction of smart oil and gas pipelines began to flourish. Actually, the Sino-Russian Eastern Route (Heihe-Changling Section) constructed by PipeChina is China's first large-scale smart pipeline, in which smart pipeline technologies were adopted for the first time, linking it to the Internet technology and making a pioneering attempt [1–3].

X. Zhang (✉) · Y. Yang · S. Jia · Q. Zhang · R. Wei
North Petro China Pipeline R&D Center Affiliated to National Pipeline Network Group, National Engineering Laboratory for Pipeline Safety, Langfang 065000, Hebei, China
e-mail: zhangxx11@pipechina.com.cn

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2 Background and Actual Needs

2.1 Development Background of Smart Pipeline Network

In January 1998, the then-Vice President of the United States Albert Gore put forward the concept of 'digital earth' in a speech [8], applying digital technology to reproduce the earth and other fields. As time went by, the application of digital technology has gradually expanded from earth science to the areas of electricity, communications, medical care, transportation and energy. In August 2009, IBM released a report entitled *Smart Earth Prevails in China* [4–7], in which such concepts as Smart Power, Smart Medical, Smart City, Smart Transportation, Smart Supply Chain, and Smart Banks were proposed, making the perception more comprehensive, interconnection smoother, and smart thinking more thorough. In 2015, the Columbia Pipeline Company of the United States applied the smart pipeline solution [9, 10], making it have comprehensive pipeline management functions by integrating pipeline-related aspects including production, operation, risk management, equipment, etc.

In April 2011, the Ministry of Industry and Information Technology of China, together with other departments, jointly issued *Opinions on Accelerating the Deep Integration of Informatization and Industrialization*, emphasizing the importance of information technology in promoting effective services, giving the direction of informatization and industrialization, namely towards intelligence, and introducing smart technologies such as cloud computing and the Internet of Things (IoT). In March 2015, 'Internet+' and other related concepts such as cloud computing, IoT, and big data, appeared in the government work report for the first time, marking that China has entered the era of smart construction. The proposal that pipeline network system should be integrated with IoT, cloud computing, and other advanced technologies were mentioned both in the 2016 *Guiding Opinions on Promoting the Development of 'Internet + Smart Energy'* (National Energy Administration of National Development and Reform Commision [2016] No. 392) and the 2017 *Medium and Long-term Oil and Gas Pipeline Network Planning*. Many scholars in China have carried out related research accordingly [11–15].

2.2 Current Status of Pipeline Integrity Management

Pipeline integrity management is one of the crucial means to ensure the safe operation of pipelines. The United States promulgated the *Natural Gas Pipeline Safety Act* in 1968 and began the work of pipeline protection through legislation. In addition, the *Pipeline Act* of the United Kingdom and the *Special Law for Public Use of Deep Underground Space* of Japan [1] all mention the importance of protecting pipeline construction and operation processes in accordance with the law.

China's State Council issued the *Oil and Natural Gas Pipeline Protection Law of the People's Republic of China* in 2010, which clarified the legal rights and obligations when oil and natural gas pipelines intersect with the establishments of other projects, providing laws for the pipeline protection work.

By referring to integrity management experiences in other countries, China formed its own integrity management process [4] by conducting many types of research and practices. In 2015, the national standard GB 32,167–2015 *Oil and Gas Pipeline System Integrity Management Specifications* was released. Later in 2019, the ISO 19345–2019 Pipeline Integrity Management Specifications was issued, marking China's pipeline integrity management has reached the world's highest level.

2.3 Actual Needs

2.3.1 Lack of Orientation Regarding How to Explore Smart Pipe Network

The current smart pipe network architecture mostly relies on IoT technology, cloud computing, big data and other algorithms to form a relatively complete management architecture. However, to what extent this kind of architecture can promote pipeline management still lacks scientific evidence. The lack of a scientific guide for the construction of a smart pipeline network is a systematic bottleneck to be dealt with by the industry urgently.

2.3.2 Insufficient Digitization Levels of China's Pipeline Industry

At present, there are many problems in the digitalization of China's pipeline industry, including difficulty in pipeline data collection, low collection efficiency with redundant data, etc. Moreover, most of the pipeline data are still recorded manually, impairing the timeliness and accuracy of data collection.

3 Smart Pipeline Network Architecture Based on Pipeline Lifecycle Integrity Management

Onshore pipeline integrity management runs through the entire lifecycle of the pipeline, including phases such as feasibility study, design, procurement, manufacturing, transportation, storage, installment, pre-commissioning and commissioning, handover, operation, maintenance, repair, and suspense/discard. The specific processes include data management, risk evaluation, monitoring, completeness evaluation, mitigation measures, and evaluation and improvement of performance and efficiency. According to the relevance of different functions, this paper divides the pipeline integrity management process into three links: the data acquisition link, the inspection and evaluation link, and the decision-making improvement link, as shown in Fig. 1.

In view of the above analysis, a smart pipe network architecture based on Pipeline lifecycle integrity management generally includes a state-sensing layer, a data-transmitting layer, a data-processing layer, and a decision-supporting layer. A 'terminal + cloud + big data' architecture is formed, which clarifies the functions and roles of each layer as shown in Fig. 2.

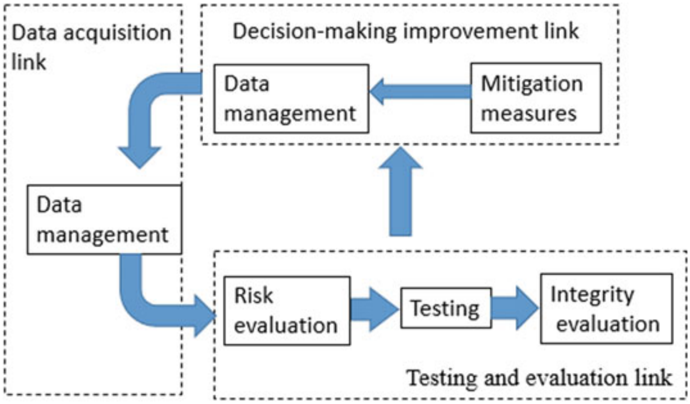

Fig. 1 Pipeline lifecycle integrity management process

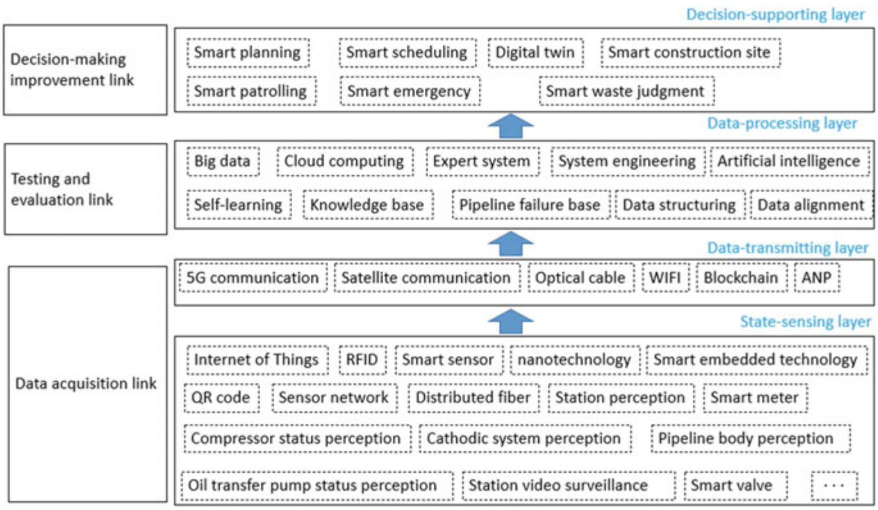

Fig. 2 Smart pipe network architecture based on pipeline lifecycle integrity management

3.1 Data Acquisition Link

The first link of pipeline lifecycle integrity management is to acquire data, which relates to the collection and transmission of pipeline-related data and involves the corresponding state-sensing layer and data transmission layer in the smart pipeline network architecture. Data management includes definition and collection of necessary data and information for pipelines and perception of data throughout the pipeline's life cycle, including phases such as feasibility study, design, procurement, manufacturing, transportation, storage, installment, pre-commissioning and commissioning, handover, operation, maintenance, repair, and suspense/discard. The state-sensing layer is to apperceive the data of the pipeline, and then the apperceived data is uploaded to the next level through the data-transmitting layer.

Data acquired for integrity management mainly comprises pipeline station data perception, pipeline body data perception, pipeline line data perception, surrounding environment data perception, and emergency data perception. At present, most of the pipeline data-collecting methods are based on 'manual collection + upload,' while some systems are based on 'automatic collection + upload,' such as pipeline system SCADA, pipeline integrity management system PIS, natural gas and pipeline system ERP, pipeline construction management system PCM and pipeline production management system PPS. Notably, the pipeline system SCADA can automatically collect some data of the pipeline, such as pressure, temperature and flow data. Besides, it can simplify the management process of the pipeline system (its valves, for example) through the remote terminal unit (RTU) and programmable logic control (PLC)). Although it has played an essential role in the pipeline industry, its functions such as smart perception and analysis need to be further strengthened.

As for station perception, the IoT technology is adopted to digitally transform pipeline station instruments to automatically sense and record the data related to conveying pressure, medium temperature, and medium flow rate, etc. Smart sensors around the compressors and pumps in the station yard are installed to monitor and record data related to temperature, noise, etc., forming a sensor network to sense their status. The valve perception is realized by installing sensors that monitor the pressure and flow rate of the medium on both sides of it to detect the jam and leakage in time automatically. Concerning the cathodic protection systems, satellite clock synchronization technology and smart sensor technology are adopted to automatically record and upload the power-off potential of equipment such as process pipelines and storage tanks in the station. Besides, laser cameras and infrared cameras are used to perform video perception on the station yard, and to record and upload real-time images. Smart inspection robots equipped with flammable gas leak detectors, temperature sensors, etc. are taken to conduct regular inspections on the station yard. Technologies such as QR code, radio frequency identification (RFID) and image recognition are adopted to grasp the real-time status of station equipment accurately, and to record and upload the corresponding data.

Pipeline body perception is realized by equipping pipeline robots with internal and external pipeline inspection devices, stress monitoring devices, and vibration monitoring devices through nanotechnology to record the body information, such as weld defects, sheet defects, pits, fatigue, etc. Meanwhile, perations such as pipeline internal and external inspection are carried out based on the risk assessment results. In the stages of pipeline procurement, manufacturing, transportation and storage, QR code, radio frequency identification (RFID) and other technologies are adopted to collect and record in advance the pipeline-related parameters and data. Then data management is carried out for later data traceability and simulation analysis.

Pipeline line perception is realized by installing vibration warning systems and cameras in third-party construction sites to monitor and upload the vibration conditions and video images in real time. Pipeline sites that may cause a serious adverse impact on society and the environment if leakage happens are equipped with explosive gas detection devices and video surveillance devices to detect their conditions in real time and upload data accordingly. Pipeline inspection is achieved by smartly planning the inspection route through GIS and GPS technology, recording the inspection route and time of the inspector. The inspector is equipped with GPS inspection devices to automatically report such information as the pipeline coordinates and the pipeline pile, as well as alert notification if something unusual happens, which can also be conducted by using smart inspection robots. Devices to monitor temperature, pressure, and flow sensors of the pipeline, and video instruments are installed at the pipeline crossings to record its status information that is then uploaded in real time to realize real-time perception. The smart line patrol is realized by equipping drones with temperature sensors, acousto-optic sensors, remote sensing image recognition devices, etc., to record and upload the data related to the sensors. An optical fiber pipeline safety warning system is installed along the pipeline to record and upload pipeline vibration status that is taken as the data source for automatic pipeline line perception. The cathodic protection piles along the pipeline are upgraded to smart ones in order to realize automatic measurement, remote monitoring and instant upload, as well as monitor the stray current along the pipeline.

Environmental perception is realized by installing distributed optical fiber tools for monitoring soil displacement in key areas such as geo-hazard prone sites to record and upload soil displacement data that is used together with satellite remote sensing images to record, alarm and predict geological disasters around the pipeline. Sensors to detect atmospheric humidity, temperature and pH are installed along the pipeline to monitor the atmospheric corrosivity of crossing and aerial crossing of the pipeline and exposed sections. Precipitation sensors are installed in areas prone to geological disasters such as landslides and mudslides to record and upload precipitation data and monitor the situations in those areas in real time. Meanwhile, it can also perform functions such as flood prediction based on historical data. Sensors to detect soil moisture, soil pH, etc., are installed in areas with low altitudes, where rivers cross, lakes, swamps, and wetlands to monitor the degree of soil corrosion. The environmental data on the pipeline route to be laid is sensed and recorded to provide a basis for later analysis and decision-making in the feasibility and design stages.

Pipeline emergency perception is realized by establishing a pipeline emergency resource management system to record and upload real-time data related to pipeline maintenance, emergency repair, and equipment configuration, track the distribution of staff involved in pipeline maintenance and emergency repair, and collect public emergency resources along the pipeline such as public security, medical treatment, and fire protection to have an overall perception of emergency forces along the pipeline.

Data management also involves the safe and reliable transmission of collected data, which is completed by the data-transmitting layer of the smart pipe network. The data-sensing layer records the relevant data of the pipeline and then transmits it through the data-transmitting layer by dint of different manners. Large-volume of audio, image, video, and pipeline data can be instantly transmitted and uploaded by adopting 5G technology in areas covered communication base stations. In areas not covered by communication base stations, such as sparsely populated deserts and mountainous regions, relevant data can be transmitted through mobile communication satellites. In addition, pipeline communication optical cables and WIFI where conditions permit can be used as supplementary data transmission. Technologies such as APN private networks and blockchain are used in the process of data transmission to establish encryption channels so as to encrypt data to prevent it from being invaded securely.

3.2 Testing and Evaluation

The testing and evaluation link includes three parts: risk assessment, testing, and integrity assessment. It mainly revolves around data processing and analysis based on the data obtained in the data acquisition link.

Data processing is to handle the data in a unified manner. The data collected and transmitted through the data acquisition link are various, and different data are stored in different formats. To reduce storage space and improve computing efficiency, the data is structured to form unified formats such as PIDM so as to facilitate storage and recall. Besides, although the same indicators can sometimes be obtained through different paths, there are some discrepancies in the values corresponding to those indicators. So data alignment is required, including data verification and cleaning, to ensure data continuity and integrity.

The data analysis includes risk evaluation, monitoring, integrity evaluation and various data algorithms. The risk assessment of the pipeline is carried out according to the data obtained, and the semi-quantitative risk assessment of the entire pipeline and the quantitative risk assessment of the key sections of the pipeline are carried out according to the way data is acquired and the degree of refinement. Corresponding detection methods, such as internal detection, external detection, direct evaluation and pressure test, are chosen to monitor the pipeline according to the risk assessment results of the previous step. Pipeline integrity assessment based on risk assessment results and testing results are conducted, and measures such as risk elimination, physical control, and procedural control are adopted. In the process of testing and evaluation, cloud computing is fully exploited. Based on various professional file

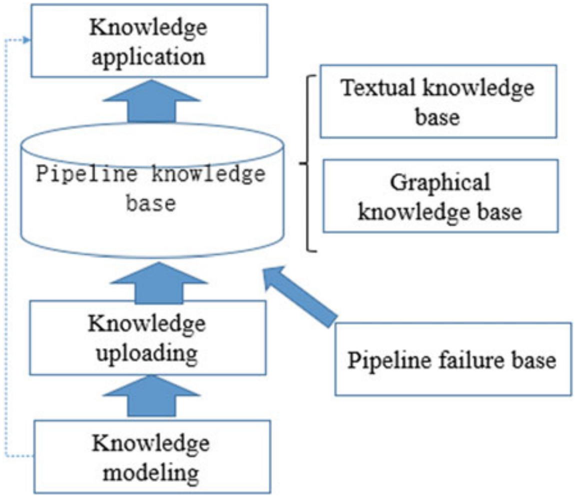

Fig. 3 Architecture of pipeline knowledge base

systems distributed on the Internet, users upload the data to be evaluated through different terminals; the system terminals on the cloud platform then perform calculation and evaluation regarding data about instrument abnormalities, valve abnormalities, station image abnormalities, internal and external detection results, image abnormalities in high-consequence areas, soil displacement, and flammable gas leakage by dint of methods such as big data, expert system, system engineering, and self-learning. At the same time, various professional knowledge is collected to form a pipeline knowledge base (as shown in Fig. 3), which includes knowledge modeling, knowledge upload, pipeline knowledge base and knowledge application. Meanwhile, the pipeline knowledge base combines with the relevant content of the pipeline failure database to form the pipeline knowledge neural network that can optimize the logical relationship between the various subjects and elements in the pipeline knowledge map. The relevant calculation and evaluation methods are continuously upgraded and optimized and the utilization and reasoning efficiency of the pipeline data are improved. Eventually, a textual knowledge base and a graph knowledge base are formed, which are then applied to improve the decision-making process.

3.3 Decision-Making Improvement Link

The decision-making improvement link includes two parts: mitigation measures, and efficiency evaluation and improvement. The results from testing and evaluation are analyzed by the advanced technologies such as cloud computing and big data in the previous step to provide pipeline operators with the best safety, efficiency, and environmental protection. The smart planning function is applied in the pipeline feasibility study phase and the design phase; the smart site function is applied in the pipeline construction phase; the smart scheduling, inspection and emergency function is applied in the pipeline operation phase; and the smart waste judging function is applied in the pipeline suspension/discard phase. The pipeline digital twin is used to virtually map the physical quantity, object, and scale of the pipeline entity. It can be applied in the pipeline lifecycle for functions such as simulation, analysis, and prediction.

4 Conclusion

4.1 Pipeline Integrity Management Helping the Realization of Smart Pipe Network

There is an excellent industrial foundation for pipeline integrity management in China. As China launched its own ISO standard for pipeline integrity management, the integrity management in China's pipeline industry has reached the international level, which marks a milestone of China's achievement in pipeline integrity in recent years. On the one hand, the existing pipeline integrity management system can provide oriented support for the smart pipe network so that it has a direction to expand and develop, making it easier to achieve safety, efficiency and environmental protection goals. On the other hand, many indicators, processes, and mechanisms in the existing pipeline integrity management system have been established, which can provide a great convenience for the smart pipeline network, while avoiding redundant construction, saving money, and reducing the workload of the grassroots staff.

4.2 Smart Pipeline not Equivalent to Smart Pipeline Network

The function of the smart pipeline is to ensure that if certain parameters of the pipeline are abnormal, such as the pressure is lower than the critical value, or the pipeline appears to be leaking, the pipeline RTU valve will be automatically closed and an alarm is issued to complete the smart pipeline operation. If the same scenario occurs in a smart pipe network, it will analyze the cause of the abnormality based on the perceived historical data, environmental data, ontology data and through the Internet, big data, artificial intelligence, cloud computing, expert system, and system engineering. It will further determine whether there is third-party construction damage, whether stress corrosion cracking on the pipeline occurs, or whether the pipeline is broken or sheared by geological disasters, and judge whether there is a false alarm. If the valve is to be closed, we should consider the operational status of the compressor and pump, and whether it is necessary to open the bypass line and increase transmission and deployment of adjacent pipe networks to complete the smart decision-making process.

4.3 Relationship Between Smart Pipeline Network and Digital Twin

The pipeline digital twin technology and the smart pipeline network are relatively independent, which means that the former does not have to be realized through the latter, and vice versa. According to PetroChina's definition of a smart pipeline network, its basic characteristics are pipeline digitization, comprehensive perception, integration and interconnection, and decision support. As long as a pipeline network has these characteristics, even if it has not adopted digital twin technology, it can be said to be a smart pipeline network.

4.4 China's Smart Pipeline Network Boasting Greater Advantages Than that in Foreign Countries

An interconnected pipeline network has been established within the EU, but it is managed separately by operating companies set up in each country. each country, and pipeline, which makes it unable to become a whole pipeline network, and therefore cannot realize smart management. In the United States, several pipeline network companies are responsible for the operation of the national network, and there are certain defects in the national system that make it impossible to operate it in a unified manner. In Russia, the work is now focused on energy development, and progress in smart pipeline networks is relatively slow. In contrast, China's advantages existing in its political system, together with the establishment of PipeChina, make it gradually form an 'X + 1 + X' management grid, and now a nationwide, interconnected pipeline network has been formed. In addition, information technology in China has achieved obvious progress in recent years, so our country's smart pipeline network will certainly accomplish great success on a global scale.

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