Application Note

Liquid Level Detection System Based on MSP430 CapTIvate Technology

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ABSTRACT

This application note introduces a system solution for liquid level detection using a capacitive touch MCU. It introduces the basic principles of capacitive touch to detect liquid level. Then it uses MSP430FR2533 capacitive touch MCU to design the system, finish the debugging of the software code, and verify the solution with a bench test. The test results show that the solution can accurately measure the depth of the liquid. Furthermore, four different electrode connection methods and two different capacitance measurement methods are tested and compared. Ultimately, it introduce a software optimization for the large error in small liquid heights.

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1 Introduction

In some application scenarios of capacitive touch, the customer might not want to use capacitive touch to detect whether the button is pressed, but instead they want to use the principle of capacitive touch to detect the depth of a liquid, such as the depth of the humidifier water tank or a vacuum robot water tank. To meet the needs of customers, this paper designs a liquid level detection system based on the MSP430FR2533 capacitive touch MCU, which can be simple, convenient and flexible for liquid depth measurement, and at the same time can achieve high accuracy water level measurement and low system cost. Figure 1-1 is a simplified schematic diagram of the liquid level detection system.

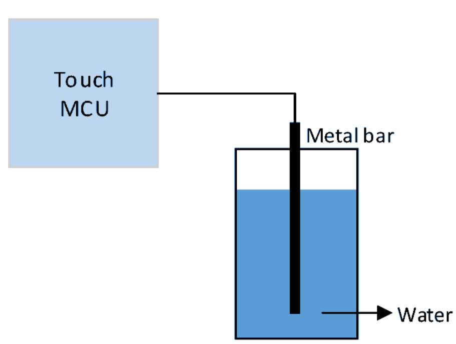

Figure 1-1. Simplified Schematic of Liquid Level Detection System

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2 Basic Knowledge and Principles of Self-Inductive Capacitive Touch

Taking the simplest single button as an example, Figure 2-1 shows a self-inductive capacitor, and Figure 2-2 shows the detection model. The self-inductive capacitor uses a single electrode (receiving electrode Rx) formed by copper coating to detect the change in capacitance of the electrode to the power line ground. The initial capacitance of the button to power line ground is Cp. When a human hand touches it, Ct, Ch, and Cg are introduced into the circuit, thereby increasing the capacitance of the button to ground

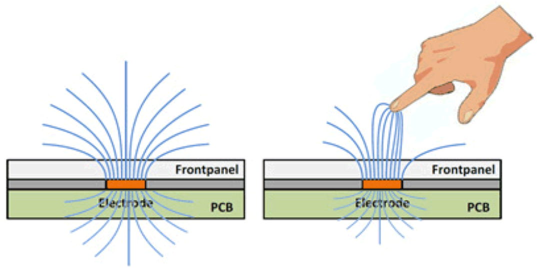

Figure 2-1. Self-Capacitive Detection

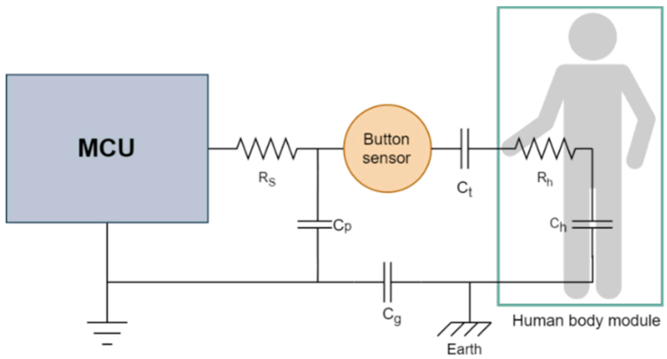

Figure 2-2. Self-Capacitive Detection Model

In Figure 2-2, the solid line indicates the PCB routing, and the dashed line indicates the touch-related routing. Gray components indicate equivalent capacitance or resistance.

R_h = Human body resistance.

R_s = Series resistance. The recommend value is 470 Ω.

C_p = The parasitic capacitance of the button and the connected wire to the power line ground.

C_g = The capacitance between the power line ground and the earth ground. For battery applications, it is approximately 1pF. For grounding applications, it is a short circuit.

C_h = Series capacitance between the human body and the earth ground.

C_t = The capacitance formed by the electrical level and the human fingertip, which is similar to the structure of a parallel plate capacitance.

For ease of analysis, the influence of R_h and R_s is ignored. Equation 1 shows the equivalent capacitance of the button to the power line ground. Sensitivity can be characterized as the ratio between the capacitance change caused by the touch and the base capacitance, as shown in Equation 2. Among them, C_h is larger than C_g and C_t, so it can be ignored.

$$C_{equal} = C_{touch} + C_{base} = C_t\,||C_h\,||C_g + C_p \approx C_t\,||C_g + C_p \tag{1}$$

$$Sensitivity = \frac{C_{equal} - C_{base}}{C_{base}} = \frac{C_t||C_h||C_g}{C_p} \approx \frac{C_t||C_g}{C_p} \tag{2}$$

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The parallel plate capacitance is calculated by:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{3}$$

Where:

- A = The contact area between the finger and the sensor pad covering layer.
- d = The thickness of the overlay.
- ε_0 = Air dielectric constant.
- ε_r = The dielectric constant of the overlay.

It can be seen from Equation 2 and Equation 3 that the methods to change the sensitivity are:

- Reduce the thickness of the cover plate to increase the sensitivity.
- Reduce the density of the grid ground, or increase the PCB thickness to reduce the sensitivity.
- Connect the power ground to the earth ground to increase the sensitivity.
- Increase the contact area A between the finger and the sensor pad covering layer to increase the sensitivity.

The electrode size cannot increase indefinitely. The main reason is that the maximum effective area of the parallel plate capacitance C_t is the same as the finger touch area. Therefore, C_t would also increase, resulting in a decrease in sensitivity.

TI's CapTIvate capacitive touch sensing technology is based on charge transfer collection. The operation includes 1) charging the sensor input capacitor C_{equal} and 2) transferring the accumulated charge to the internal sampling capacitor C_{sample}.

This process repeats until the voltage on both sides of C_{sample} reach the trigger voltage V_{trip} of the internal comparator. The number of charge transfers required to reach the threshold directly characterizes the size of C_{equal}. When the capacitive sensor is touched by a human hand, C_{equal} and charge transfer values change. The MCU senses the occurrence of a touch event by comparing the numbers of different charge transfer cycles. The MSP430 MCU uses a current mirror to control the proportional relationship between the input current of C_{sample} and the discharge current of C_{equal}, to equivalently amplify C_{sample} and have a larger range. For self-capacitive detection, C_{equal} is equal to the capacitance between ground and RX I/O port. Through the charge and discharge to the ground, the electric charge in C_{equal} is transferred to the internal C_{sample}.

The above is about the change of the capacitance value of the key when the human hand touches the button. Similarly, if the button is replaced by a metal conductor bar, and the human body is replaced by a liquid substance (such as water), it causes the capacitance of the whole metal bar to the ground to change when the water touches the metal conductor bar. The capacitance value of the metal bar to the ground also changes when the water level changes. Through the change in capacitance value, we can determine whether there is water in the object being detected, as well as the depth of the water level. Figure 2-3 shows the detection model.

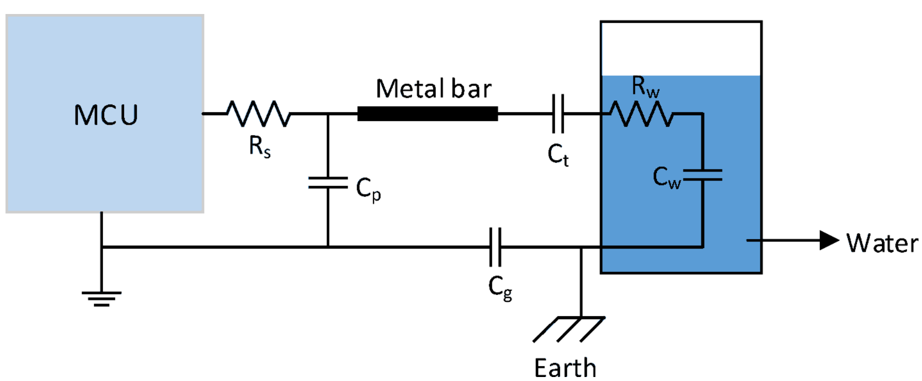

Figure 2-3. Liquid Level Detection Model

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3 MSP430FR2533 Liquid Level Measurement Application

This chapter uses CapTIvate Design Center to complete the design of the liquid detection system. Based on this, the MSP430FR2533 hardware platform for liquid level detection and system algorithm writing are completed. Meanwhile, different electrode connection and measurement method comparison tests are carried out. Finally, for the issue of large error at low heights, a software optimization method is introduced.

3.1 System Design

Configure the GUI. Configure the corresponding MCU and virtual sensors and generate the program source code. Refer to the CapTIvate handbook for the specific process. Figure 3-1 shows the capacitive touch project file and the generated source code

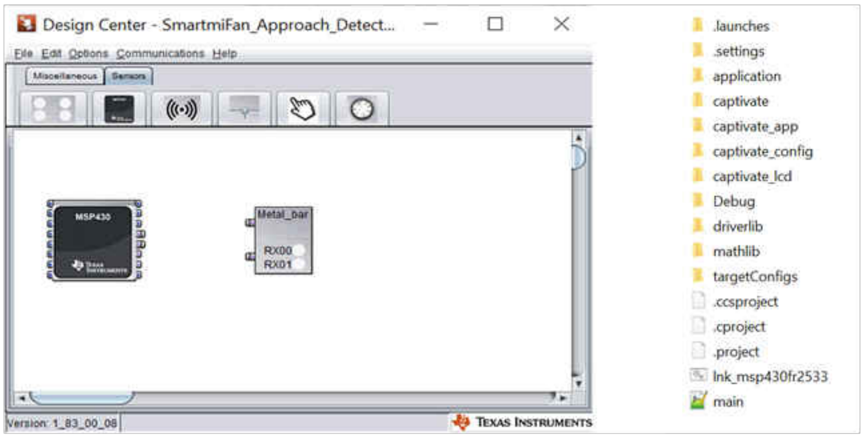

Figure 3-1. Capacitive Touch Project File and Generated Source Code

Figure 3-2 shows the important parameter relationships in CapTIvate, where the parameters are relevant to the liquid level detection

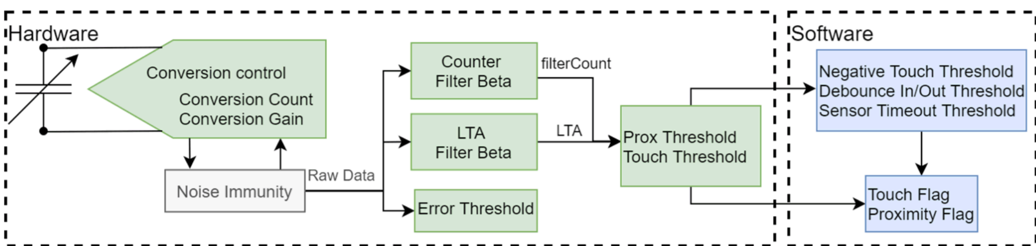

Figure 3-2. Parameter Relationships

The parameters are divided into hardware configuration parameters and software configuration parameters. First, the sampling module generates raw data by detecting the external capacitance. Conversion Count and Conversion Gain determine the gain of the sampling module. Then the data passes through the optional anti-noise module (sampling frequency spread spectrum, oversampling, and other functions) to achieve noise filtering. The output data is first compared to the Error Threshold. Then filterCount is generated through IIR filtering of different intensities, which is used to characterize real-time capacitance changes, and LTA (long time average, default is 7) is used to characterize the base capacitance of the environment. Here filterCount corresponds to "Count" in the GUI data monitoring module, and LTA corresponds to "LTA". The Delta between the two is used to characterize the change of capacitance generated by a touch. The relationship between the capacitance change percentage caused by the touch and the filterCount and LTA is shown in Equation 5. For self-capacitance detection, Delta is a positive value.

$$Delta = \text{filterCount} - \text{LTA} \tag{4}$$

$$\Delta C_{touch} = C_{touch} - C_{base} = \alpha^{*}\text{Gain}\left(\frac{1}{\text{LTA} + \text{Delta}} - \frac{1}{\text{LTA}}\right) \tag{5}$$

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3.2 Hardware Design

The hardware of this design mainly includes power supply, MCU, LCD display, and communication interface. The power supply converts 5-V USB to 3.3 V for the MCU. Figure 3-3 shows the design of the MCU and peripheral circuits. Figure 3-4 shows the LCD design. Communication protocol uses I2C and UART.

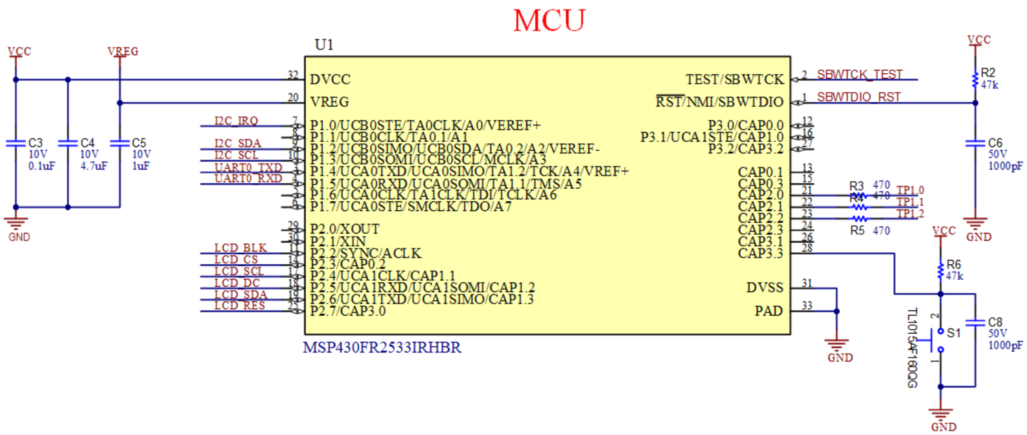

Figure 3-3. Schematic Diagram of MSP430FR2533

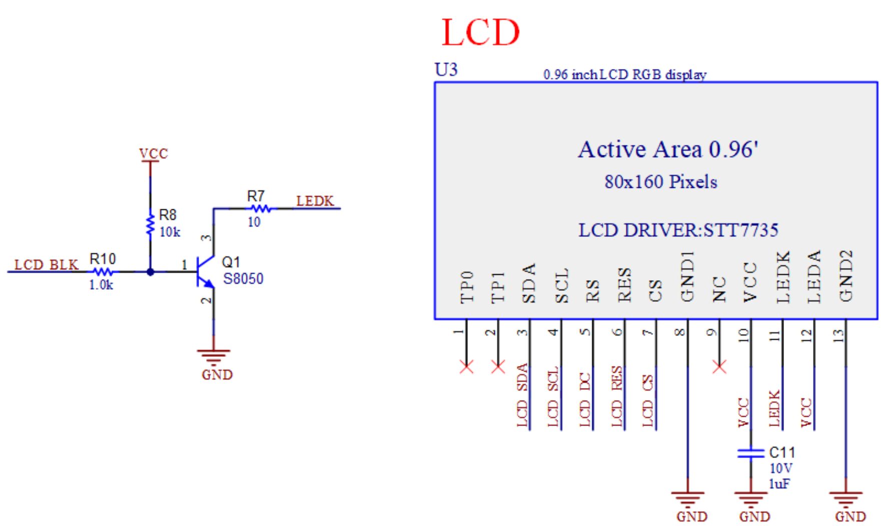

Figure 3-4. Schematic Diagram of LCD

Figure 3-5 shows the 3D PCB. Three electrodes are designed in this circuit, which are respectively used for environmental calibration, actual liquid level measurement and liquid level alarm prompt.

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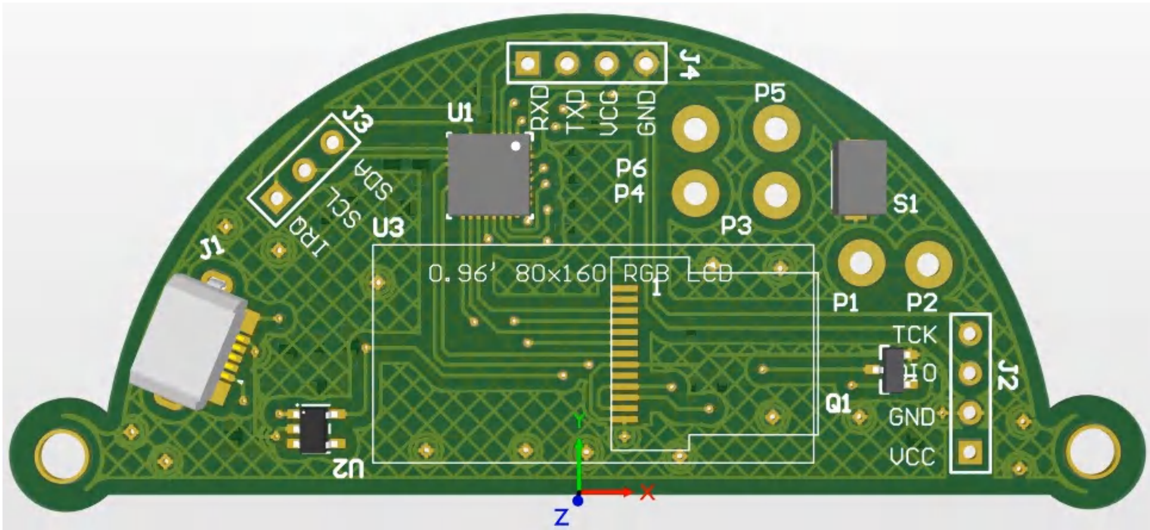

Figure 3-5. PCB and Circuit Board of Liquid Level Measurement Application

3.3 Software Design

A. Liquid Level Height Calculation

To show level height on the LCD, the application must measure the capacitance value at different liquid level heights. As Equation 6 shows, measure LTA and COUNT, and then calculate the ΔC_{touch} .

$$\Delta C_{touch} = C_{touch} - C_{base} = \alpha * \mathrm{Gain}\left(\frac{1}{\mathrm{LTA + Delta}} - \frac{1}{\mathrm{LTA}}\right) \quad (6)$$

By measuring multiple sets of data, Figure 3-6 shows the relationship between the liquid level height and the capacitance value change. According to the fitting result, the relationship between the liquid level height and the ΔC_{touch} is: $Y = 341.5X - 34.249$.

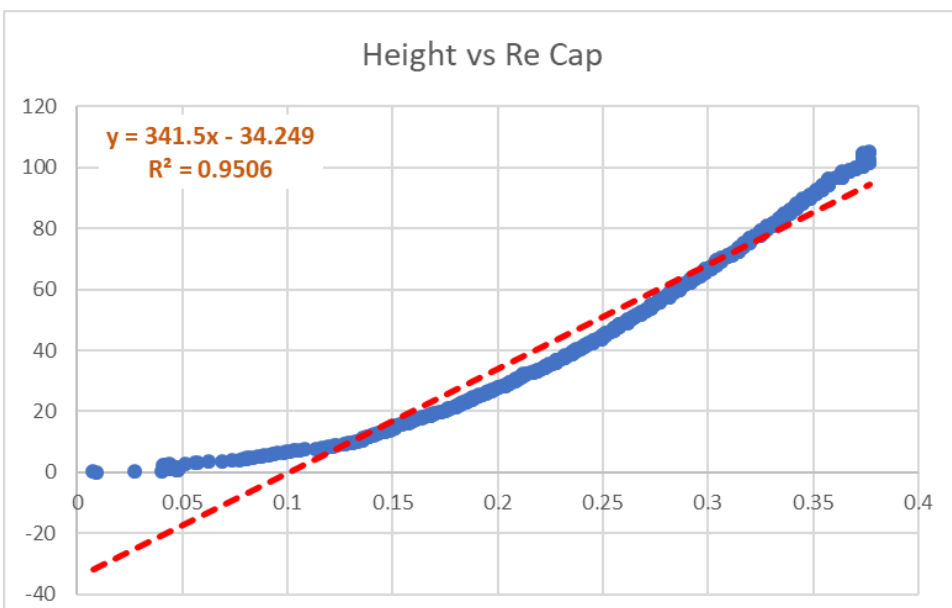

Figure 3-6. Correspondence Between Height and Capacitance Change

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B. Flow chart

The software design mainly includes three parts: capacitance detection, LCD display liquid level height and I2C communication. Figure 3-7 shows the overall code design flow chart.

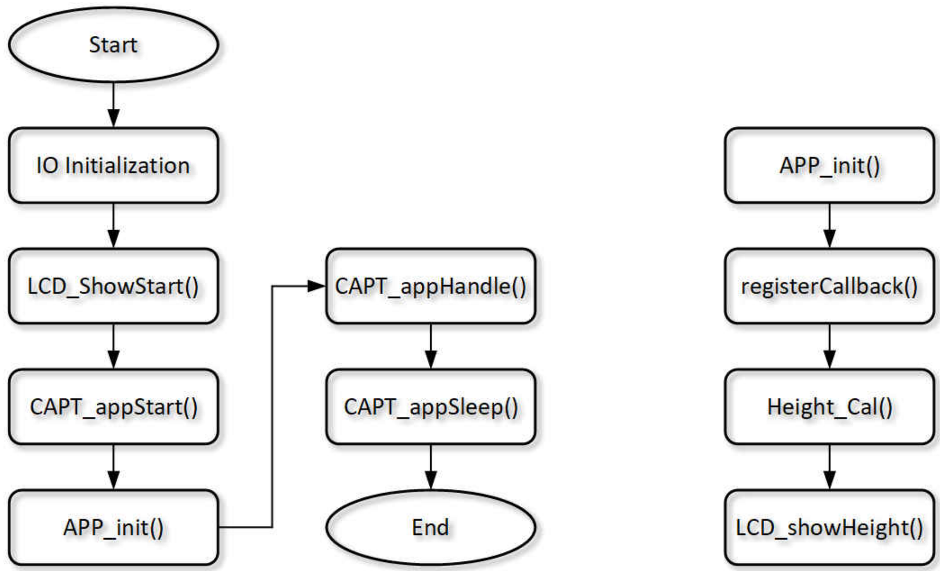

Figure 3-7. Overall Code Design Flow Chart

When the program starts, the MCU initializes the IO ports, clock, etc. Then the LCD displays "Start" to indicate that the measurement can be performed. After a short delay, the measurement is started through *CAPT_appStart()*, and the measurement function is called back in *APP_init()*. The *APP_init()* function includes continuously scanning each channel, calculating the height in real time according to the scanned data, and displaying it through the LCD.

C. Calibration and Communication

Communication with the host MCU is recommended for development using the provided UART and I2C library functions. First of all, the default code generated by the GUI will complete IO configuration and clock configuration of the UART (eUSCI_A0) and I2C (eUSCI_B0) in the *BSP_configureMCU()* function. Therefore, it is only necessary to configure the communication module and write the communication protocol. This design uses the I2C to communicate with the host, which can send commands to perform calibration and receive data from the slave. The specific operation steps are as follows:

1. Directly modify the definition of CapTIvate_config→CAPT_UserConfig.h→CAPT_INTERFACE , the default is UART, change to I2C communication
2. Write a custom frame processing function, because I2C send and receive share a 32-byte buffer here, and the receive and send data segment in this buffer has an offset of 3 bytes. Therefore, the fourth byte of the buffer corresponds to the first byte of the received or transmitted data. Table 3-1 shows the communication protocol.

Table 3-1. I²C Communication Protocol

Master	Host
pBuffer[0]-[3]	Not care
pBuffer[4] = 01	Do calibration
pBuffer[5] = 01	Save height data to pBuffer[6]
pBuffer[7] = 01	Save code version to pBuffer[8]
pBuffer[9] = 01	Bootloader, software update

When the MCU receives the data sent by the host, if the fourth bit of the data is 0x01, the MCU performs calibration. If the fifth bit of the data is 0x01, the height data is stored in *pBuffer[6]*, and the host can read it. If

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the seventh bit is 0x01, the host can read the version number from *pBuffer[8]*. If the ninth bit is 0x01, that is for bootloader, the software can be updated.

3.4 Test Results

A. Test Environment

Figure 3-8 shows the test environment, which requires a sink, pump, PCB, and electrodes (metal bar). The PCB is designed to be semi-circular to facilitate filling the cup with water.

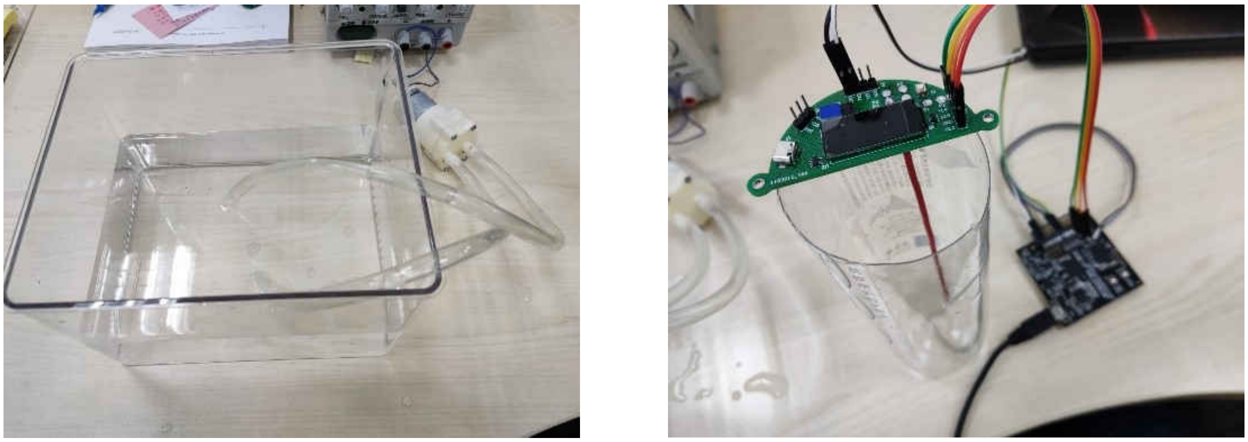

Figure 3-8. Test Environment for Liquid Level Detection

B. Electrode Connection Test

To explore the impact of different electrode connections on the measurement results, relative capacitance changes and height measurements were performed for different electrode connections. Four different electrode connection tests are carried out (see Figure 3-9).

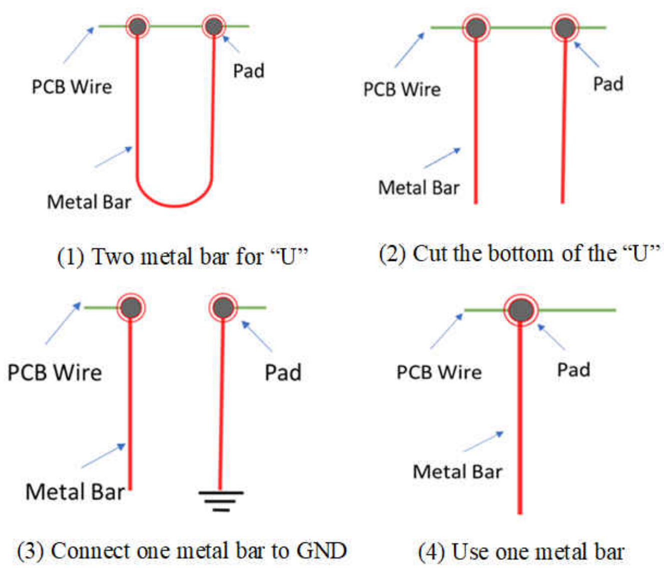

Figure 3-9. Four Different Electrode Connection Tests

Based on four different electrode connection methods, Figure 3-10 shows the test results.

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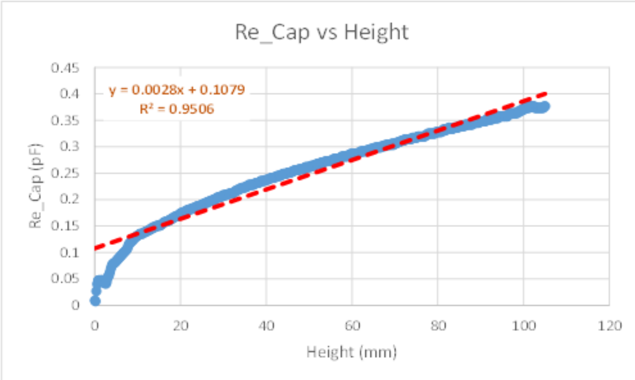
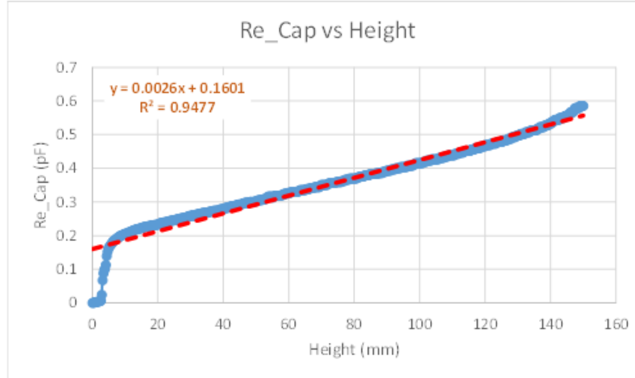
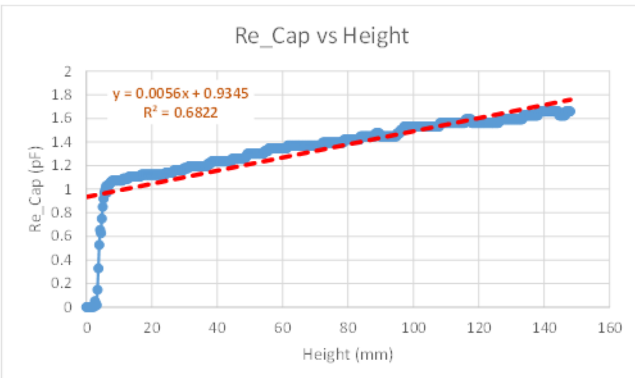


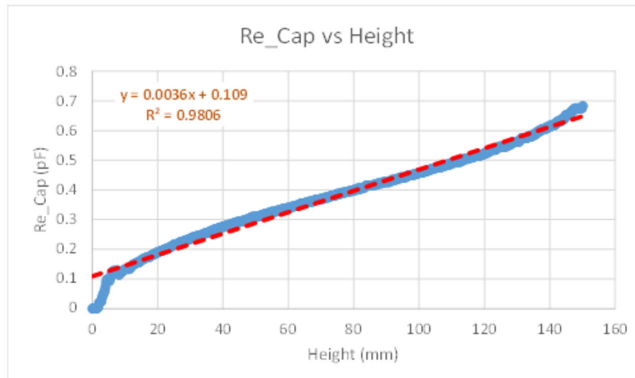
(1) Electrode Connections Test 1



(2) Electrode Connections Test 2



(3) Electrode Connections Test 3



(4) Electrode Connections Test 4

Figure 3-10. Relative Capacitance Change vs Height Curve of Four Connections

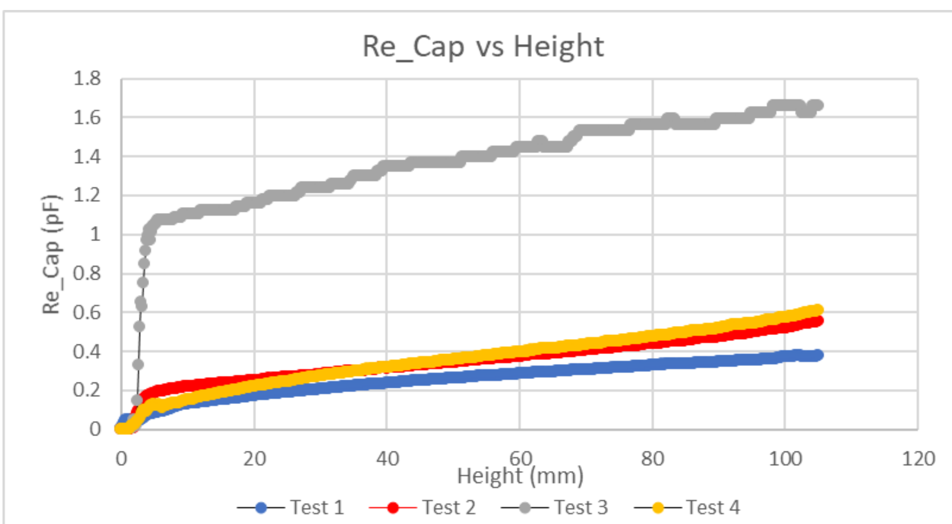


Figure 3-11. Comparison of the Results of Test 1 Through Test 4

According to the test results, when Height < 10 mm, the error of all tests is large due to the poor curve fitting. In addition, Figure 3-11 shows that the performance of Test 3 was poor because the bottom copper wires of the two electrodes were connected together by water creating a short circuit. For the remaining three sets of tests, the trend of the curves is basically the same, and the performance of each test is carefully compared, as shown in Table 3-2.

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Table 3-2. Comparison of the Performance of All Tests

Test	Capacitance Change (H = 10 mm)	Linearity (R^2)	Sensitivity (per 10 mm)
1	14%	0.9506	2.5%
2	20%	0.9477	2.88%
3	110%	0.6822	4.75%
4	15%	0.9806	3.25%

According to this table, comprehensively comparing capacitance change (H=10mm), linearity and capacitive sensitivity, Test 4 has the best performance. Meanwhile, Test 4 has the simplest structure for easy implementation and application.

C. Absolute Capacitance Test

There are generally two measurement methods for capacitive test. The first one is to test relative capacitance change, and the other is test absolute capacitance change. In order to compare the difference between the two methods, the measurement of absolute capacitance was carried out at the same time as the above measurement. Here only take Test 1 is as an example, and the measurement results are showed in Figure 3-12.

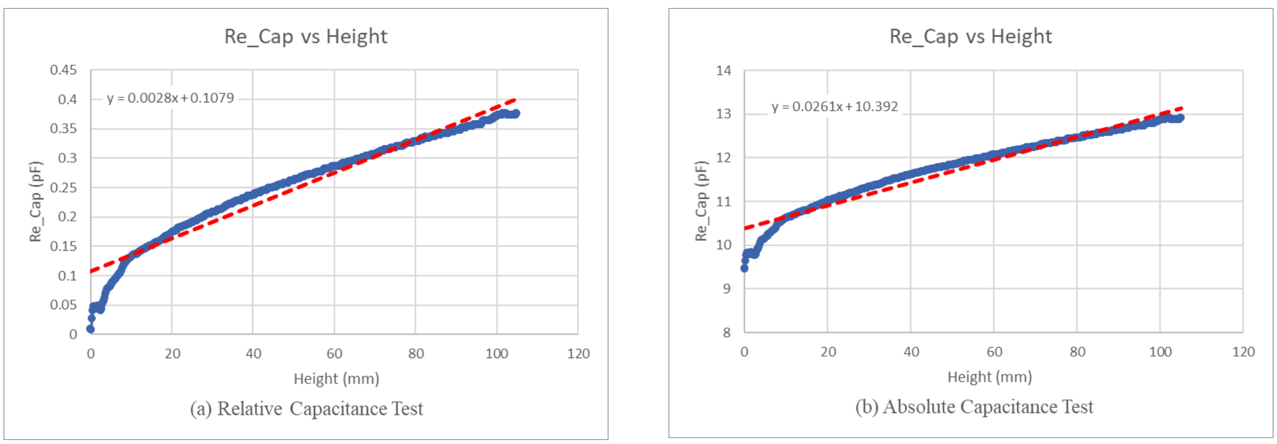

Figure 3-12. Comparison of Relative and Absolute Capacitance Test

Comparing the above results, it is found that the absolute capacitance measurement can read the actual value of the capacitance, and it is between 9.5 and 13 pF. Its changing trend is the same as that of relative capacitance.

Comparing the resolutions of the two, since the base capacitance of the relative capacitance is smaller, the resolution during measurement is higher, but the absolute capacitance can suppress the influence of temperature drift on the measurement results. Therefore, in different applications, the corresponding measurement method can be selected for measurement.

D. Software Optimization

According to the previous test, when height is small (less than 20 mm), the curve fitting is not good (take Test 4 as an example), as shown in Figure 3-13, the fitting function can be expressed as: $Y= 248.5X-21.604$.

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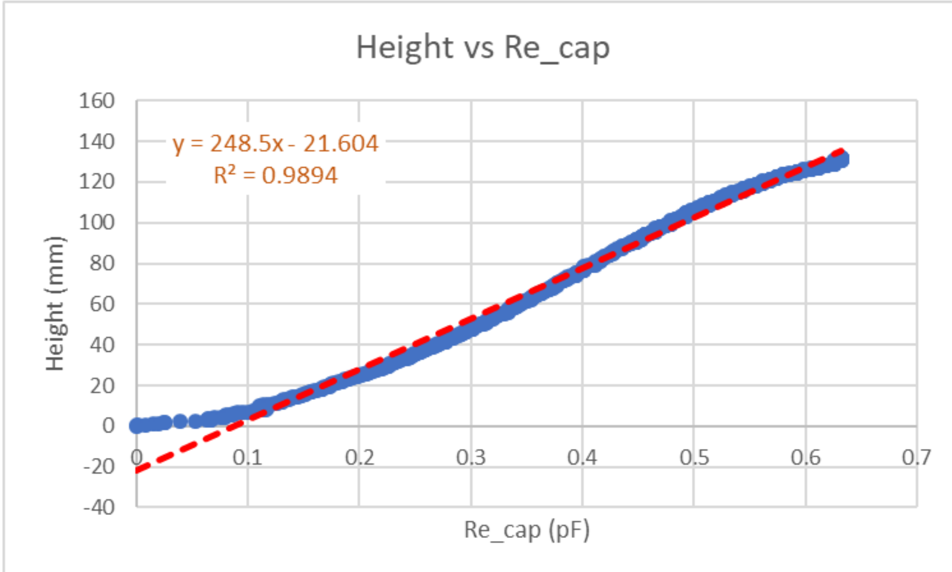

Figure 3-13. Height vs Relative Capacitance Change Curve Fit

To express the measurement error more intuitively, the software is optimized for the measurement. When Height<20mm, use quadratic function fitting, when Height>20mm, use linear function fitting, as shown in Figure 3-14.

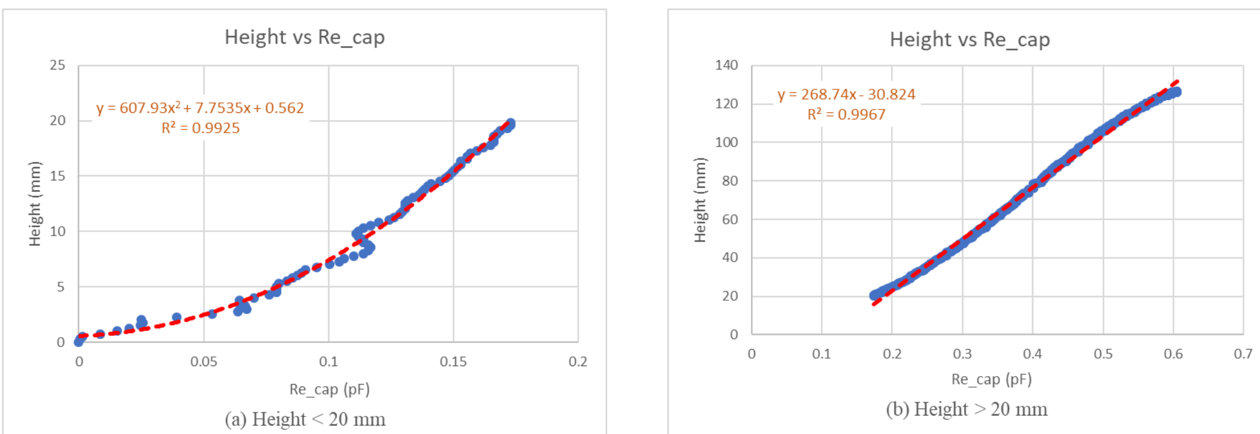

Figure 3-14. Height vs Relative Capacitance Change Curve Fit (Software Optimization)

For the two fitting methods, measurements are taken every 10 mm, and Table 3-3 lists the obtained errors.

Table 3-3. Performance of the Software Optimization Test

Actual Height (mm)	LTA	Count	Delta	Simulation1 Height (mm)	Error1 (%)	Simulation2 Height (mm)	Error2 (%)
10	496	319	0.111867	6.194880069	-38.051199	8.96200886	-10.379911
20	496	266	0.174327	21.71624618	8.581230	20.206227	1.031135
30	496	234	0.225738	34.49177474	14.972582	29.8407022	-0.530992
40	496	212	0.267871	44.96186022	12.404650	41.1635625	2.908906
50	496	19	0.308591	55.08090783	10.161815	52.1067933	4.213586
60	496	183	0.344835	64.08754328	6.812572	61.8470074	3.078345
70	496	173	0.376422	71.93681205	2.766874	70.3355889	0.479412
80	496	163	0.411884	80.74918128	0.936476	79.865714	-0.167857
90	496	155	0.443548	88.61777419	-1.535806	88.3751936	-1.805340

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Table 3-3. Performance of the Software Optimization Test (continued)

Actual Height (mm)	LTA	Count	Delta	Simulation1 Height (mm)	Error1 (%)	Simulation2 Height (mm)	Error2 (%)
100	496	147	0.478659	97.3428126	-2.657187	97.8108749	-2.189125

Figure 3-15 shows the test error of the two methods.

Figure 3-15. Test Error Comparison

Obviously, the first method has a very large error before 20 mm, and the second method uses a quadratic function to fit when height<20 mm, and the overall error is within 10.4%, which greatly reduces the measurement error.

In conclusion, according to the above measurement results, in this experiment, the use of a single electrode (Test 4), relative capacitance and software optimization can get the better measurement results. Of course, according to different application, other measurement methods or electrode connection methods can be selected.

4 Conclusion

This application note proposes a simple liquid level depth measurement system based on MSP430FR2533 capacitive touch MCU, and displays the liquid level height through LCD. It mainly introduces the working principle of capacitive touch and the corresponding software and hardware design. Based on the design, several tests were carried out, including the test of different electrode connections, the test of absolute capacitance and relative capacitance, and the test of software optimization. The test results show that in this application, **the software-optimized, single-electrode, and relative capacitance measurement method** can achieve better measurement results.

MSP430 family provides other types of MCU to realize liquid level detection. For less I/O ports demand, MSP430FR2512 can implement the required functionality. Also, for specific application, customer need to choose the appropriate system design, electrode connection, and measurement method.

5 References

1. *CapTIvate™ Touch MCUs Getting Started Guide*
2. *MSP430FR263x, MSP430FR253x Capacitive Touch Sensing Mixed-Signal Microcontrollers data sheet*
3. *MSP430FR4xx and MSP430FR2xx Family User's Guide*
4. *Liquid Level Detection System Reference Code and PCB Design*

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6 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (January 2022) to Revision A (October 2022) **Page**

- Changed the title of this application note; major updates throughout to change the application to using the MSP430FR2533.. 1
- Changed all of to new application based on the MSP430FR2533.. 4

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