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AN INTERNET OF THINGS (IOT) MANHOLE COVER STATUS MONITORING SYSTEM BASED ON CH32

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Abstract: According to 2024 data from the Ministry of Housing and Urban-Rural Development, China has more than 200 million urban manhole covers. The traditional manual inspection approach suffers from delayed response, high missed-detection rates, and elevated operation and maintenance costs. The resulting damage and loss of manhole covers have caused over 2,000 traffic accidents and hundreds of billions of yuan in direct economic losses. To address these issues, this study designs an IoT manhole cover status monitoring system based on the RISC-V core CH32L103C8T6. The system adopts multi-sensor fusion technology to preprocess parameters such as manhole cover displacement and inclination, verifies data validity using GPS positioning status, enables high-speed data transmission via the ADP-L610 communication module, and realizes real-time tracking of manhole cover status through 3D visualization on the cloud platform. This system effectively resolves pain points in traditional operation and maintenance, achieves precise and real-time monitoring of manhole covers, and provides an efficient and feasible industrial-grade solution for the management of urban smart infrastructure, thereby reducing related safety accidents and economic losses.

Keywords: Intelligent manhole cover; Multi-sensor fusion; ADP-L610 communication module; 3D visualization; IoT monitoring

1 INTRODUCTION

Relevant national policies have elevated the digital transformation and intelligent management of underground pipelines to a national strategy [1]. According to statistics from the Ministry of Housing and Urban-Rural Development, China has approximately 200 million municipal manhole covers. Meanwhile, data from the Ministry of Emergency Management show that safety accidents caused by missing, damaged, or sunken manhole covers are increasing annually. Under the traditional manual inspection model, the inspection coverage rate remains below 30%, and the average fault response time exceeds four hours [2]. To address these challenges, relevant guidelines designate IoT-based intelligent monitoring technology as the core technical solution [3].

In academic research, domestic scholars have achieved considerable progress in the field of intelligent manhole cover monitoring. Wang Haiquan designed a manhole cover management system based on NB-IoT technology, leveraging its low-power characteristics to meet the long-term monitoring needs of municipal facilities [4]. Zhu Daixian's team improved the sensor circuit structure to enhance data acquisition capability and transmission reliability [5]. A research team from the School of Management, Shanghai University of Science and Technology, developed an STM32-based intelligent system that fuses multi-source data using an improved extended Kalman filter, reducing the water level measurement standard deviation to ±0.8 mm and achieving positioning accuracy to ±1.5 m, significantly lowering the false alarm rate [6]. In pilot applications, Li Yan et al. deployed an intelligent monitoring system in a power grid project in Zhejiang Province, markedly shortening the abnormal response time and greatly reducing manual inspection costs [7]. Nevertheless, existing research still suffers from limitations such as limited functionality, inconsistent equipment interfaces, and limited scalability.

In contrast, foreign research has yielded mature experience in multi-technology integration and scenario adaptation. In recent years, international research has focused on three directions: first, adaptation to flood scenarios. Kim et al. proposed a two-level, self-pressure-controlled intelligent manhole cover system to address urban flooding caused by heavy rainfall. By employing motor-driven rotating blades and a manhole cover lifting mechanism, the system alleviates flood pressure and significantly reduces internal pressure to avoid manhole cover damage [8]. Second, low-cost monitoring under complex weather conditions. Zhou et al. proposed a manhole cover detection method using a "smartphone + CNN hierarchical classification" for urban environments with alternating sunny and rainy weather. Images are roughly classified into non-rainy and rainy categories for targeted detection. This method ultimately achieves a road manhole cover detection accuracy of 86.3%, while effectively cutting down data acquisition and single-manhole detection costs [9]. Third, real-time AI-based multi-dimensional anomaly identification. Recent IEEE research uses a deep learning autoencoder model based on standard sensor data to realize real-time identification of toxic gases, sewage levels, and other parameters. The system integrates solar power supply to meet environmental protection requirements [10]. However, international solutions have obvious localization limitations: mainstream European and American equipment costs approximately $800, more than three times the cost of domestic similar equipment, making it difficult to meet the large-scale renovation needs of China's 200 million manhole covers. In addition, their communication protocols and data formats are mostly adapted to European and American urban management platforms and lack compatibility with China's smart city construction technical system.

In summary, both domestic and foreign research have verified the feasibility of intelligent manhole cover monitoring technology, but existing equipment still has two major shortcomings: first, insufficient multi-parameter integration—most devices only monitor a single parameter and struggle to cover complex risks such as displacement and sewage overflow; second, an imbalance between cost and compatibility. To tackle these problems, this paper designs an intelligent manhole cover device integrating multiple sensors, efficient communication, and cloud linkage to achieve real-time monitoring and precise early warning of multi-dimensional risks. It aims to provide a low-cost, high-reliability technical solution for the refined management of urban manhole covers and contribute to the construction of new urban infrastructure. The remainder of this paper is organized as follows. Chapter 2 introduces the overall system design. Chapter 3 presents the hardware system design, followed by the system software design in Chapter 4. Chapter 5 describes the system implementation and performance verification. Finally, Chapter 6 concludes the paper and discusses future prospects.

2 OVERALL SYSTEM DESIGN

This system adopts a three-layer architecture of perception, transmission and platform to construct an IoT closed-loop system. The perception layer, centered on the CH32L103C8T6 microcontroller unit (MCU), integrates multiple sensors to collect raw data and acquire GPS positioning information. After data fusion, the fused data are transmitted via the serial port to the transmission layer. Additionally, the perception layer supports local alarm triggering upon detecting abnormal conditions. The transmission layer, built around the ADP-L610 communication module, receives the fused data from the perception layer and uploads them to the ThingsCloud platform using the MQTT protocol, thereby enabling bidirectional serial communication between the two layers. The platform layer relies on the ThingsCloud platform to manage device access, data storage, and multi-dimensional analysis. It provides a visual dashboard to display device status, location, sensor data, and alarm logs, and also supports historical data queries. Local real-time interaction between the perception and transmission layers is realized via the serial port, while wide-area network communication between the transmission and platform layers is facilitated by the MQTT protocol. Consequently, a complete link of "local data collection — wide-area network transmission — cloud-based intelligent application" is established, offering a real-time and reliable IoT solution for the construction of new urban infrastructure. The system block diagram is shown in Figure 1.

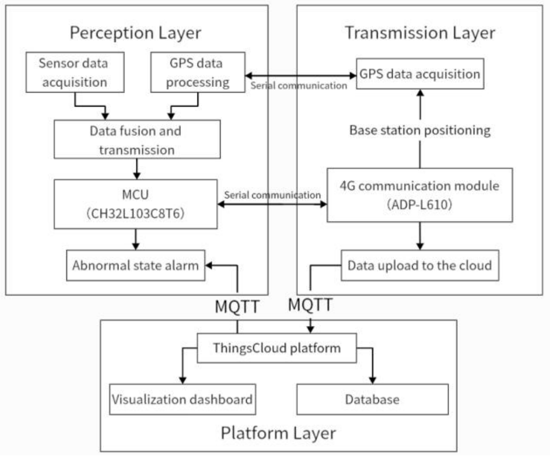

Figure 1 System Architecture Diagram

3 HARDWARE SYSTEM DESIGN

3.1 System Composition

The hardware core of this system comprises three major modules: the main control chip, the L610 communication module, and various sensor circuits. The main control chip, together with the sensor circuits, constitutes the perception layer, which is responsible for data collection, fusion analysis, and output. The L610 module serves as the transmission layer, uploading data to the IoT platform via the Cat-1 network through base stations.

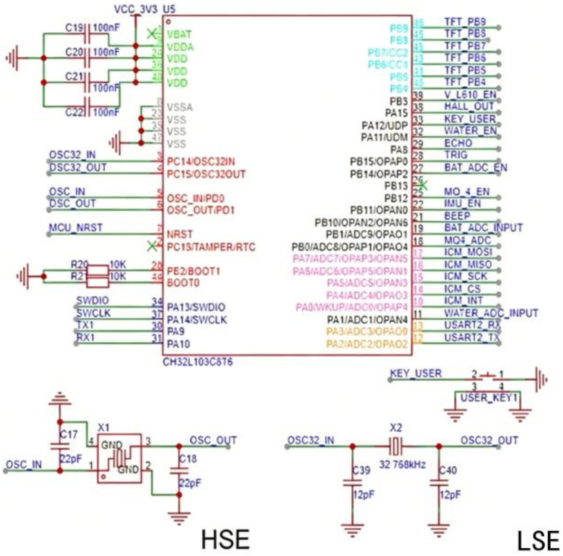

Figure 2 Schematic Diagram of the Main Control Chip

3.2 Hardware Circuit

3.2.1 Main control chip circuit design

The CH32L103 low-power chip, based on the RISC-V architecture,serves as the main control core. It operates at a maximum frequency of 96 MHz and supports USB, PD, and Type-C interfaces. The chip integrates rich peripherals, including an ADC, an OPA (operational amplifier), SPI, UART, and touch key detection, and features low power consumption, comprehensive functionality, and high cost-effectiveness. The schematic of the main control chip is shown in Figure 2, and the main pin allocation and functions are listed in Table 1.

Table 1 Main Pin Allocation and Functions

Pin	Module and Function
PA0,PA4,PA5,PA6,PA7	ICM-42688 (SPI): Collects 6-axis tilt data
PA1	Water quality sensor (ADC): Measures pH and water quality
PA2,PA3	UART 2: Serial communication with L610
PA8，PB15	Ultrasonic module: Signal transmission and reception
PA9,PA10	UART 1: Provides user-side serial debugging
PA15	Hall sensor: Monitors manhole cover open/closed status
PB0	M MQ-4 (ADC): Monitors methane concentration
PB1	Battery detection (ADC): Measures remaining power
PB4-PB9	TFT display: Hardware interface for TFT screen
PB10	Buzzer: Controls buzzer activation/deactivation

3.2.2 L610 module circuit

This design employs the ADP-L610 communication module as the core transmission unit. Its primary advantage lies in utilizing the 4G LTE Cat-1 network, which offers the broadest carrier coverage, while also supporting GSM fallback. This feature prevents disconnection in weak-signal areas and ensures adaptability to complex environments such as old urban areas and underground pipelines. Furthermore, the module integrates essential IoT protocol stacks, including TCP, HTTP, and MQTT, eliminating the need for custom protocol development and enabling direct cloud connectivity for rapid device-to-cloud data transmission.

In terms of hardware connection, UART 2 of the main control chip CH32L103 is directly connected to MCU_RXD and MCU_TXD pins of the L610 module to enable bidirectional serial communication. Specifically, it receives fused data processed by the main controller and uploads the data to the IoT cloud platform. Concurrently, it responds to GPS data collection commands, acquires positioning information, and sends it back to the main controller for data validity verification before final upload to the cloud. Additionally, the module enable pin is interconnected with the PB3 pin of the main controller, allowing flexible control of the operating status of the L610 module. Furthermore, by utilizing the module's SMS delivery and voice broadcast functions, this design implements a multi-mode alarm reminder mechanism. Even in weak-signal scenarios such as underground environments, maintenance personnel can conduct voice calls with municipal staff through this module, further enhancing the practicality of the design in complex environments. The circuit of the L610 module is shown in Figure 3.

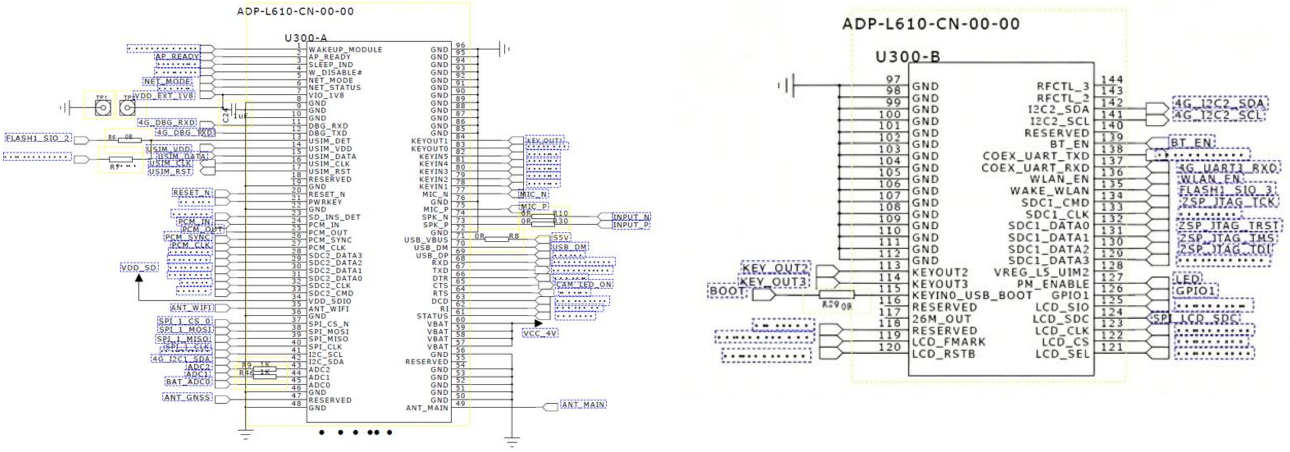

Figure 3 Schematic Diagram of the ADP-L610 Communication Module

3.2.3 Sensor circuit design

This design integrates multiple types of sensor circuits at the perception layer to enable real-time monitoring of multi-dimensional parameters, including distance, combustible gas concentration, equipment attitude, and water pH, thereby satisfying the multi-physical quantity perception requirements of manhole cover monitoring scenarios.

The ultrasonic ranging circuit employs the HC-SR04 module, which integrates a 40 kHz ultrasonic transceiver unit with a measurement range of 2–300 cm and an accuracy of ±0.3 cm. Applying a high-level pulse of 10 μs or longer to the TRIG pin triggers ultrasonic transmission. When the sound wave encounters the liquid surface and reflects, the ECHO pin outputs a high-level pulse whose duration is strictly proportional to the round-trip time of the sound wave. Based on the principle that distance equals sound speed multiplied by time divided by two, the height (H) from the manhole cover to the liquid surface can be calculated. When the measured H falls below the liquid level safety threshold, the system immediately activates the alarm mechanism and synchronously reports alarm information to the IoT cloud platform, enabling rapid response to potential hazards.

The methane gas detection circuit utilizes the MQ-4 methane sensor module. Because its analog output signal is susceptible to electromagnetic interference, an RC low-pass filter network consisting of resistor R63 and capacitor C47 is designed to suppress noise and smooth the MQ4_ADC output signal, effectively improving the stability and accuracy of methane concentration collection and enabling real-time monitoring and early warning of combustible gases.

The gyroscope angle detection circuit is built around the ICM-42688-P six-axis inertial measurement unit (three-axis accelerometer + three-axis gyroscope). This unit integrates high-precision sensing elements, supports I2C/SPI dual communication interfaces, and forms a power supply ripple suppression network with a 10 nF ceramic filter capacitor and a 2.2 μF tantalum capacitor. This configuration ensures a stable power supply and provides high-resolution real-time attitude angle and angular velocity data for the system. The module forms a complementary sensing structure with the Hall sensor and achieves high-precision monitoring of manhole cover displacement through data fusion algorithms, significantly reducing alarm redundancy caused by single-sensor misjudgment and improving monitoring reliability.

The pH water quality sensor circuit employs an RC filter circuit composed of capacitor C52 to filter the input signal from WATER_ADC_INPUT, effectively suppressing environmental noise interference. This enables continuous and accurate monitoring of water pH, meeting the high-precision measurement requirements for pH parameters in water environment monitoring scenarios.

All sensor circuits are designed with targeted signal filtering, impedance matching, and interface level adaptation, which significantly enhances the reliability and stability of output signals. They are fully compatible with the hardware interfaces and digital/analog channels of the main control chip, providing reliable hardware support for the fusion monitoring, collaborative analysis, and intelligent decision-making of multiple physical quantities. The sensor circuit design is shown in Figure 4.

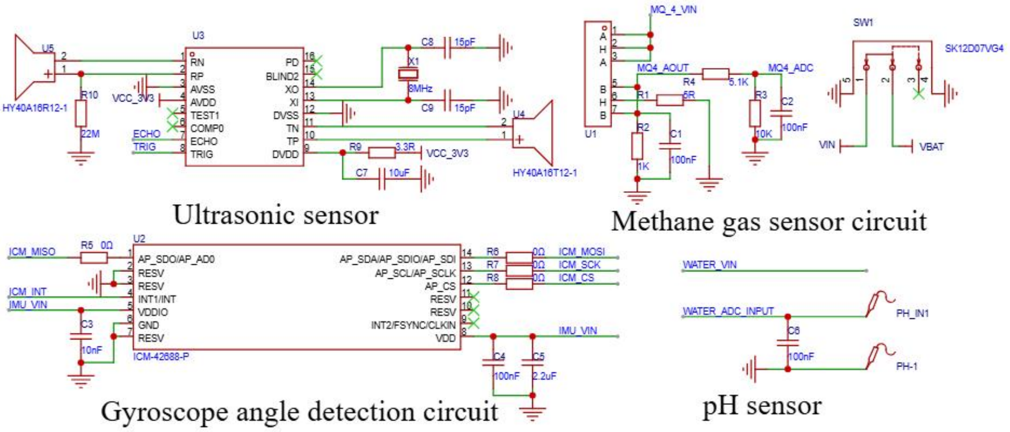

Figure 4 Schematic Diagrams of Multi-sensor Circuits

4 SYSTEM SOFTWARE DESIGN

After power-on and startup, the system first executes the initialization process, which configures hardware peripherals including the buzzer, accelerometer, pH sensor, ultrasonic sensor, methane sensor, and ADP-L610 communication module. The system then enters the data acquisition phase, during which it obtains sensor monitoring data and GPS positioning data, and performs noise filtering, data fusion, and format standardization. The processed data are first uploaded to the visual cloud platform via the ADP-L610 communication module. Subsequently, the system proceeds to the preset safety threshold judgment process.

If the data do not trigger the safety threshold, the system initiates the next cycle. If the threshold is exceeded, the local–cloud collaborative alarm mechanism is activated immediately. In this case, the buzzer is driven to produce a local audible and visual alarm, and alarm data containing monitoring parameters and GPS location are uploaded through the ADP-L610 communication module. Upon receiving the data, the visual cloud platform performs differentiated processing based on data type: normal operating data are directly displayed visually, whereas alarm data are first classified by preset thresholds and then trigger multi-channel responses. Specifically, the cloud initiates alarm prompts and pushes alarm information to maintenance personnel's mobile devices. After the emergency is resolved, the cloud can issue an "alarm off" command, which is transmitted back to the system via the ADP-L610 communication module to terminate the local alarm, thereby achieving closed-loop control of the alarm process.

The software process of this design ensures data reliability through data fusion and threshold judgment mechanisms, and achieves rapid response and closed-loop handling of emergencies via local–cloud collaborative alarms, effectively improving the system's real-time monitoring capability and operational efficiency. The software design flowchart is shown in Figure 5.

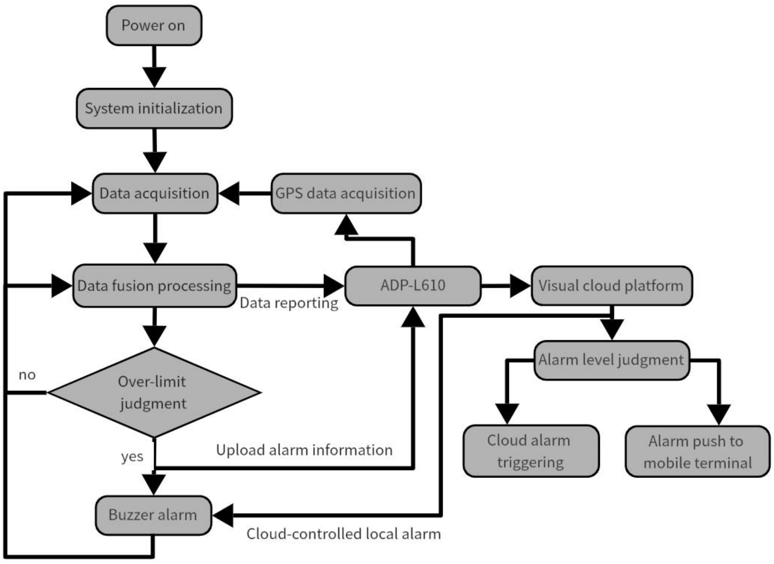

Figure 5 Software Design Flowchart of the System

5 IMPLEMENTATION AND TESTING

5.1 System Implementation and Performance

The system enables real-time monitoring of manhole cover status through a Web-based visual dashboard and an APP client. The dashboard displays real-time data, including methane concentration, tilt angle, battery power, displacement status, water immersion status, and local alarm status, as well as historical data curves and alarm logs, see Table 2. It also supports GPS map positioning and multi-dimensional data querying. The APP client provides functions such as real-time data viewing, alarm history retrieval, remote alarm control, and status push notifications, see Table 3. The Web-based visual dashboard is shown in Figure 6, and the APP client functions are shown in Figure 7.

Figure 6 Web-based Dashboard of the Monitoring System

Table 2 Web Dashboard Functions

No.	Description
1	Data and upload timestamp
2	Alarm status and logs
3	GPS location on map
4	Additional manhole cover parameters
5	Historical data records

Manhole 1 2025/07/06 17:36:07
Normal Manhole tilt angle too large
Tilt Angle: 0.91°

Manhole 1 2025/07/06 17:36:07
Abnormal Alarm Manhole tilt angle too large
Tilt Angle: 30.17°

Manhole 1 2025/07/06 17:36:27
Normal Metihole tilt angle too large
Methane Concentration: 80.29ppm

Manhole 1 2025/07/06 17:35:23
Normal Methane exceeds limit in the manhole
Emergency Alarm

Manhole 1 2025/07/06 17:25:33
Normal Water Level Status. Water -
Wethane exceeds limit in mnitoring line

Manhole 1 2025/07/06 17:25:11
Normal Allert Manhole displaconed ! ! ! !
GPS State of Rest: Device is in a stationary state

Manhole 1 2025/07/06 17:25:11
Manhole water level exceeds limit, mispositioning

Figure 7 Mobile APP Functions

Table 3 Functions Implemented on the Mobile Application

No.	Description
1	Historical alarm information
2	Data reporting time
3	APP-side alarm control button
4	Specific manhole cover data
5	Manhole cover alarm status

5.2 System Testing and Validation

The system is deployed on a 3D-printed manhole cover simulation model. Typical application scenarios are constructed using multi-dimensional test variables: the tilt angle of the simulated manhole cover is adjusted to simulate displacement; methane concentration is controlled to replicate gas leakage from underground pipelines; standard buffer solutions with different pH values are used to emulate diverse water environments; and the liquid level height is varied to simulate water accumulation. The test platform is shown in Figure 8. In this test scenario, 1000 valid data samples were acquired and documented, and the statistical results are listed in Table 4.

Figure 8 Monitoring System Test Scenario

Table 4 Monitoring System Test Data

Measuring Parameter	Test Point	System Mean	Error
Methane concentration (ppm)	500	498	-0.4
	2000	2003	+0.15
	5000	5010	+0.2
	8000	8360	+4.5
Tilt angle (°)	15	15.03	+0.03
	25	25.03	+0.03
	30	30.01	+0.01
	65	64.96	-0.04
Water pH	4.01	4.08	+0.07
	6.86	6.90	+0.04
	7.13	7.10	-0.03
	9.21	9.25	+0.04
Liquid level distance (mm)	100	101.0	+1.0
	500	502	+2.0
	1500	1498.3	-1.7
	3000	3001.8	+1.8

The measurement accuracy of methane concentration, tilt angle, water pH value and liquid level height all satisfies the design specifications. The system can accurately trigger abnormal thresholds and maintains favorable data stability, with the standard deviation of 1000 repeated tests no more than 0.05. It is capable of stably fulfilling the real-time monitoring demands of underground well environment and manhole cover operating conditions.

6 CONCLUSION

To address the problems of delayed response, high missed-detection rates, high operation and maintenance costs, and frequent safety accidents in traditional manhole cover management, this paper designs and implements an IoT-based manhole cover status monitoring system using the CH32L103 microcontroller. The system adopts a three-layer architecture consisting of a sensing layer, a transmission layer, and a platform layer. It integrates multiple sensors, including the ICM-42688 and MQ-4, utilizes the ADP-L610 communication module for data transmission, and employs edge computing to ensure data accuracy. The hardware communication is stable, and the software follows a layered modular design to maintain logical clarity. The web and mobile terminals work collaboratively to achieve real-time monitoring, multi-channel alarming, and remote control. Test results indicate that the errors of core parameters meet the design requirements. The proposed system can reduce fault detection time, lower missed-detection rates and operation and maintenance costs, thereby providing a reliable solution for the refined management of manhole covers in smart cities.

In future work, a raindrop sensor will be introduced to dynamically adjust alarm thresholds and link with auxiliary drainage devices to enable proactive risk control. Additionally, the system will be integrated with urban smart municipal platforms to enhance cross-facility collaborative governance capabilities.

COMPETING INTERESTS

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

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