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Gas Leakage Monitoring with Mobile Wireless Sensor Networks

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Abstract

In this paper, a real-time and early warning gas leakage monitoring system has been developed for large-scale region based on Mobile Wireless Sensor Networks (MWSNs). The system consists two parts: sensor terminal and center server. A sensor terminal includes TDLAS gas sensor which has remarkably high accuracy and reasonable size, microcontroller, Global Position System (GPS) receiver module, General Packet Radio Service (GPRS) module and power module. The center server is developed to receive, process and store the data. A real-time monitoring cloud platform is developed to display real-time data. A mobile wireless sensors networks, which consists of mobile sensor terminals and stationary sensor terminals, enable a large-region leakage monitoring. Experiments are carried out to valid the system. The results show that the real-time and early warning gas leakage monitoring system developed in this paper is reliable and practice. © 2019 The Authors. Published by Elsevier B.V.

Keywords—gas leakage Monitoring; Tunable Diode Laser Absorption Spectroscopy (TDLAS); mobile wireless sensors networks(MWSNs).

1. Introduction

Gas supplement is crucial to maintain daily running of city, and is named as “lifeline” of cities. Due to the large scale of pipelines systems and overtime service, gas leakage occurs quite frequently and causing serious casualty and economic loss.

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Gas leakage monitoring and detection system is of great significance for urban safety. Gas-leakage monitoring with wireless sensors network has been a wide accepted idea for developing an integrated system for real-time monitoring [1]. Somov A, Baranov A, Spirjakin D, *et al*. adopted a Wireless Sensor Networks (WSNs) with catalytic gas sensors and ZigBee module, and deployed it in a factory. They studied the catalytic gas sensors response under various conditions, and evaluate the wireless links using the received signal strength indicator (RSSI) and link quality indicator (LQI) metrics [2]. Jain P C, Kushwaha R adopted a WSNs with semiconductor sensor and ZigBee module, and discussed the potential application scenarios, such as apartment house, gas and oil pipeline industry. Experiments were carried out to study the communication quality between sensors and coordinator [3]. Most of the WSNs adopt catalytic sensors and semiconductor sensors for their low power consumption, but the accuracy is lower than optical sensors, and is limited in detecting slight leakage in early phase. Besides, fixed sensors do not fit the requirement of large-scale region monitoring. Tan Q, Zhang W, Xue C, et al designed a portable non-dispersive infrared ray (IR) gas detector, and carried out some experiments to verify its high accuracy, low power consumption and compact structure [4]. Frish M B, Wainner R T, Green B D, et al developed a standoff gas leak detector based on Tunable Diode Laser Absorption Spectroscopy (TDLAS), and deployed on automobile at ten kilometers per hour and aircraft flying at 10000 feet or higher, and evaluated its feasibility in various real condition [5]. Xu B, Yu D, Wu J, et al proposed an airborne infrared laser leak detection technology, and a lot of experiments were conducted to demonstrate that the airborne infrared laser leak detector can detect the leakage when the helicopter flies with the speed in 30-50m/s and the flight height less than 80m [6]. Researches also tried to combine high accuracy optical sensor into gas leakage detector, and mounted it to handhold device, automobile or aircraft simultaneously.

In this paper, gas leakage monitoring and early warning system, based on mobile wireless sensor networks (MWSNs), is developed. The system consists two parts: remote sensors and analysis server. Remote sensors are defined as sensor terminals in this research, and each sensor terminal is composed of gas sensor, microcontroller module, Global Position System (GPS) receiver module, General Packet Radio Service (GPRS) module and power module. They are integrated and mounted on both mobile devices and stationary place to form stationary sensor terminal and mobile sensor terminal. The field data, including gas concentration, speed data, GPS and time information, will be collected by them, and then be transmitted to analysis server by GPRS module via the Asymmetric Digital Subscriber Line (ADSL). Subsequently, the data coming from GPRS module will be received by NetAssist, and saved and processed by MySQL database. Meanwhile, a real-time monitoring cloud platform is developed to display the sensor number, location (latitude, longitude and height), and methane concentration timely. Meantime, an alert will be generated once the detected concentration exceeds the warning-threshold. In addition, the analysis server will analyze location of suspected leakage, and send a warning message to maintainers, managers and others relevant staffs.

2. Hardware Architecture

A sensor of DLGA-7000 gas sensor, high accuracy, reliable performance and reasonable size, has been produced and applied to this system. The TDLAS is the core technology and multiple reflections technology has been utilized specially. The TDLAS technology is developed with Beer-Lambert law. Beer-Lambert law states that when a radiation of wavenumber passes through an absorbing medium, the intensity variation along the path of the beam [6]

$$\frac{I_t}{I_0}=e^{-K_v L} \quad (1)$$

$$k_v=S(T)\emptyset(v-v_0) \quad (2)$$

where,

I_t is the transmitted intensity of the radiation after it has traversed a distance L through the medium;

$I_0$is the initial intensity of the radiation;

k_v is the absorbance of the medium;

S(T) is the line strength of the absorbing species at temperature T;

$\emptyset(v-v_0)$ is the line-shape function for the absorption line;

v_0 is centre frequency of spectrum.

The initial light I_0 transmitted across a measurement path, length L and containing the methane, is attenuated to I_t according to the Beer-Lambert law. The attenuated intensity of the light is proportional to the length of the optical path and the methane concentration. The DLGA-7000 gas sensor consists of laser, drive of laser, signal processing electronics and open measurement pool. The architecture is shown as Fig.1. Fig.2 is the diagram of light routine. The sensor is characterized by low-voltage alarm and self-diagnosis failure function, low false alarm and missing alarm in various tough and complicated environment, and without interference by others gas, long calibration cycle (exceed six mouth), free from calibrating frequently and user-defined measurement range; remarkably high sensitivity and accuracy, one second or faster response. Fig.3 is the open measurement pool architecture. It has been specially designed for its working ambience in this system, such as high hardness and strength, reasonable size. The light justified degree and position by 1 and 5, then go through a hole of the optical mirror 2, and reflect between optical mirror 2 and optical mirror 4, and come out from the same hole, finally, it will be measure by an analyzer. The whole system architecture is shown is Fig. 4.

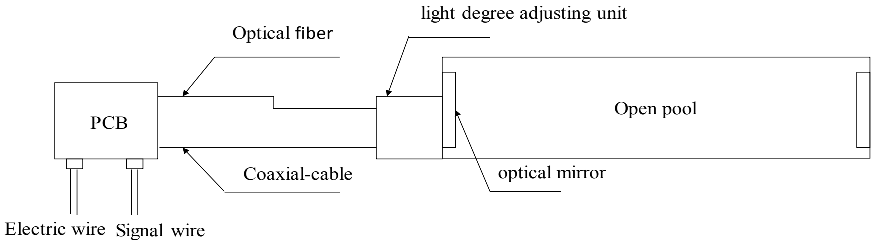

Figure 1 Gas sensor system

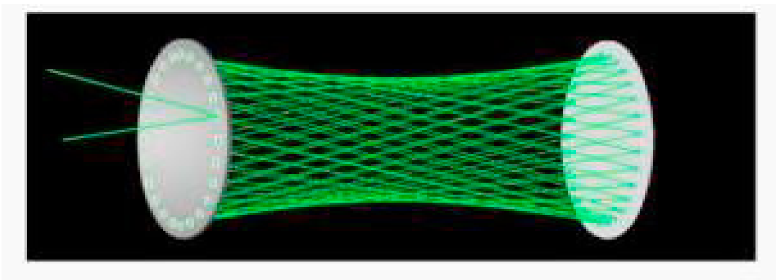

Figure 2 Light routine diagram

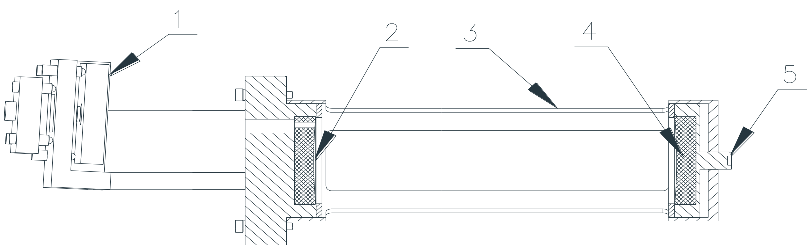

Figure 3 Measurement pool architecture diagram,1-light degree adjusting unit; 2,4-optical mirror; 3-steel support bracket; 5-light position adjusting unit

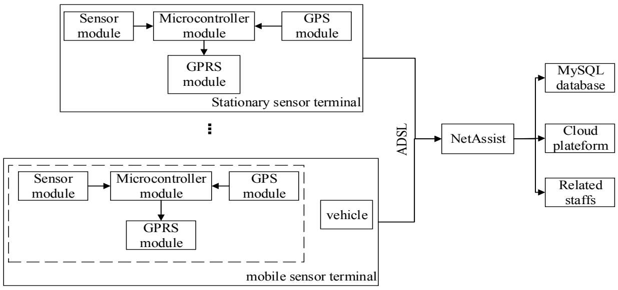

Figure 4 System architecture

The STM32F103RBT6 microcontroller was chosen as data processing unit. The STM32F103RBT6 is a 32bit processor which is based on Arm Cortex-M3 CPU, and it operate at CPU frequencies of up to 72 MHz. The peripheral complement of the STM32F103RBT6 includes 128 KB of flash memory, 20KB of Random-Access Memory (RAM), 12-bit Analog to Digital Converter (ADC), four 16-bit timer/counters, 9 communication interface (3 USARTs, 2 SPI interfaces, 2 IC interfaces, CAN interface, USB2.0 interface), and up to 80 general purpose I/O pins.

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3. Sensors placement mode

Nowadays, the sensors' placement has two ways: (i) at stationary place. The gas sensors are designed to deploy in stationary place, such as gas, oil pipeline industry, chemical plant etc., with fixed distance. The collected data are transmitted to coordinator via ZigBee module, then transmitted to centre sever by coordinator [7-10]. It is featured by its simple operation, high reliability and low power consumption. Besides, the position accuracy is higher than mobile placement mode whose position changes all the time. It is suitable for a relatively small area, such as chemical plant, combustible and hazard substance tank and so on, which need to be monitored all the time. But, it restricts its abroad application on large-scale region for its high cost if we deploy the sensors along all the pipeline. （ii）on mobile devices or vehicles. An autonomous mobile inspection robot was developed that it is equipped with several remote gas sensing devices and local intelligence [11]. The remote methane leak detector is mounted on specific vehicles to monitor the gas leakage [5,6]. Mounting sensors in robots or special vehicles is a flexible and high-precision method, and a large area can be detected by one device. It can detect the gas leakage when moving around or through leaking point. A network detection method helps monitoring pipelines all the time.

In the monitoring system developed in this paper, sensor terminals are supposed to deploy in taxis or buses (most of the gas pipelines is undergrounded along streets in the city), which move through and around cities, thus gas leakage may be detected real-timely with the sensor terminal networks. Gas concentration data are collected per minute by each mobile sensor terminal, and transfer the field data, including methane concentration, speed, position (latitude, longitude and height) and time information, to centre sever via GPRS module when detected data exceed transmission-threshold. Meanwhile, the stationary sensor terminals will be mounted in some area where taxis and buses are inaccessible and some special area required intensive monitoring, such as joint of old pipeline, frequently leakage area. The stationary sensor terminals adopted sleep-mode, wake-mode, and transmit-mode. The sensor terminals work on sleep-mode when the measure concentration is less than 3 part per million (ppm), and the gas concentration is measured per 30 minutes. Wake-mode is adopted when gas concentration is between 3ppm and 10ppm, and the gas concentration is measured per 10 minutes. Transmit-mode will be adopted if the detected value exceeds 10 ppm, in this state, the sensor terminal detects gas concentration per minute and transmit data to center sever simultaneously. In this way, a real-time and early warning gas leakage monitoring system for large-scale region is developed based on mobile and stationary sensors terminals network.

The location and distribution of stationary sensor terminals is determined by sensitivity requirement and calculated by equation

$$\mathrm{C(x,y,z,H)} = \frac{Q}{2\pi u \sigma_y \sigma_x} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\{\exp\left[-\frac{(z-H)^2}{2\sigma_y^2}\right] + \exp[-\frac{(z+dH)^2}{2\sigma_y^2}]\} \tag{3}$$

where,

C is the detected methane concentration at optional position， g/m3;

Q is the source emission rate, g/s;

σ_y is horizontal dispersion coefficient;

σ_z is vertical dispersion coefficient;

U is the wend speed at the source location, m/s;

H is the height of the source location, m;

X is the distance from the source in downwind direction, m;

Y is the distance from the plume axis in the crosswind direction, m；

Z: is altitude, m。

4. Firmware flow

At sensor terminals, sensors detect gas concentration and GPS receiver module collects position, speed and time information, and all the data will be transferred to USART 1 and USART 2 with microcontroller respectively, if the gas concentration exceed transmission-threshold. The microcontroller read data from USARTs directly and send data to centre sever through ADSL by GPRS module. All data are integrated to a real-time monitoring cloud platform.

The firmware flow is described in Fig.5, and procedures are as follows:

1) initialize GPS receiver module. It is the process of GPS receiver to get connection to satellites' information.

2) initialize gas sensor. The gas sensor is independent to microcontroller. The detected gas concentration will be sent to USART 1 with fixed time step automatically.

3) initialize GPRS module. An infinite loop was designed to achieve the dial-up of GPRS module. Afterwards, the connection between GPRS module and centre sever can be achieved and the point to point communication will be established.

4) Transfer data. Data from both stationary sensor terminals and mobile sensor terminals will be transferred to centre sever via ADSL by GPRS module.

5) Data management in MySQL database. All data are cleaned and stored in MySQL database, and is avalible for online query.

6) Display in the real-time monitoring cloud platform. All data, including sensor number, location (latitude, longitude and height), and methane concentration, will be be displayed with tablelist and maps timely.

7) Inform related staffs. If a suspected leakage point is detected, a warming and alart massage will be send to related staffs, such as maintainers, managers and others relevant staffs.

5. Experiments

5.1Preparation

The experiment was carried out outdoors taking the risk of methane into account. There is good visibility and the experiment temperature is 3 degrees Celsius. The experiment gas, 3% methane in the air, leaked from valve-well to simulate the leakage from underground. Meantime, the mounting direction of stationary sensor terminals and the moving direction of mobile sensor terminals were all along the wind direction. A FR-HW handheld anemorumbograph was used to measure the wind direction and speed.

Stationary sensors are placed around the leakage point with distance of 0.1 meter, and the detected concentration is recorded during the gas diffusion process.

The results are shown in Fig.6 and Fig.7. Fig.6 is the gas concentration along-wind direction (curve 1) and vertical-wind direction (curve 2), Fig.9 is the linear fitting results (dotted line) of upwind concentration (curve 1), vertical-wind concentration (curve 2) and downwind concentration (curve 3) respectively. It is evident that (i) the deviation of peakμ is about 0.6 in along-wind direction which is consistent with the wind speed; (ii) the sequence: upwind rate>vertical-wind rate>downwind rate.

The second experiment is carried out considering mobile sensors with different moving speed, to detect the concentration value near the leakage point. The result is shown in Fig.8. It indicates that: (i) the concentration profile of mobile sensor has a deviation compared with the stationary sensor, and the deviation direction is in accordance with moving direction thoroughly. Besides, the faster the mobile sensor move, the larger deviation is. This is caused by the response time of sensors, which causes the detected concentration value lags. (ii) peak concentration value detected by mobile sensors is lower than that by stationary sensors. In addition, with the speed of mobile sensor increases, the decrease of peak concentration value becomes more apparent. This may be due to the air flow turbulence caused by the moving of mobile sensors. (iii) it can be predicted that, with the speed of mobile sensor increasing, the concentration profile will lag more and the peak concentration value will drop more. It needs more study to find mechanisms.

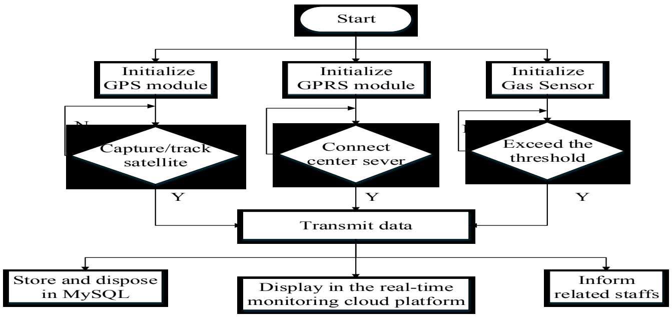

Figure 5 firmware flow diagram

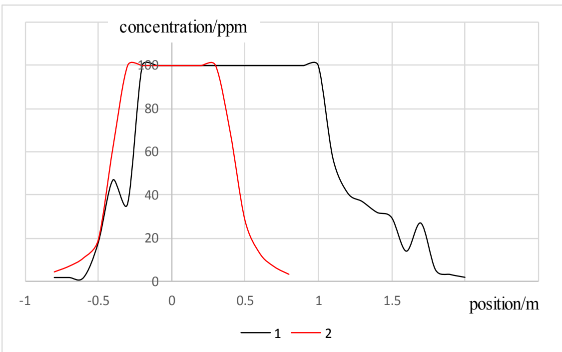

Figure 6 the measure concentration around leak source (wind velocity v=0.6m/s)

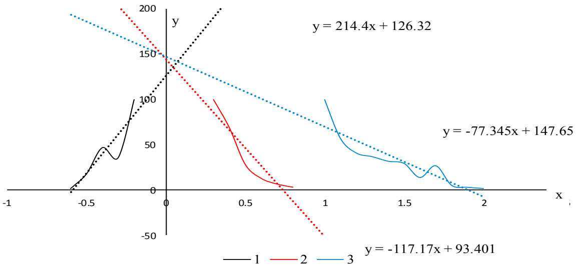

Figure 7 the linear fitting of upwind concentration ,1- upwind concentration; 2- vertical-wind concentration; ;3-downwind concentration

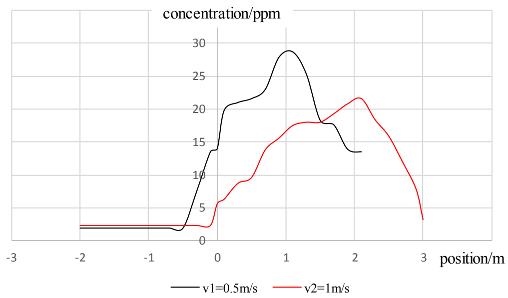

Figure 8 the concentration value with different sensor moving speed

5.2 Application

A real-time and early warning monitoring system for gas leakage developed in this paper. The hardware is composed of DLGA-7000 gas analyzer, STM32F103RBT6 microcontroller, sim908 module, power module. It was deployed on a mobile vehicle traveling at 5-10 kilometers per hour. The testing routine has total length of 2 kilometers, and a leak point was detected.

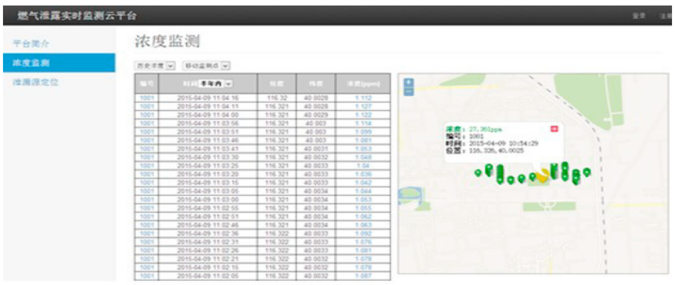

Figure 9 Real-time monitoring cloud platform

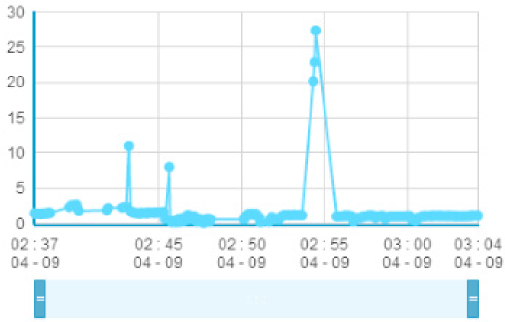

Figure 10 concentration distribution (ppm)

Collected data, including methane concentration, GPS data (longitude, latitude and height), speed, and time information, were transferred to centre server by GPRS module. The data were stored in MySQL database, and displayed on the real-time monitoring cloud platform. The MySQL database can be queried, analysed, and downloaded by user. On the real-time monitoring cloud platform, both real-time data and history data, including sensor number, latitude, longitude and methane concentration, will be shown with table-list as well as on the maps, which is employed to provide position information. The susceptible leak point will be calculated. If there be concentration value that exceeds warning threshold, it will be designated on the maps simultaneously. The warning massage will be sent to maintenance person and related management person. Fig.9 and 10 are the concentration profile of this field test. It is obvious that there are three point whose concentration value exceeded the warning threshold at 2:55. And the suspected leak point is calculated.

6. Conclusion

A real-time and early warning gas leakage monitoring system for large scale region was developed in this paper. The system employed high accuracy methane sensor based on TDLAS, GPS receiver module, GPRS module and power module. A mobile WSNs was highlighted through mounting sensor terminals on stationary place and mobile vehicle, and the mobile sensor terminals could be powered continuously by vehicles and overcome the power supply problem. Experiments were carried out to evaluate the detected data at different speed for mobile sensors terminal (e.g. 0m/s、0.5m/s and 1m/s). A real-time monitoring cloud platform was developed to show sensor number, latitude, longitude, methane concentration and suspected leakage point. Field test has been executed and the results show that the system developed in this paper is able to achieve real-time monitoring and early warning reliably.

7. Acknowledgement

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