International Journal of Smart Home
Vol. 9, No. 11, (2015), pp. 211-224
http://dx.doi.org/10.14257/ijsh.2015.9.11.22

Discussion and Design of Dynamic Liquid Level Intelligent Monitoring System

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Abstract

The problem of how to calculate the height of the liquid level under tilting status is considered. A custom algorithm for obtaining the real height of liquid level according to the difference of distance measured by ultrasonic sensors is proposed. A set of intelligent monitoring system is designed as well. The system, which takes S3C6410 processor as the control core of the front-end system, measures distance by multiple HC-SR04 ultrasonic sensors, compensates temperature via external temperature sensor ds1820, collects data via inserting driver modules, and then gets the liquid level angle by means of the difference between distance, to calculate the liquid level height, both of which will be sent via Bluetooth chip CC2541 and wireless network. The data, received by PC, will be used for graphical interface display and speech broadcasting depending on Processing software programming. The smart phone can also read data and control devices from the front-end. The results of simulation experiment of this system are considered.

***Keywords**: ultrasonic sensors; Bluetooth communication; Processing program; dynamic liquid level; intelligent monitoring*

1. Introduction

With a non-contact characteristic, ultrasonic ranging is applied to automation, oil monitoring and sewage monitoring. Conventional ultrasonic ranging system uses one ultrasonic transducer to collect data in order to get the distance. However it can not be used in dynamic level measurement, especially in the tilting condition. New sensor nodes are hard to be added to the system's sensor network, which hinders extensions of sensor network. Moreover terminal control interface is rarely intelligent graphical monitoring. For the above, a method for calculating the height of the liquid level using a custom algorithm is proposed [1]. This design makes use of ultrasonic sensors, Processing, Bluetooth wireless technology and Yeelink cloud server in one level monitoring system to improve the shortcomings of the old method. Multiple ultrasonic sensors work together to provide data to the front-end system, and the values of the height of liquid level are sent to the terminal by Bluetooth and wifi. Java programming in Processing software is used for graphical monitoring. Due to one Bluetooth device can be connected by several slave devices, the system can continue to increase the number of nodes, which facilitates the expansion of sensor networks. A dynamic self-tuning ultrasonic level measurement system is proposed in [2], however it uses special liquid level constraints tube, and needs complicated hardware circuit and software design. Compared with traditional liquid level measurement systems, this system can realize the accurate measurement of liquid level under tilting condition as well as intelligently monitor liquid level, in addition Bluetooth

ISSN: 1975-4094 IJSH

low energy technology can facilitate sensor network expansion. This method is not only applicable to ultrasonic ranging, but also can be applied to other ranging systems with non-contact characteristics, such as laser ranging.

2. Algorithm of Calculating the Height of the Liquid Level

Traditionally, ultrasonic range finder measures the distance to the surface of the required object [3], and liquid level is measured under horizontal state, which is as shown in Figure 1.

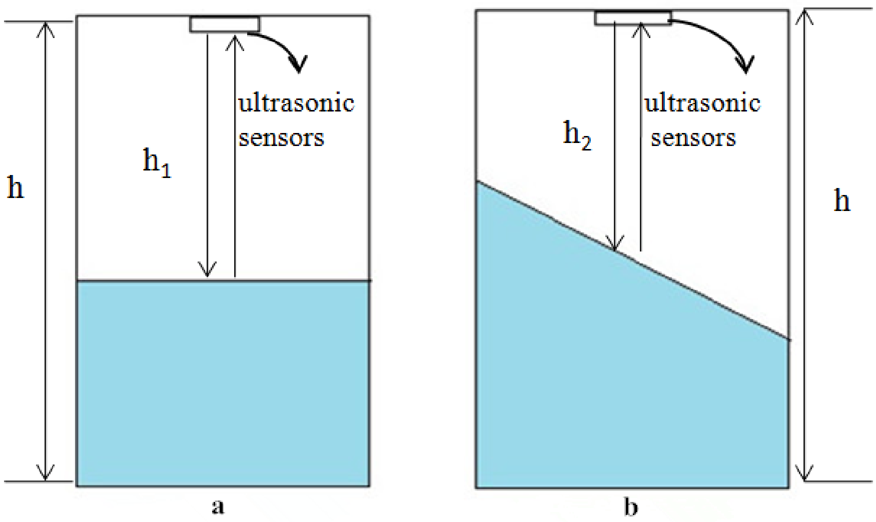

Figure 1. Liquid Level State: a. Horizontal State; and b. Inclined State

In the light of analysis on liquid level, the liquid level height H, can be calculated by equation (1).

$$H = h - h_1 \tag{1}$$

As is shown in Figure 1, when the level is tilted, a big error will occur if re-using the equation (1) to calculate the height.

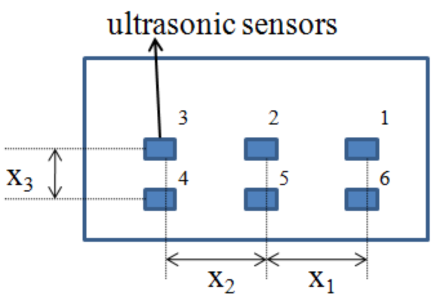

Figure 2. Top View of the Container

In our research, several ultrasonic sensors applied to collect data can avoid big error mentioned above. The sensors are placed in the top position of the container, and the top view of this container is shown in Figure. 2.

According to Figure 2, sensor 2 is placed at the midpoint position. x_1, x_2 and x_3 can be previously measured. Figure 3 shows the liquid inclines left, and six sensors will measure the distance from the liquid surface in this case. To simplify the problem, the case in Figure 3-a is considered. Respectively, the distances measured by sensor1,2,3 are h_1, h_2, h_3. The liquid angle of inclination can be obtained by equation (2).

$$\tan \alpha = \Delta h_1/x_1 = (h_2 - h_1)/x_1 \tag{2}$$

It can also be applied to the case in Figure 3-b. The relational expression of $\tan \alpha'$ is the same with $\tan \alpha$.

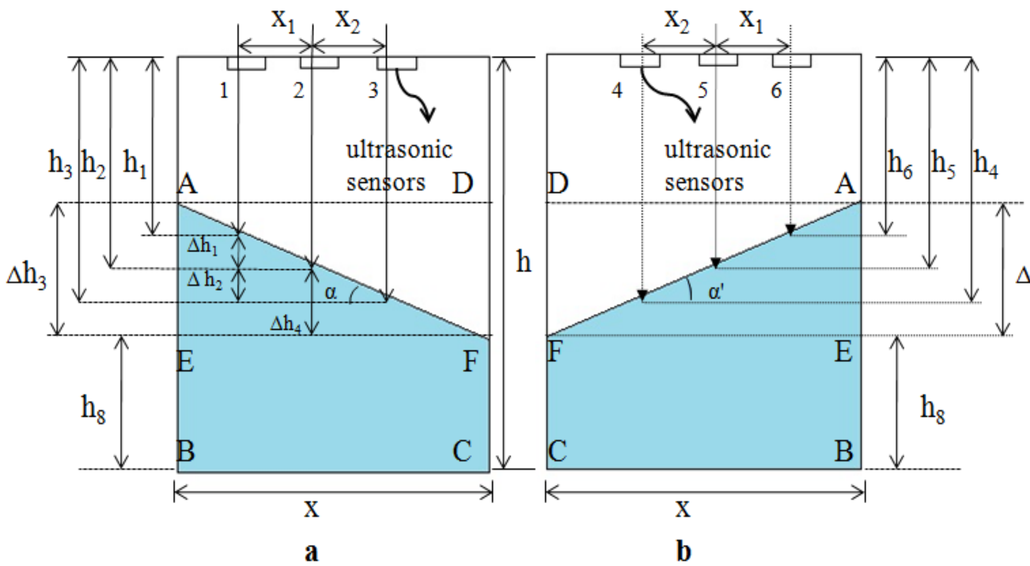

Figure 3. Liquid Tilts Left: a. Back View and b. Front View

In fact the container is a three-dimensional structure, it is reasonable to assume that V_1 represents corresponding liquid volume of point A, E and F andV_2 represents corresponding liquid volume of point A, E, F and D. According to the volume calculation formula in solid geometry, it is known thatV_1equals $V_2/2$.

In other words, it is known that H_1 equals $\Delta h_3/2$. In this equation, it is assumed inclined liquid is converted to a horizontal status, H_1 represents the height of the liquid level relative to EF. From the analysis above, H, the true height of liquid level, equals H_1 plus h_8, and the calculation formula is as shown in formula (3).

$$H = (h - h_2 - \Delta h_4) + \Delta h_3/2 = h - h_2 \tag{3}$$

Similarly, H, the true height of liquid level, can also equals h-h_5.So, it can be concluded that, when the liquid tilts left, which is as shown in Figure 3, the real liquid level height can be calculated by formula (4).

$$H = [(h - h_2) + (h - h_5)]/2 \tag{4}$$

When the tilted status of liquid is as shown in Figure 4, the case is a little different with it in Figure 3, that is(h - h2) is less than AB/2.To simplify the problem, the case in Figure 4-a is considered. According to Figure 4-a, it can be known that AB equals AH plus BH and BC equals BG plus GC. It is assumed that the inclined liquid is placed into a horizontal state, and the real liquid level height, H, can be calculated by formula (5) below.

$$H = BC \times AB / 2x \tag{5}$$

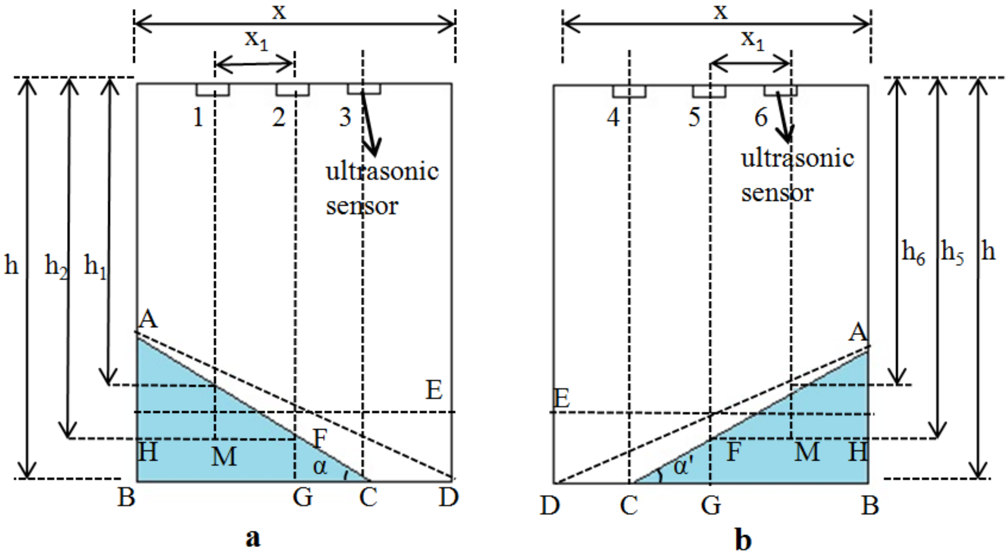

Figure 4. Liquid Tilts Left when Liquid is Little: a. Front View and b. Back View

With all above analyzes, when the liquid tilts left or right, the calculating formula of the liquid level height is as shown in formula (6).

$$H=\begin{cases}[(h-h_2)+(h-h_5)]/2 & (h-h_2 \geq AB/2)\\ (x\cdot\tan\alpha/2+x\cdot\tan\alpha'/2+2h-h_2-h_5)[(x+\cot\alpha\cdot(h-h_2)+\cot\alpha'\cdot(h-h_5)]/8x & (\text{else})\end{cases} \quad (6)$$

In formula(6), $\tan\alpha = |h_2 - h_1|/x_1$, $\tan\alpha' = |h_5 - h_6|/x_1$.

As is shown in Figure 5, when the liquid tilts back or forward , the liquid level height can be calculated according to formula (7).

$$H = h - (h_1 + h_2 + h_3)/3 \quad (7)$$

When the liquid leans to one edge, it is difficult to find a solution to calculate the liquid level height. More sophisticated analyses may be needed under this condition. An approximate method is proposed to calculate liquid level height, which is can be seen in formula (8).

$$H = (S \cdot H_{MC} + V_{E-ABCD} + V_{E-ADFG})/S \quad (8)$$

S represents the base area of the container, and H represents the actual height of the liquid level.

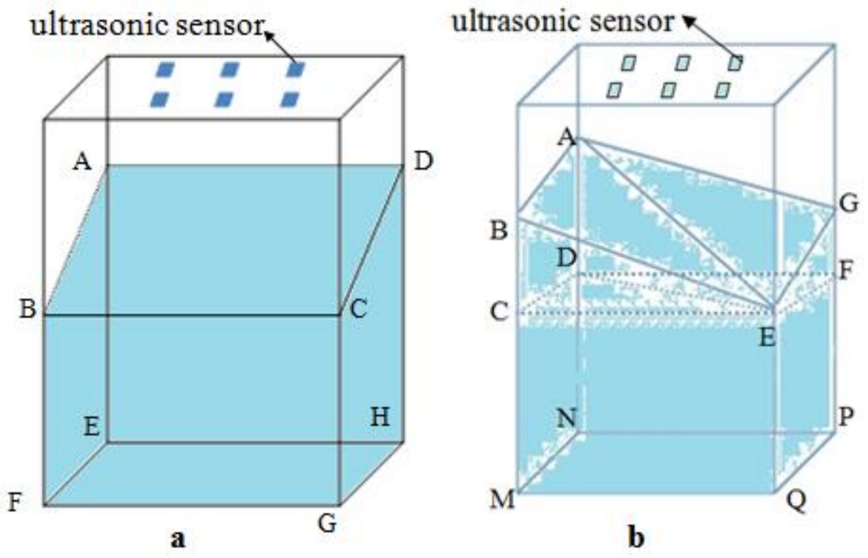

Figure 5. Inclined Status of Liquid: a. Forward Lean; and b. Liquid Leans to One Edge

3. System Design

In this intelligent liquid level monitoring system, Bluetooth chip and USB wireless network card are used for communicating with the back-end so as to realize remote data collection and remote control. Ultrasonic sensors take charge of data acquisition.MCU S3C6410 which is transplanted LINUX operating system is used for getting transit time value of sound waves, then the time is multiplied by sound velocity which needs temperature compensation. As a control core of the front-end, MCU S3C6410 processes data, transmits data and constructs QT interface to achieve visual monitoring. Values of liquid level and angles can be displayed in TFT-LCD relying on the Qt. MCU S3C6410communicates with Bluetooth chip via a serial port. Bluetooth chip send data to the remote in transparent mode. Java program in Processing software can directly receive and send data with Bluetooth chip by serial port communication, and then construct a graphical monitoring interface. The system can also communicated with smart phone. Android APP can control the front-end devices and read the data, and data can also be seen in the specified website.

3.1. Hardware Design

The whole system contains three parts which are as shown in Figure.6. The front-end system contains a data acquisition unit, a control unit, a wireless communication unit, a display unit, and a terminal control unit. The PC terminal contains a voice announcement unit, a Bluetooth communication unit. The smart phone terminal can establish links with the front-end via Bluetooth and network.

HC-SR04 ultrasonic sensors work together [4] to measure distance in the data acquisition unit. HC-SR04 sensors detects the distance from 2cm to 400cm, and the accuracy can reach 0.3cm. Bluetooth chip CC2541 is a power-optimized true system-on-chip (SoC) solution for both Bluetooth low energy and proprietary 2.4-GHz applications. It enables robust network nodes to be built with low total bill-of-material costs. The CC2541 is highly suited for systems where ultralow power consumption is required. This is specified by various operating modes. DS18B20 is a programmable resolution 1-wire digital thermometer and it provides 9 to 12-bit (configurable) temperature readings which indicate the temperature of the device. Speedy wireless transmission of USB wireless network card TL-WN725N is up to 150Mbps ideal for video streaming or internet calls. 7-inch TFT-LCD module is used in the front-end display unit to display the measurement results which can be compared with the terminal data.

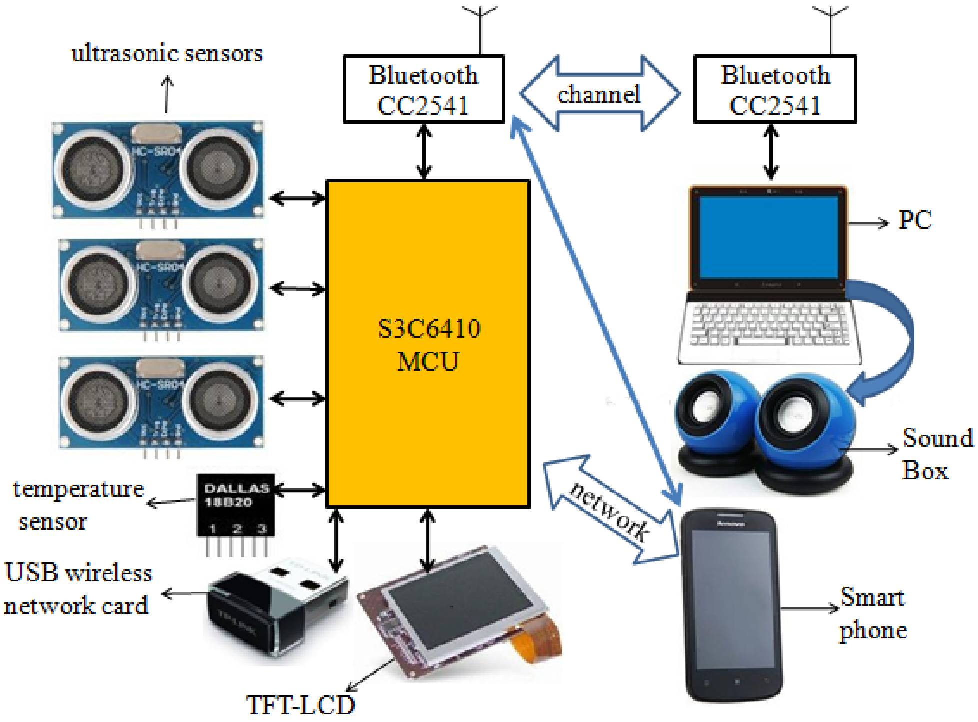

Figure 6. Diagram of the Whole System

An embedded Linux operating system is transplanted to S3C6410 [5] . The back-end terminal uses PC or smart phone for remote monitoring.

3.3. Software Design

3.3.1. Task Scheduling in Linux

There are multiple tasks in this system that are as shown in Figure 7. If the device works well in Linux, the device driver needs to be added to kernel space. According to the design, there are four kinds of drivers are designed to meet the requirement. In order to get the temperature via ds1820, driver file programmed by C language should be mounted to the kernel in the mode of ‘insmod’. It is valid to make HC-SR04, TFT-LCD and wifi card work well in Linux in the same way. In user space, a Qt application program is designed based on QT4.8.5. Qt combines functionality with productivity. You can amaze your users with stunning UIs and native performance by developing your desktop and multiscreen applications with Qt. In this application program , there are five tasks to achieve an overall performance. Each task shares out the work and cooperate with one another. Typically Bluetooth chip CC2541 is mostly transmitting single parameter, and the system needs to transmit a number of parameters, which is supposed to consider how to distinguish different parameters. Without increasing the number of Bluetooth chip, the data needs to be simple coding process to make the PC recognize different parameters. In this design, different parameters are multiplied by different numerical values, which will have a different characteristic, then the processed data is sent to Bluetooth chip through the serial port.

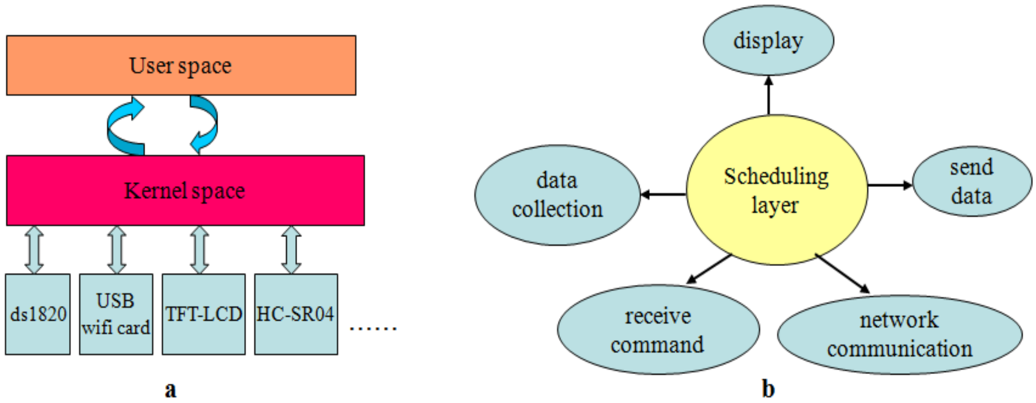

Figure 7. Scheduling Graph in Linux: a. Low Layer Drivers and b. Application Program

3.3.2. Temperature Correction for Ultrasonic Velocity

The distance S, from obstacle to the test point, can be computed by equation (9)

$$S = vt / 2 \tag{9}$$

v is the velocity of ultrasonic waves in air[6][13], t is the transit time of ultrasonic waves.

Relationship between ultrasonic velocity and temperature is as shown in equation (10).

$$v = 331.4\sqrt{1 + T / 273} \tag{10}$$

T is the ambient temperature.

According to equation (10) , it can be get that at 25 °C ultrasonic propagation velocity in the air is 346. 24 m/s, at 0 °C reduced to 331.4 m / s, so the ultrasound propagation velocity in the media is influenced by temperature [7]. To improve the measurement accuracy, temperature compensation should be introduced [8]. In this design, ds1820 collects temperature around, and the data can be applicable to temperature compensation.

3.3.3. Implementation of Filter

General ultrasonic ranging delay algorithm is introduced in [4]. A simple and practical method is adopted in this system. In fact, once the HC-SR04 is triggered, the ECHO port emits a certain time's high level to reflect the ultrasonic transit time, due to noise, deviation of the output of high level may occur, therefore the system need to do some filtering process. After detecting the rising edge, timing interrupt in S3C6410 is triggered. When electrical level appears reversal, the timer will be stopped and the value of the counter represents the time of high level. S3C6410 collects multiple values, then removes the deflection values, averages these remaining values at last. High-performance filter need complex designs, however the above method meets the requirements of this design.

3.3.4. Yeelink Cloud Server

Yeelink is a platform for the Internet of things, which supports data two-way interaction. Sensor data can be read or uploaded on the platform. Equipment data can be uploaded to the Internet via a serial port or TCP[9], then the data is drawn into a curve. On the platform people can create a new long connection to control local equipment including switching device, the motor or other device, then read the value of sensor. As is shown in Figure 7, the front-end device in the system can be controlled by smart phone. The phone can read data which you want to know.

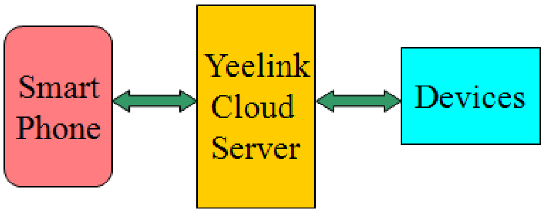

Figure 7. Flow of Control in Yeelink

The equipment data can be obtained via network. Mobile phone which is installed the APP can access to the Internet to check the data from the front-end equipment. The temperature monitoring interface in phone is as shown in Figure 8. At the same time, visiting the corresponding website can also see the same result on the computer.

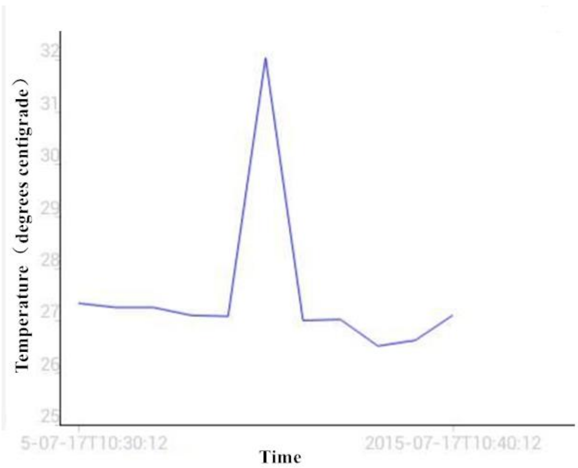

Figure 8. Temperature Monitoring Interface in Smart Phone

3.3.5. PC Terminal Design

PC is the control core in the terminal, and Processing software constructs graphical control and monitoring interface by Java programming[10]. Flow chart of the program is as shown in Figure 9. Principle of voice broadcast is that the Arabic numerals 0-9 are recorded and stored in the 'wav' format in advance, and then the complete distance value is played according to user-defined selection algorithm.

4. Experimental Results

In this section, a simulated test is done to check the accuracy of this ranging system. Actually, distance can be exactly measured by the system within the range of the ranging measurement[11]. In the distance range from 0 to 300 cm, we conducted experiments to test the system, and results are shown in Figure 10. According to the figure, the error rate is confined to2%, and it is accorded with the expecting demand.

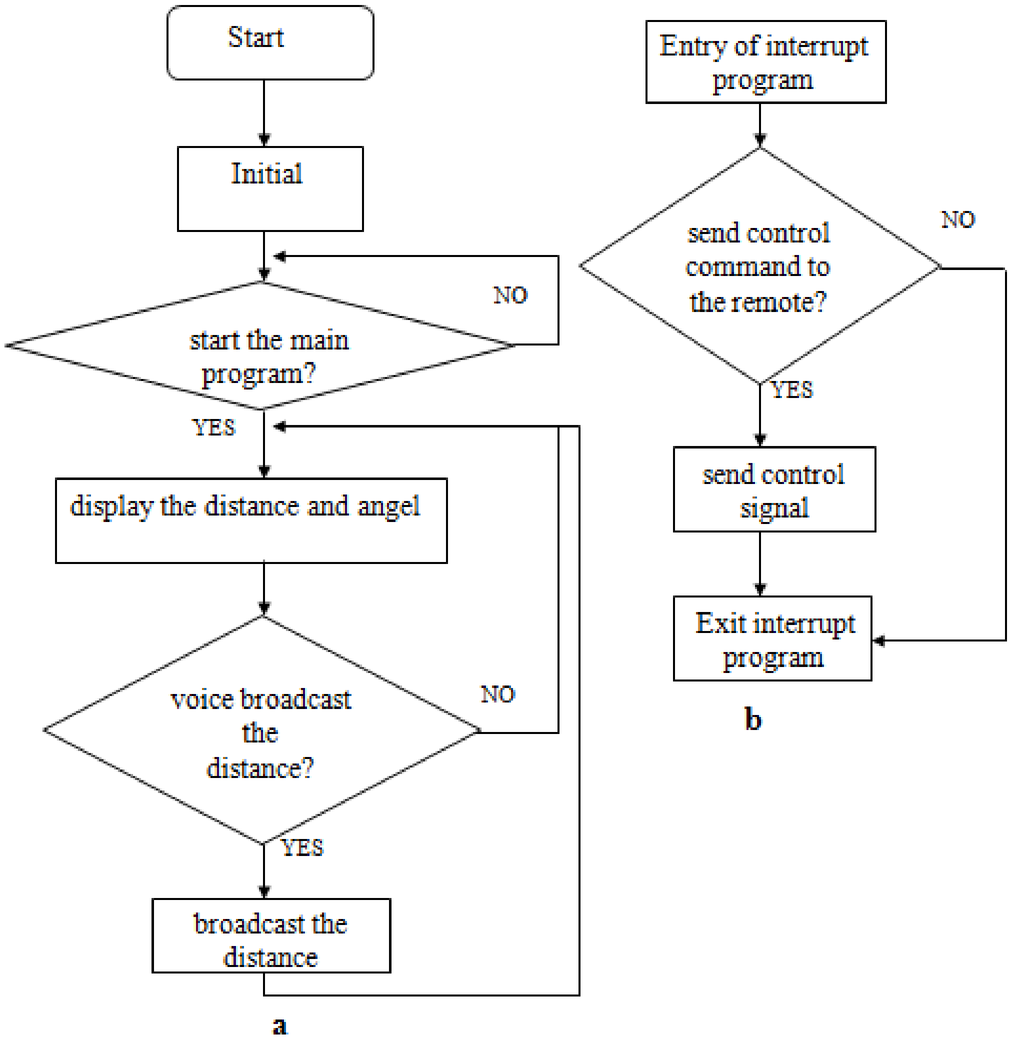

Figure 9. Processing Program: a. Flow Chart of Main Program; and b. Flow Chart of Interrupt Program

Measured values and artificial values are very close, the maximum of error rate is not more than 4%. The 2cm's area in the beginning is sensor's unmeasurable area, so there is a large error at that point. Then as the distance increases, the error rate is decreased. When the distance is more than 50cm, the error rate is increased. The reason may be that the acoustic signal attenuation and divergence can have an impact on the measurement, however it is in acceptable range.

Furthermore, sensors are moved up and down to make a pitch for simulating left incline status, assuming the container height h equals 40cm, width of the container x equals 20cm, the sensor spacing $x_1 = x_2 = 5$cm, and the distance measured by sensor 2 $h_2$equals 35cm. The experimental data is as shown in Table 1 at different inclinations.

Table 1. Test Data Under Simulated Tilt Status

Angle between the sensors	Theoretical height	Measured height
0°	5cm	4.76cm
30°	5.03cm	4.47cm
45°	5.625cm	5.24cm
60°	7.19cm	7.62cm

According to Table 1, the system measurement values are close to the theoretical calculated values, a larger error rate occurs at 30°, but the difference between the theoretical value and the measured value is 5.5mm.In general the level measurement is to meet the requirements, and error rate is less in other angles situation.

A further experiment is set up to measure the distance under tilting condition [12]. A second way to simulate liquid inclined state is to tip a square piece of cardboard in an empty container. The height of the container is 34cm, the length is 25cm, and the width is 19cm. Ultrasonic sensors are fixed to the top of the container, one of them is placed at the midpoint position, which is as shown in Figure 2. Then we tilt the cardboard to make a forward tilt angle to do the test, and some of the data is shown in Table 2.

Table 2. Test Data under Simulating the Leaning Forward Status of Liquid

Tilt Angle of the cardboard	Artificial measurements	Measured height
9°	22.5cm	23.5cm
23°	16.8cm	17.6cm
33°	8.15cm	7.2cm
53°	12.88cm	13.4cm

From the data above, there is a difference of 1 cm or so between the measured and the true value. One of the reasons is that there are errors in the electronic components. another one of the reasons is this system's filtering effect maybe need to be improved better. However, it can be used in many kinds of different occasions which don't require high accuracy of range accuracy.

Meanwhile monitoring interface in Processing terminal as shown in Figure 11. Display interface includes a display section and a control section, the blue histogram display the liquid height from surface to the bottom of the container, the blue circle graph shows the angle, there are three control buttons on top of the display part to remotely control devices from the front-end. The temperature can also be added as a secondary display in the interface, which is convenient for the latter upgrades. Note that terminal is created by Processing programming, it can also be easy to carry out speech broadcast the data.

This program is a simple module which is easy for the upgrade later. It does not need writing many codes to achieve more functions, instead uses inner classes libraries to do the work[14].

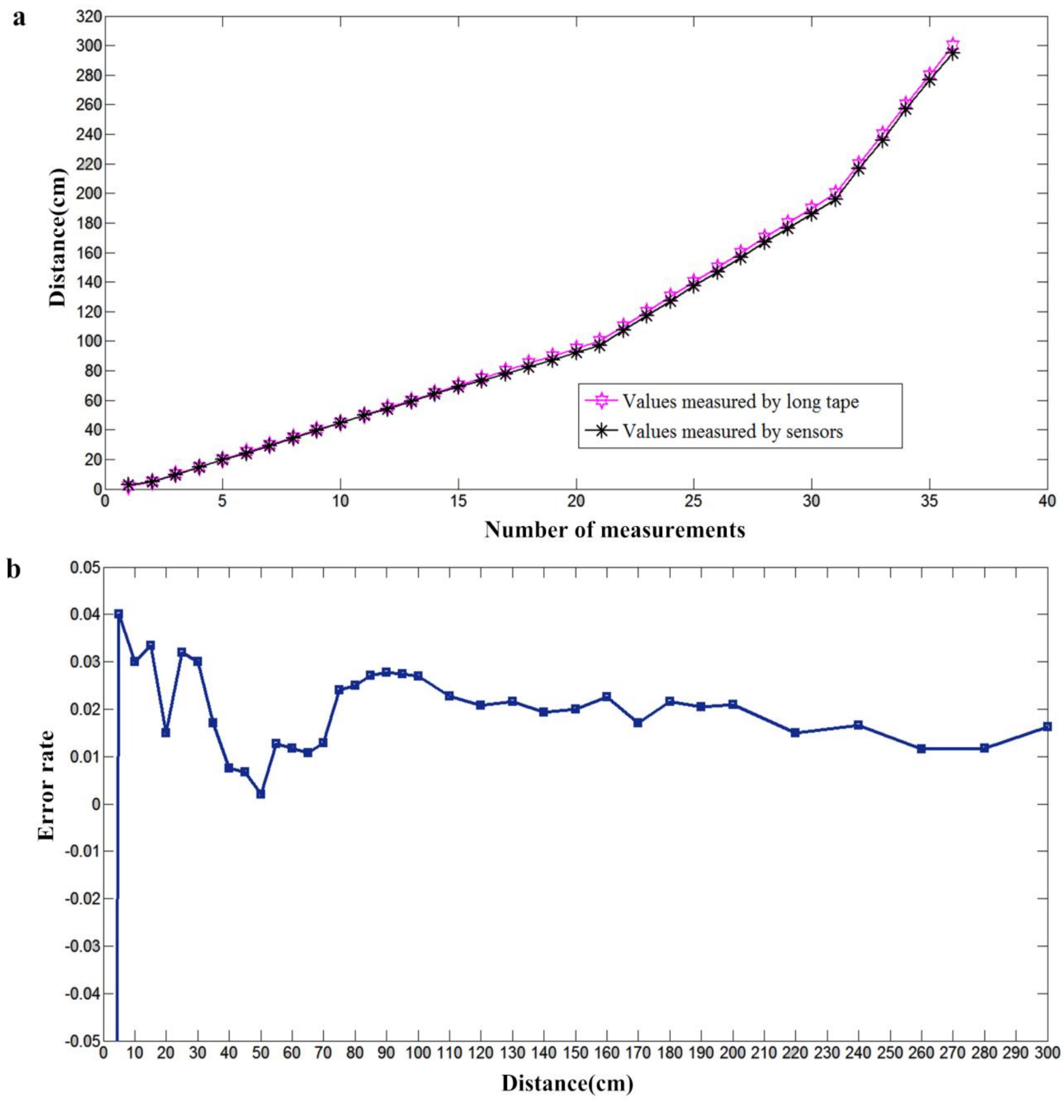

Figure 10. Experiment Data : a. Comparison between the Measured Values and Actual Values; and b. Error Rate

5. Conclusions

In this work, we propose a method of using ultrasonic sensors to work together to monitor the dynamic level, and an algorithm is put forward based on mathematical analysis of liquid level, which the liquid level height can accurately be known in the case of tilting or shaking. Meanwhile, Processing software constructs a graphical display interface by programming to facilitate monitoring, and finally Bluetooth chip CC2541and wireless LAN are used to implement wireless data transmission. The mode of point to multipoint is allowed in Bluetooth protocol, and CC2541 can achieve a single master connects with multi-slavers, so it can be convenient to expand the sensor network in the system. Smart phone is another terminal to monitor the front-end system.

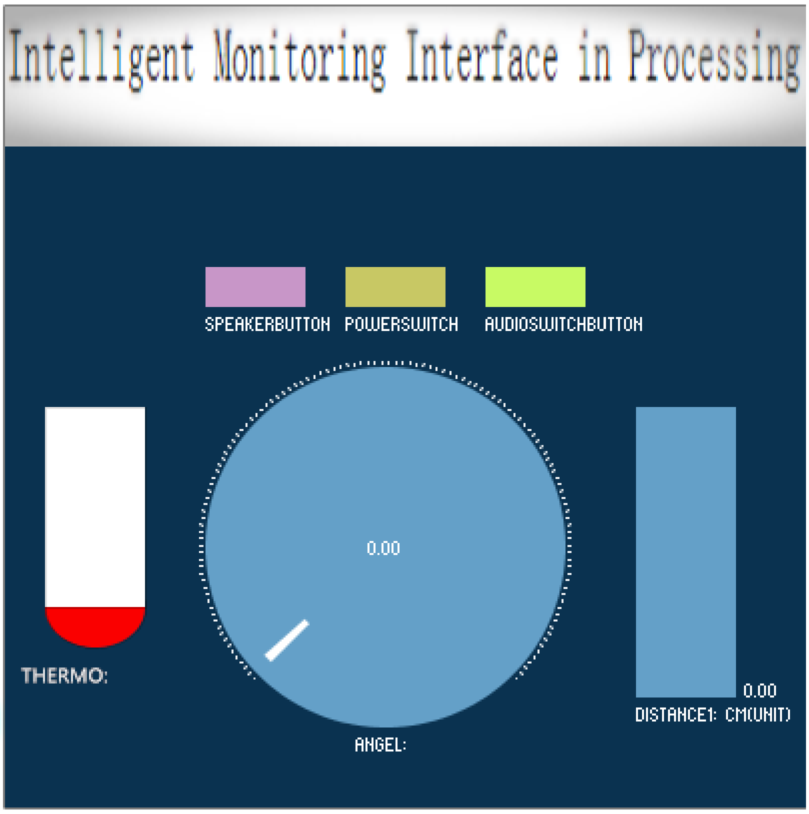

Figure 11. Intelligent Monitoring Interface in PC

Since this design only uses three sensors, when the liquid appears bigger tilt, large errors may occur, but as long as increasing the number of sensors, errors can be reduced according to the analysis above. The design also needs some improvement later, for example, we need to further enhance the accuracy of distance measurement, and we should pay attention to the communication between different gateways. In short, this system should be more intelligent by improving the performance of each part.

Acknowledgments

This work was financially supported by the Program for Changjiang Scholars and Innovative Research Teams in Universities Project (No. IRT13064), Guangdong Innovative Research Team Program (No. 2011D039) and Shenzhen Science and Technology Plan (No.JSGG20130922112354765).

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