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High-precision Ultrasonic Flowmeter for Mining Applications based on Velocity-area

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Abstract

The flowmeter is widely used in coal mining because of its higher measurement precision and simple installation without channel project modification. In this paper, a flow measurement method based on velocity-area is investigated, and a functional flowmeter for mining applications with higher precision is designed. The two key parameters, the liquid level and flow velocity are required to be obtained for achieving the proposed method. The proposed flowmeter is composed of three main functional modules: (1) flow velocity detection module based on ultrasonic time difference method, (2) liquid level detection module, and (3) mud level detection module based on ultrasonic pulse echo method. All the measured data are transferred to the monitoring station for analysis and displayed in real-time through M-BUS. The flowmeter is designed focusing on mining applications, and has higher benefits for preventing water disasters in coal mines.

Keywords: *flowmeter, open channel, ultrasonic, transit-time, velocity-area*

1. Introduction

Water related disasters in mining have been a major problem in domestic mining operations. Most of the mining drainage systems unable to respond directly because of sudden increase of water yield. Applications of flowmeters are crucial in such circumstances. The flow measurement techniques with installation, calibration, and operation studies have been popular especially to understand the fluid mechanics principles [1]. Ultrasonic flowmeters are one of the fastest growing technologies for process monitoring, measurement and control [2]. In mining, the open channel flow monitoring is a major solution to prevent damage caused by water. For example, several researchers in the past studied the methods to prevent any such damages. In [3], researchers proposed real-time control of open channel flow rate to prevent any causality in coal-mines. In addition, the influence of sediment deposition and ways of measuring open channel flow is also discussed. A similar application for measuring physical and mechanical properties of silty clay is studied in [4]. The purpose of their work is to investigate the influence of temperature, water content, and dry density on ultrasonic wave velocity, and ultrasonic tests were conducted on frozen silty clay using the supersonic test meter. Moreover, the relationship between ultrasonic wave velocity and frozen silty clay strength was obtained through analysis. In [5], the measuring methods of open channel discharge are presented, and an ultrasonic open channel flowmeter with secondary instrument based on AT89S52 is designed.

In general, flowmeters generate a representative signal of a given quantity of fluid passing through them. Accurate flow measurement is an important aspect of environmental protection, especially while measuring discharge sewage. For example, a new design of open channel flow meter is presented in [6]. Ultrasonic flowmeters are widely used in many applications, which make a precise measurement of the flow by measuring the flow velocity. In [7], the ultrasonic flowmeter with MSP430 as microprocessor designed which uses improved time difference method to measure the flow velocity. The authors also presented several advantages of ultrasonic flowmeters such as minimized loss of pressure, low consumption cost and full functionality. A very small ultrasonic flowmeter for liquids with measuring pipe diameter

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down to 0.5 mm was developed using disk ultrasonic transducers in [8]. This flowmeter can measure a liquid flow rate below 1 *ml/min*, which corresponds to a Reynolds number of about 40. The flow patterns in ultrasonic liquid flowmeter and several flow visualization studies with performance of an ultrasonic transit time flow meter have been discussed in [9]. A study on ultrasonic flowmeter for measurements of the flow rate of viscous liquids with viscosity substantially dependent on temperature is presented in [10]. According to 2005 research, ultrasonic flowmeters captured approximately 10% of sales volume combining all types of flowmeters. Moreover, no single technology, nor one type of interaction within a technology, can be best for all fluids, occasions and situations [2].

In this paper, a flow measurement method based on velocity-area which is especially suitable for mining application is proposed. The two key parameters liquid level and flow velocity are required for archiving this method. Earlier, several techniques and sensors are used for liquid level measurement such as liquid level sensor using float, capacitance liquid level sensor, static pressure liquid level sensor, and ultrasonic liquid level sensors [11]. Considering the characteristics and applications of various methods, ultrasonic liquid level sensor is adopted to measure the liquid level of mine open channel. These techniques can be used for flow velocity measurements such as flowmeter, electromagnetic induction, and ultrasonic velocity methods. However, ultrasonic velocity method is more applicable to open channel flow measurement due to their advantages of installation without changing the channel. The basic principle is to obtain the velocity of fluid through the transit-times or transit-time difference (TTD) of upstream and downstream traveling ultrasound signals [12]. In addition, mud position sensor is used to reduce measurement error of liquid level resulted from the coal sludge and impurities deposited on the channel bottom. Ultrasonic mud position sensor can achieve accurate measurement of mud level when the field calibration of acoustic velocity is applied according to the practical requirements. In summary, the proposed flowmeter is composed of three main functional modules: (1) flow velocity detection module based on ultrasonic time difference method, (2) liquid level detection module, and (3) mud level detection module based on ultrasonic pulse echo method. All the measured data are transferred to the monitoring station for analysis and displayed in real-time through M-BUS. The flowmeter is designed for focusing on mining applications, and has higher benefits for preventing water disasters in coal mines.

2. Measurement Principle

The measurement of cross-sectional flow area is realized through open channel liquid level and mud position detection based on the ultrasonic pulse echo method. The height of water and mud are measured to receive water flow cross-sectional area. Schematic diagram of the measuring principle is shown in Figure 1.

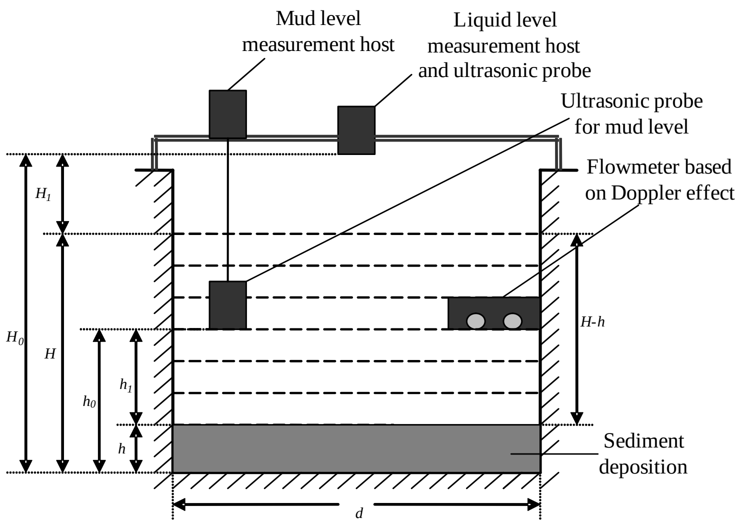

Figure 1. Schematic diagram for measuring the water flow in cross-sectional area

Ultrasonic wave is transmitted from ultrasonic transducer, and received by ultrasonic probe after the reflection from water surface. The travelled distance of ultrasonic wave is obtained from the product of sound velocity and elapsed time, which is double the distance between the probe and the water surface. The liquid level height can be determined by the following formula:

$$H = H_0 - H_1 \tag{1}$$

$$H_1 = \frac{c \cdot \Delta t}{2} \tag{2}$$

Here, c is sound velocity, Δt is elapsed time, H_0 is the height of the ultrasonic probe, H_1 is the distance between the probe and the water surface, H is the height of the liquid level. Based on the above principle, the height of mud position can be obtained from following formula:

$$h = h_0 - h_1 \tag{3}$$

Here, h_0 is the height of ultrasonic probe for mud position, h_1 is distance between the probe and the mud surface. So, the water flow cross-sectional area is determined by the formula:

$$S = (H - h) \cdot d \tag{4}$$

Here, d is the width of open channel.

The key principle of flow measurement using ultrasonic method is the measurement of velocity of the fluid. The velocity is obtained from flow velocity module based on ultrasonic time difference method. Relative to a fixed coordinate system (such as the side wall of the open channel), the ultrasonic propagation velocity in the flow medium is different from the propagation velocity in the static medium, and the changes in velocity value depend on the flow velocity of the medium. The propagation time difference of ultrasonic wave can be measured to determine flow velocity of the medium [13, 14].

The schematic diagram for measuring the water flow velocity based on principle of time difference method is shown in Figure 2. The ultrasonic downstream transducer T_1 and upstream transducer T_2 are installed on both walls of the open channel. L represent the ultrasonic path length, θ express the angle between ultrasonic propagation direction and flow direction, and D is the width of open channel.

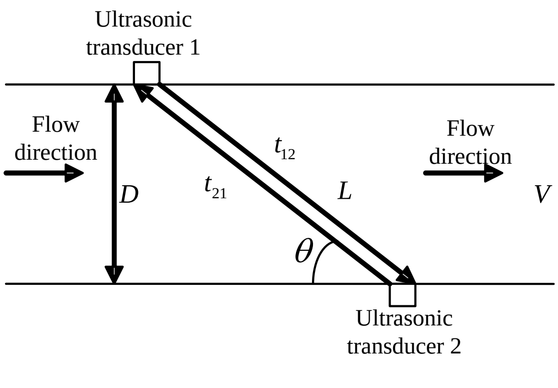

Figure 2. Schematic diagram for measuring the flow velocity

The relationship among them is illustrated in the following equation:

$$L = D / \sin\theta \tag{5}$$

So, ultrasonic downstream propagation time t_{12} from the transmitting transducer T_1 to the receiving transducer T_2, can be determined by the following formula:

$$t_{12} = L / (c + v\cos\theta) \tag{6}$$

Here, c is the ultrasonic propagation velocity in water, and v is the flow velocity. And, ultrasonic upstream propagation time t_{21} from the transmitting transducer T_2 to the receiving transducer T_1, also can be determined by the following formula:

$$t_{12} = L / (c - v\cos\theta) \tag{7}$$

Due to the continuous fluid flow, ultrasonic downstream propagation time is less than the upstream propagation time. The time difference is derived as follows:

$$\begin{aligned}\Delta t &= t_{21} - t_{12} \\ &= \frac{2Lv\cos\theta}{c^2 - v^2\cos^2\theta} \\ &= \frac{2vL\cos\theta \big/ c^2}{1 - (v/c)^2\cos^2\theta}\end{aligned} \tag{8}$$

As the ultrasonic propagation velocity c in water under normal temperature and pressure is equal to $1450 m/s$, which is far greater than the flow velocity v, so $(v/c)^2$ is approximately equal to zero. Therefore, the time difference is simplified as follows:

$$\Delta t = \frac{2vL\cos\theta}{c^2} \tag{9}$$

Thus, formula for calculating water flow velocity in open channel is shown as follows:

$$v = \frac{\Delta t \cdot c^2}{2L\cos\theta} \tag{10}$$

From the above equation, the flow velocity has relationship with the parameter c, which is influenced by temperature, water depth and other physical parameters. So, combining the two equations (6) and (7), the mathematical transformation can be used to remove the parameter c for calculating water flow velocity.

$$t_{12} \cdot t_{21} = \frac{L^2}{c^2 - v^2\cos^2\theta} \approx \left(\frac{L}{c}\right)^2 \tag{11}$$

Finally, the flow velocity v is determined by the following equation:

$$v = \frac{\Delta t \cdot L}{2t_{12}t_{21}\cos\theta} \tag{12}$$

In the above equation, because $\frac{L}{2\cos\theta}$ is constant, the flow velocity v can be computed after downstream and upstream propagation time are measured as described in [12]. Therefore, the average flow Q of open channel is determined according to the flow velocity v (which is measured by flow velocity sensor module) and the water flow cross-sectional area S (which measured by water level and mud level sensor modules) shown in the following formula:

$$Q = vS = v(H-h)d \tag{13}$$

3. Hardware Design

In this section, the design of different hardware modules of ultrasonic open channel flowmeter for mining application is described. The hardware modules include liquid level sensor module, mud position sensor module and flow velocity sensor module.

3.1. Design of liquid level (or mud position) sensor module

The measuring principle of liquid level is based on the ultrasonic pulse echo method, similar to mud position measurement. So their general design process is discussed together. This module is composed of six components: microcontroller, ultrasonic transducer, ultrasonic excitation circuit, signal processing circuit, electric source and communication circuit. The overall block diagram is shown in Figure 3.

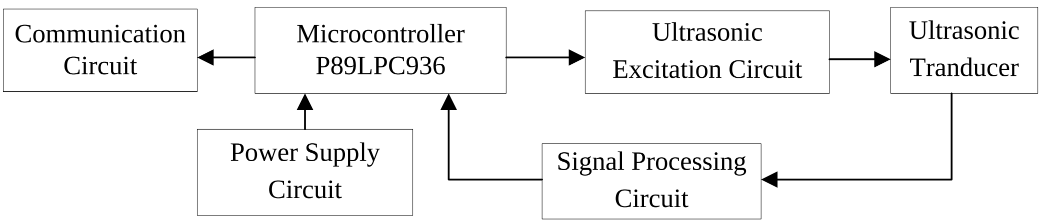

Figure 3. Comprehensive block diagram of liquid level or mud position sensor module

In this design, P89LPC936 is adopted as the main microcontroller, which is based on principles of high performance processor architecture and generally available in low cost packages. In addition, capture/compare unit (CCU) provides PWM, input capturing, and output comparison functionalities. The center frequency of 40 KHz is used in ultrasonic transducer transceiver. In ultrasonic excitation circuit, NOT gate oscillator and its drive circuit is designed to excite ultrasonic waves (*see Appendix A-1*). Signal processing circuit consists of four modules: signal amplification, band-pass filtering, rectifier circuit, and voltage signal comparison (*see Appendix A-2*). Bus transceiver TSS721A and its peripheral circuits are used to realize the communication between liquid sensor module and communication substation (*see Appendix A-3*).

M-BUS communication mode is adopted to improve anti-interference ability and performance. To avoid the interference between communication circuit and microcontroller, optical coupler 6N139 is used. The power supply circuit which is mainly composed of HT7150, HT7130, DY24S12-W5, 78L05, 78L15 and FAN5660 (*see Appendix A-4*). The reverse voltage is provided by FAN5660. In addition, power supply circuit is intrinsically providing safe DC power supply, which can meet the specific requirements of coal mining.

3.2. Design of flow velocity sensor module

The flow velocity can be calculated by the specific formula after ultrasonic propagation time of upstream and downstream are measured. As the measuring principle is same as principle of liquid level or mud position sensor modules, their respective hardware and software design modules are also fundamentally same. The only difference is that ultrasonic propagation time of upstream and downstream should be measured respectively. Therefore, one transceiver control circuit should be designed to achieve conversion of transmitting or receiving control.

4. Design of the Software Modules

As part of software module design, liquid level or mud position sensor module required to send the measuring data to master computer. As each liquid level sensor has one unique and parallel address code, sensor should be activated to realize measurement from idle mode when it receives the updated matching address code. Moreover, the liquid level sensor is connected to the setting device to configure the address code after all the sensors are installed in place. According to the formula of calculating the liquid level, ultrasonic propagation velocity C is a parameter susceptible to some environmental factors. The ultrasonic velocity field calibration needs to be completed by means of connecting the setting device to remove effects of environmental factors on measured distance. The main program flowchart of sensor module is shown in Figure 4.

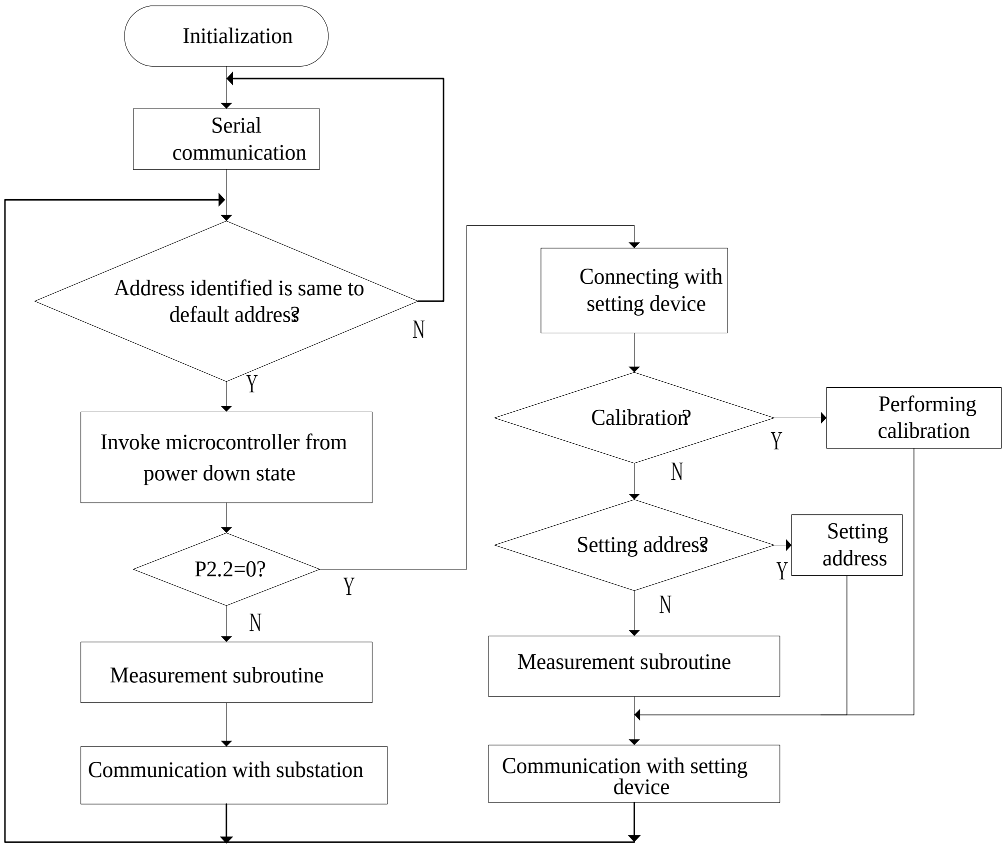

Figure 4. The flowchart of main sensor module

The Figure 5 shows the flowchart of the liquid level measurement program. Initially, through the processing circuit signal amplification is controlled by the analog switch. When the distance is short, smaller magnification is adopted in order to prevent the clutter effect; when the distance is larger, higher magnification is needed for the weak echo signal.

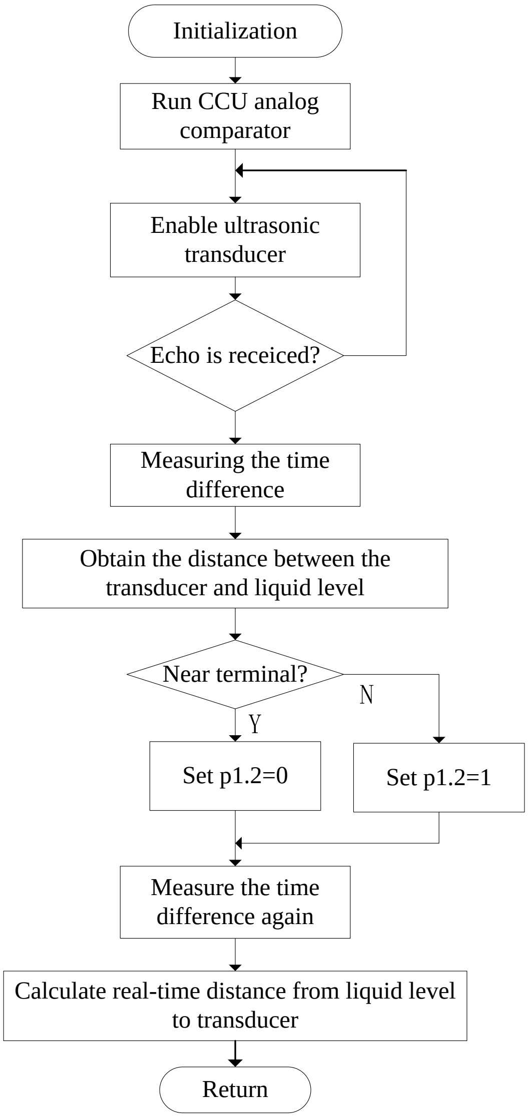

Figure 5. The flowchart of liquid level measurement program

5. Circuit Testing and Experimental Results

In this section, the results after testing the designed circuits, and the experimental data collected are presented. According to the circuit design, the signal output waveform of the circuits is shown in Figure 6. Through the signal processing circuit, the launch time and the reception time of the ultrasonic echo signals are shown in Figure 7. The rising edge of the first rectangle is the launch time of the ultrasonic wave, the second rising edge of the rectangular wave of ultrasonic wave is the reception time. The distance is obtained by measuring the elapsed time between the two rising edges. The propagation time is 2.98*ms*, and the distance from the liquid surface to ultrasonic transducer is calculated as shown below. More accurate distance value is obtained when the sound velocity is calibrated in the field.

$$\frac{2.98ms \times 340m/s}{2} = 506.6mm$$

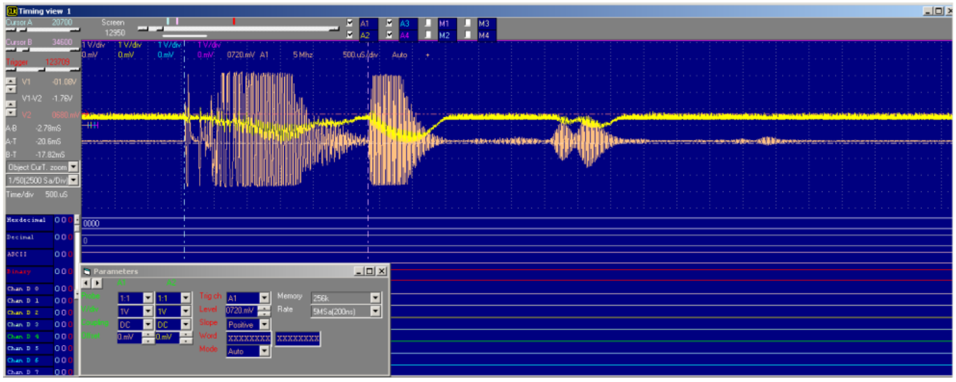

Figure 6. The rectification ultrasonic echo (*top*)

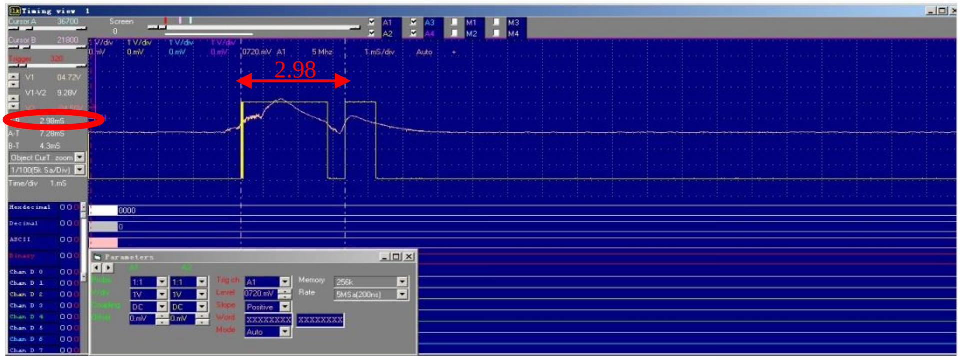

Figure 7. The ultrasonic echo after voltage comparison

The data from channel level sensor is compared with the measured distance. The Table 1 shows the obtained data and error of liquid level sensor module. The Table 2 shows the obtained data and error of mud position sensor, and Table 3 shows the data and error obtained through flow velocity sensor module. The relative errors of the liquid level sensor, mud level sensor and flow velocity sensor are kept within 4%, and meet the expected requirements.

Table 1. Obtained Data and Error of Liquid Level Sensor Module

Distance(m)	Measured distance(m)	Relative error(%)
3.00	3.05	1.7
3.00	2.99	0.3
2.00	2.03	1.5
2.00	2.01	0.5
2.00	1.00	.0.0
1.00	0.96	4.0

Table 2. Obtained Data and Error of Mud Position Sensor Module

Distance(m)	Measured distance(m)	Relative error(%)
1.00	0.98	2.0
1.00	0.96	4.0
0.8	0.81	1.25
0.8	0.76	5.00
0.5	0.51	2.0
0.5	0.48	4.0

Table 3. Obtained Data and Error of Flow Velocity Sensor Module

Flow velocity using instrument(m/s)	Flow velocity using sensor(m/s)	Relative error(%)
15.00	15.235	1.57
15.00	14.567	2.89
10.00	10.022	0.22
10.0	9.870	1.30
5.00	4.899	2.02
5.00	4.961	0.78

6. Conclusion

This paper describes a novel ultrasonic flowmeter for open channel, which can be applied in a number of coal mines. The flowmeter has several features such as high accuracy, stable communication, easy installation, and has a power supply circuit. The power supply circuit is designed for intrinsic safety and can satisfy the requirements of coal mines. The proposed ultrasonic flowmeter can perform liquid level, mud position, and flow velocity detection. The working principle, hardware modules and software design are introduced in detail. Experimental results and error analysis are given to verify the stability of flowmeter. In addition, the ultrasonic flowmeter for mining has a higher measurement accuracy compared to other open channel flowmeters. Therefore, it can be useful in several applications which involve open channel flow measurement such as plant drainage, irrigation, and water conservation applications.

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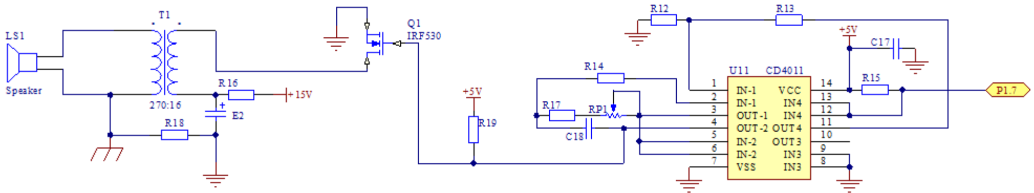
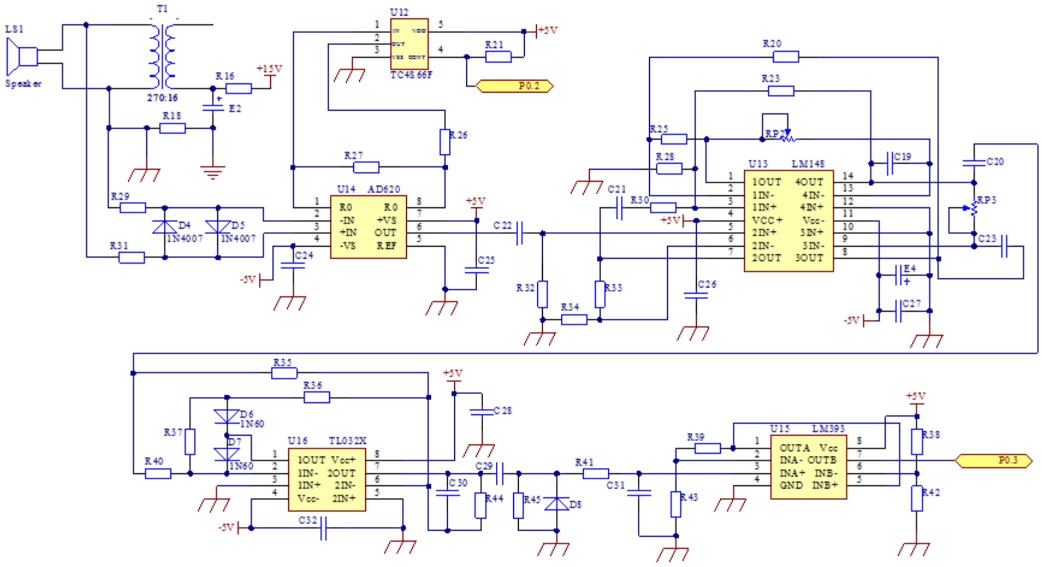
Appendix A

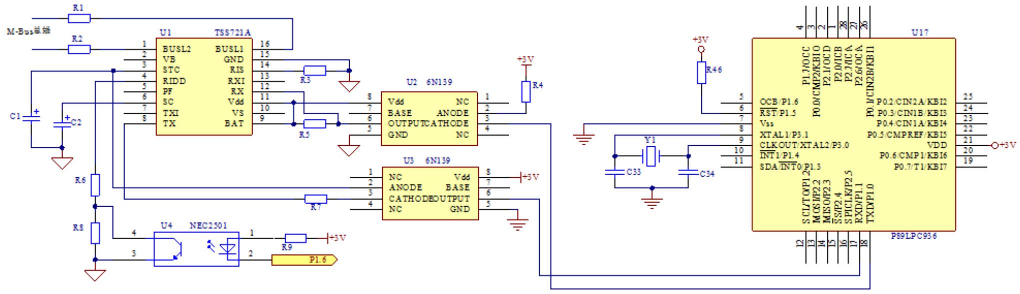
Appendix A-1: The ultrasonic excitation schematics of liquid level sensor module



Appendix A-2: The signal processing schematic of liquid level sensor module



Appendix A-3: The communication schematic of liquid level sensor module



Appendix A-4: The power supply schematics of liquid level sensor module