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Detection of Odorous Gas Content in the Air Based on Ultrasonic Wave

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This paper aims to develop a high-precision method for identifying the gas content in the air. Considering the features of ultrasonic wave, an ARM-system was established to detect the content of sulphur hexafluoride, a gas denser than the air. The theories, hardware and software of the system were introduced in details. Then, the system performance was verified through tests on sulphur hexafluoride leakages under the same environment. It is proved that the system can identify the sulphur hexafluoride content in the air with a high precision. With the development of computer, communication and network technologies, the proposed system will have broad prospects in the detection of gas content.

ARM; ultrasonic wave; gas content

1. Introduction

The emission of flues from coal-fired boilers is commonly place in modern industry. The excessive emission of these gases may cause economic losses and even casualties. Thus, it is imperative to measure the exact contents of gases in the air, some of which are colourless, tasteless and difficult to burn. There are many ways to identify the contents at home and abroad, such as gas chromatography, thermal conductivity method, optical interference method, etc. However, none of the existing methods is easy to be popularized in industry.

By contrast, the ultrasonic wave has been widely adopted in such fields as industry, agriculture, medicine and national defence, as it propagates with different frequency, power and intensity in different materials. Therefore, the content of a gas in the air can be detected based on the propagation features of the ultrasonic wave in gases of different densities. One of the most important applications of ultrasonic wave lies in ultrasonic echo ranging. The ranging model supports simple and easy implementation, requires no direct contact with the object and adapts to harsh working conditions.

Traditionally, the ultrasonic ranging circuits mostly rely on microcontrollers (MCUs) like 51 series single-chip microcomputer and some small-scale integrated circuits (Bischoff et al., 2012). Nevertheless, the measuring accuracy is as low as 0.5~1% and the traditional 8-bit MCUs cannot realize intelligent control or output intelligent products. These defects are solved by the emergence of the ARM chips, which feature low cost, limited power consumption and high performance (Chen et al., 2012). So far, the ARM technology has been used in embedded control, multimedia, mobile communication and many other industries.

In light of the above, this paper employs the ARM technology to detect the content of sulphur hexafluoride, a gas denser than the air. The chip of our detection system is LPC2140, which enjoys high command throughput and real-time mid-range response.

2. Operating Principle

Ultrasonic wave can travel through gases, liquids and solids and the speed varies with the material compositions (Chen et al., 2012). A small change in the material content can lead to a variation in the propagation speed. According to the ARM technology, the counting function will send a signal to the ARM when the transmitter starts to send the ultrasonic wave, and send another signal to the ARM when the wave is reflected. The ARM will start and stop counting upon receiving the first and second signals, respectively. The propagation speed of the ultrasonic wave can be derived from the counted results. Meanwhile, the

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temperature and humidity will be detected by the sensors in the ARM, and the theoretical transmission speed of the ultrasonic wave will be determined by table look-up method. Then, it can be confirmed if the odor gas of sulphur hexafluoride is leaked in the air. If the content of sulphur hexafluoride exceeds the threshold, the ARM will issue an alarm or open the fan to warn about the excessively high content.

In total, there are 7 input sensors on Timer 0 and Timer 1 of an ARM chip. The sensors are responsible for counting the time of external signals. Generally, the ARM chip has a frequency of 10MHz~25MHz. Here, the frequency is set to 11.06MHz. It is assumed that the transmission distance and speed of ultrasonic wave were 10m and 340m/s, respectively. Then, it takes 2.94×10-2s for he ultrasonic (Yang et al., 2018) wave to cover the assumed distance. If the speed is changed to 341 m/s due to the content of the odorous gas, the propagation time will be reduced to 2.93×10-2s (Chun et al., 2014). Related to the chip frequency, the resolution of the ARM is 9.42×10-8s, while the detection accuracy reaches the industrial standard. The ARM system could enhance the detection accuracy by increasing the distance and frequency of the ultrasonic wave (Jackson et al., 2013).

3. System Design

3.1 Hardware design

As shown in Figure 1, the ARM system requires two power supplies, a 3.3V one for input/output and a 1.8V one for the core. The low-voltage differential signalling (LVDS) was adopted for the power supplies because it is difficult to switch between them at low power and under strict requirements. Specifically, the voltage of the power supplies was rectified and filtered to 5V via the 7805, and then stabilized by a low-dropout (LDO) chip. The output voltages are 3.3V and 1.8V, respectively (Zuo et al., 2013). The LDO chip is featured by high current, high precision, good stability, and low power consumption.

When the power is on, the system is not stable for normal operation. Thus, a reset signal was sent to the ARM chip for stabilization. The reset circuit uses the monitoring chip MAX708S. The reset threshold was set to 2.93V, i.e. the reset signal will be generated when the voltage falls below 2.93V (Mohd et al., 2015).

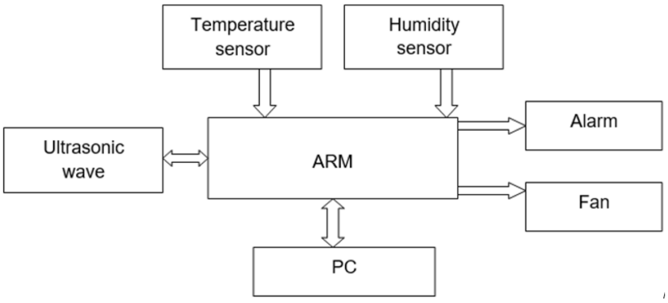

Figure 1: System structure

The technologies for the peripheral circuits (probe, temperature sensor, humidity sensor, alarm, fan etc.) are relatively mature. Both the temperature sensor and the humidity sensor are voltage output sensors, which convert the analogue output into signals. Specifically, the humidity sensor is an HS1100 series sensor (Apollo) while the temperature sensor is an LM35 sensor (National) (Hui et al., 2006). The two sensors are responsible for collecting and sending data to the ARM chip for processing. Besides, a special COM port was installed such that the system can be regularly checked and upgraded through communication with the PC.

3.2 Transmission and reception circuits

The transmission circuit (Figure 2) receives the periodic 40kHz square wave generated by the CPLD, which is controlled by an embedded microprocessor, and amplifies the wave for the ultrasonic transducer to transmit. Here, a high-performance integrated operational amplifier (LF353) (bandwidth: 4MHz) is selected to amplify the ultrasonic signals (Ping et al., 2014). This directly-coupled high-gain amplifier was selected because it has all the advantages of monolithic IC: small size, high reliability, low price and good temperature tracking. In addition, the amplifier makes it possible to perform many linear and some nonlinear jobs. If a network with different feedbacks is added between the input and output, a circuit with mathematical operation function can be constructed for various purposes.

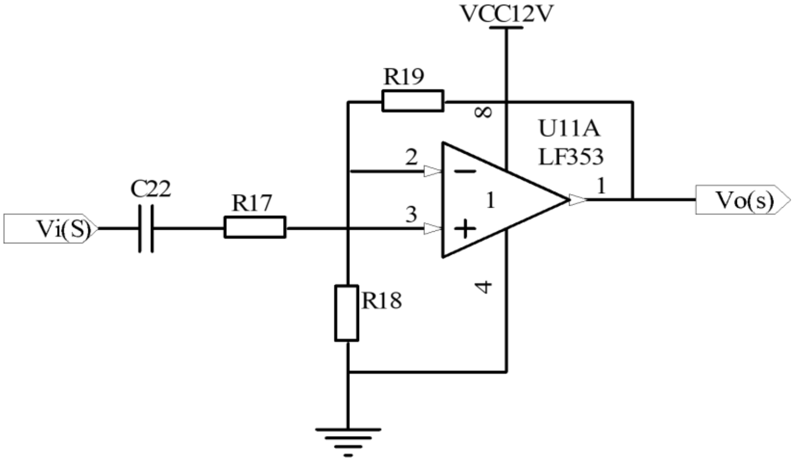

Figure 2: Transmission circuit

As shown in Figure 3, the reception circuit consists of a receptor, a front buffer, a signal amplifier, a comparison circuit and an optocoupler isolator. Considering the obvious attenuation of ultrasonic wave in the air, the echo signal received by the probe will be as weak as tens of millivolts if the distance is too far. This calls for amplification of the echo signal (Tsaklis, 2010). In our system, the amplification is implemented in two stages with a factor of 100, and the amplified signal is contrasted in the comparator LM393 against the reference level. After that, the signal is separately coupled with H11L1 and sent to the CPLD echo recognition pin. Overall, the reception circuit adopts vertical separation, filtering and shaping measures.

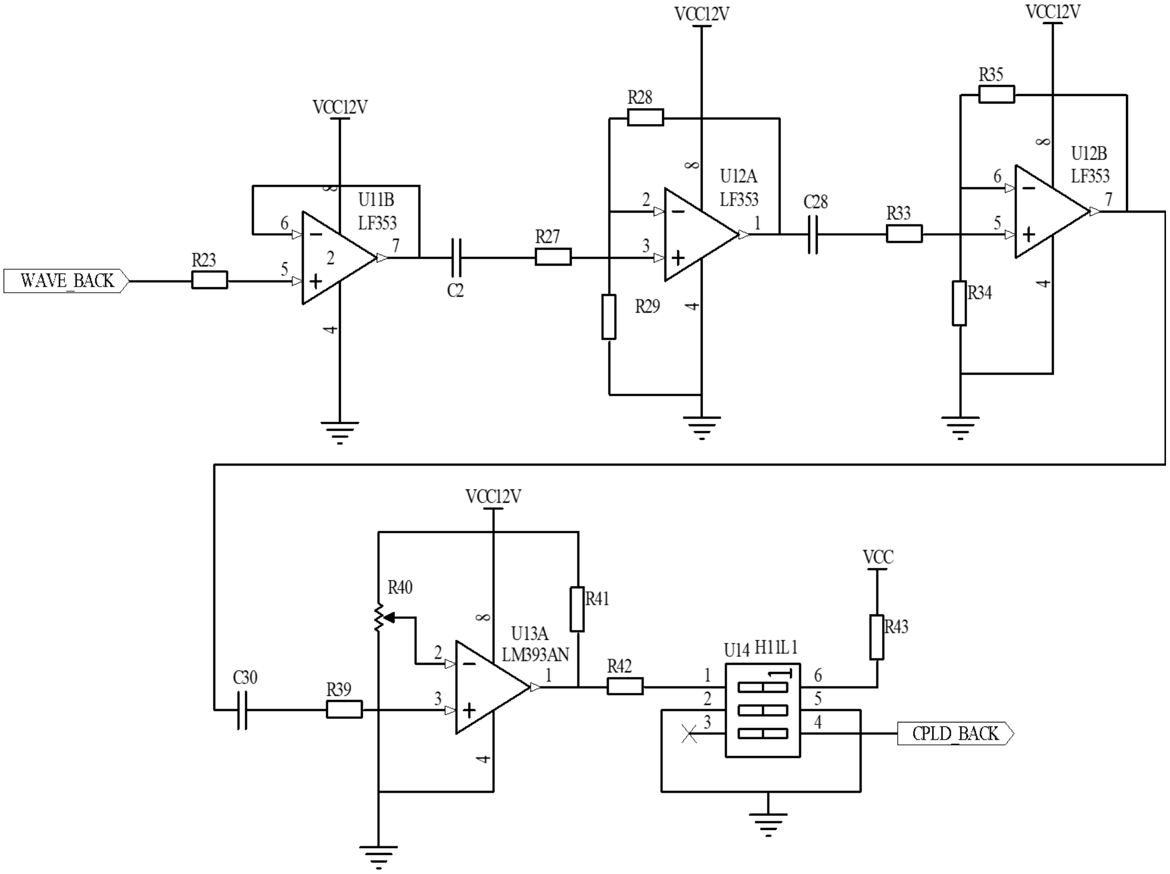

Figure 3: Reception circuit

3.3 Temperature compensation

At normal temperature and pressure, the air can be viewed as an ideal gas. The propagation speed of the ultrasonic wave in the ideal gas can be expressed as:

$$c = \sqrt{rRT / u} \tag{1}$$

where u is the mole number of the gas (Barrozo et al., 2018); r is the specific heat ratio of the gas; R is the gas constant; T is the thermodynamic temperature. For a certain gas, both r and u are constants. It can be seen from equation (1) that the sound speed is positively correlated with the square root of the thermodynamic temperature (Kono et al., 2011). Considering the test value of 331.45m/s at 0°C, the sound speed in the air can be expressed as:

$$c = 331.45\sqrt{(\theta + 273.16)/273.16} \ \ (m/s) \tag{2}$$

The distance can be calculated as:

$$S = 331.45 * N / f_r \bullet \sqrt{(\theta + 273.16)/273.16} - 15 \ \ (mm) \tag{3}$$

where N is the number of counts; f_r is the reference frequency; θ is the temperature; S is the distance (Ohga et al., 2011).

In our system, the temperature is collected by the temperature sensor and transferred to the processor for compensation (Singh et al., 2001).

3.4 Software design

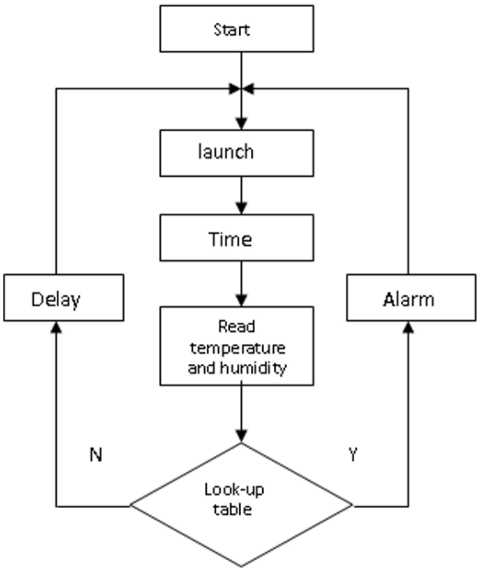

Figure 4: Program flow

Based on the hardware, the system software was designed to include Bootload, embedded operating system, user code, etc (Yang et al., 2014). The program flow of the user code is presented in Figure 4 above. In this system, the operating system is uC/OS, which boasts good real-time performance. The user's application can run various tasks on the operating system. According to the requirement of each task, the operating system will perform resource management, message management, task scheduling or exception handling. The uC/OS was integrated into the ARM by modifying the OS_CPU.H, OS_CPU.C and processor-related assembly language files (Li et al., 2015; Lu et al., 2009). When the ARM chip is reset, the system initializes and jumps to the Rest. The procedure for Rest is as follows:

```
Rest
BL InitStack
BL TargetRESETnit
B _main
```

After booting, the system first calls InitStack to try out various mode stacks, then calls TargetRESETnit to preliminarily initialize the system, and finally jumps to the main function developed by the user.

Upon initialization, the system enters the main function, sends a message to the probe, starts sending ultrasonic wave and counting time, and stops timing when the ultrasonic wave returns (Zuo et al., 2013). Next, the readings on the temperature and humidity sensors are collected. If the accuracy requirement is relaxed, the timer can be set as follows:

```
    T0TC=0;
    T0PR=0;
    While(iopin&0x01)!=0)
    T0TCR=0x01;
    While(iopin&0x01)==0)
    T0TCR=0x00;
    TIME=T0TCR;
```

The next step is to check the deviation between the actual and theoretical propagation times according to the temperature and humidity checklist. If the deviation is greater than a certain threshold, the system will generate an alarm and open the fan for ventilation (Henry et al., 2006; Song et al., 2006). This is mainly for the search and comparison of 2D arrays. The system relies on the detection interval set by the timer to detect, and the other time is in the sleep state.

There is a button designed specifically for the communication between the system and the PC. When the button is pressed, the system will be interrupted. The system is connected to the COM port of the PC through UART0, which is initialized as follows:

```
void UART0_int(void)
    {
    U0LCR=0x83;
    U0DLL=0x00;
    U0DLM=0x00;
    U0LCR=0x03;
    }
```

3.5 Test data analysis

The proposed system was applied to measure sulphur hexafluoride leakages under the same environment. Table 1 lists the 100 sets of data measured by the time collector.

Table 1: Test data

The actual distance (mm)	No leak acquisition time (us)	Leak acquisition Time (us)	No leakage measurement distance (mm)	Leakage measuring distance (mm)
1004	2990	2915	1016.60	998.56
2002	5924	5878	2014.16	1998.59
3005	8895	8821	3024.30	3007.73
4000	11843	11732	4026.62	4004.53
5001	14810	14736	5035.40	5009.32

It can be seen from Table 1 that the leakage of sulphur hexafluoride was measured accurately when the echo was processed by the ARM. However, the distance measured by the ARM was greater than the actual distance. The deviation is attributable to the interruption of the chip on response time, which is difficult to overcome in programming.

4 Conclusions

This paper proposes a gas detection system based on ultrasonic wave technology, and proves through tests that the system can identify the sulphur hexafluoride content in the air with a high precision. Of course, the proposed system can be applied to the detection of other gases. With the development of computer, communication and network technologies, the proposed system will have broad prospects in the detection of gas content.

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