

A Capacitive Transparent Liquid Concentration Detecting System Based on LabVIEW

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Abstract. The accurate detection of transparent liquid concentrations holds widespread applications in production and daily life, making the design and development of novel detection systems crucial. In this study, a capacitance-based detection system for measuring the concentration of transparent liquids was successfully designed and implemented. The system utilized a cylindrical capacitive sensor and FDC2214 module for capacitance measurement, with data acquisition, processing, and display accomplished through an Arduino microcontroller and a LabVIEW program. The results of practical detections demonstrate that the developed system exhibits advantages such as non-contact operation, low cost, high accuracy, minimal sample requirement, and rapid detection speed. This system effectively meets the demands for transparent liquid concentration detection.

Keywords: Concentration Detection, Capacitive Sensor, FDC2214, Transparent Liquid.

1. Introduction

Liquid concentration is a primary parameter characterizing the properties of solutions. Achieving accurate measurement of liquid concentration holds significant practical importance in various fields such as chemical engineering, food industry, pharmaceuticals, aquaculture, and environmental monitoring. In laboratory settings, reevaluation of the concentration of chemicals stored for extended periods is necessary due to factors like volatilization. In industrial production, precise control over the addition of liquids is crucial as product quality is often directly related to the concentration of added liquids. In the food industry, determining the concentration of colorless liquids such as sucrose, alcohol, tea polyphenols, and others holds considerable significance [1].

Among mature detection methods, the density method, which relies on extensive sample solutions to analyze liquid density, incurs substantial sample loss [2]. Optical methods often involve measuring the minimum deviation angle or optical rotation to determine liquid concentration [3], demanding high stability of the light source. Chemical analysis methods, such as titration, require manual sampling of the solution, often involving corrosive chemical reagents and posing high safety risks[4].

To address the limitations of these methods, researchers have developed a minimal microfluidic metamaterial sensor. By introducing an enhanced coupling effect between improved split-ring resonators (SRR) and metamaterial transmission lines (MTL), this sensor demonstrates better performance in measuring high-loss samples[5]. However, direct contact between the test sample and the sensor may lead to chemical reactions. Another approach proposed by scholars involves the use of ultrasonic sensing technology[6], which reduces the quality factor of the sensor but requires improvement in stability.

Therefore, improving existing methods for detecting the concentration of transparent liquids to achieve low cost, high precision, and automation holds practical significance. This study focuses on the determination of transparent liquid concentration, designing and developing a capacitance-based system for detecting the concentration of transparent liquids using LabVIEW. The system enables automatic data acquisition and real-time display of liquid concentration, enhancing the automation level of the device. While ensuring the ability to acquisition liquid concentration, the system also achieves improved precision, reduced errors, and lower uncertainty.

2. System design and implementation

2.1. Overall system outlook

The detection system employs a modular design, and the overall system architecture is illustrated in Figure 1. The detection system consists of four modules: a capacitive sensor, an FDC2214 capacitance detection module, an Arduino microcontroller as the lower computer, and a PC-based upper computer using the LabVIEW software system. The working principle of the system is as follows: cylindrical capacitive sensors convert the concentration of a transparent liquid into capacitance(C). Capacitive sensors are connected to the external LC parallel resonant circuit of the FDC2214 capacitance detection module. Through the detection and conversion circuit, capacitance(C) is able to be transformed into an oscillation frequency f . FDC2214 then converts the frequency f into a ratio Data with respect to the reference frequency f_{REF} and outputs this ratio Data in the form of a 28-bit binary number. The Arduino microcontroller reads the 28-bit binary number, which corresponds to the capacitance value, through the IIC interface. The Arduino microcontroller operates under the control of the LabVIEW program running on PC, enabling the acquisition of the 28-bit binary data. The collected data is further processed by LabVIEW and finally displayed graphically as the concentration value of the tested solution.

The physical device, constructed based on the above-mentioned design, is depicted in Figure 2. In this apparatus, a four-channel detection configuration is employed, with Channel 1 and Channel 4 serving as detection channels, while Channel 2 and Channel 3 function as reference channels.

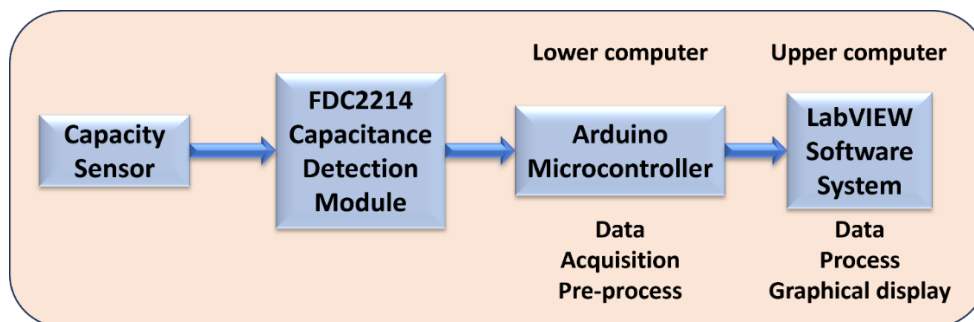


Figure 1. Diagram of the functional part of the measurement system.

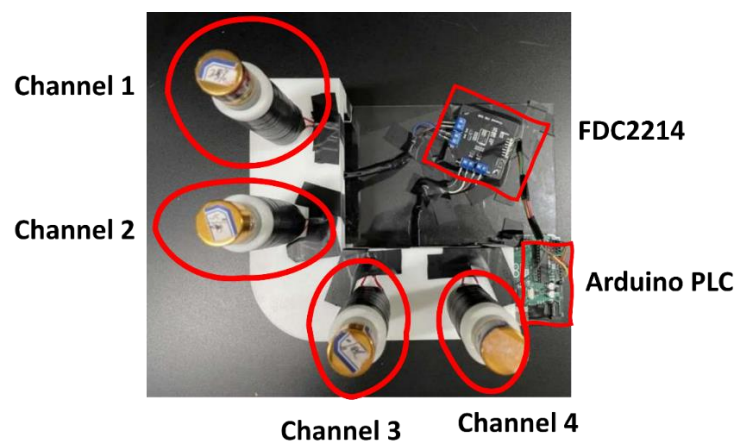


Figure 2. The physical object of the system for each part.

2.2. Design of capacity sensors

During the development process, it was observed that using a single cylindrical capacitor as the capacitance sensor for detection led to significant susceptibility to external factors such as connection lines and electromagnetic interference [7]. Moreover, mitigating these interferences proved challenging, resulting in poor stability and repeatability of the detection data, along with substantial detection errors.

Leveraging the characteristics of the FDC2214 module's four-channel capacitance measurement, we designed and produced a monolithic cylindrical capacitive sensor with both dual-channel and four-channel capabilities through 3D modeling and printing. The model is depicted in Figure 3. In this device, copper electrodes were affixed to the outer surface of the resin cylinder and secured with insulating electrical tape. The electrodes were then connected using lead wires to create the capacitive sensor. Through practical testing, the sensor met the detection requirements.

During specific measurements, data was acquired by differentially measuring the capacitance between two channels. One channel was dedicated to the solution under test, while the other served as a reference liquid (distilled water was used as the reference liquid in the design).

Due to the identical design parameters of the capacitance in both channels and the effort to maintain the wiring connection to FDC2214 as consistent as possible, the external interferences experienced by the two channels are nearly identical. The capacitance values of both channels were simultaneously measured, and the difference between them was used as the detection data. By differentially measuring the capacitance values, the common external interferences affecting both channels were effectively eliminated. This detection approach significantly reduces external interference. Through practical testing and comparison with the working mode of a single-channel capacitor, both accuracy and stability have been greatly improved, as shown in Figure 4.

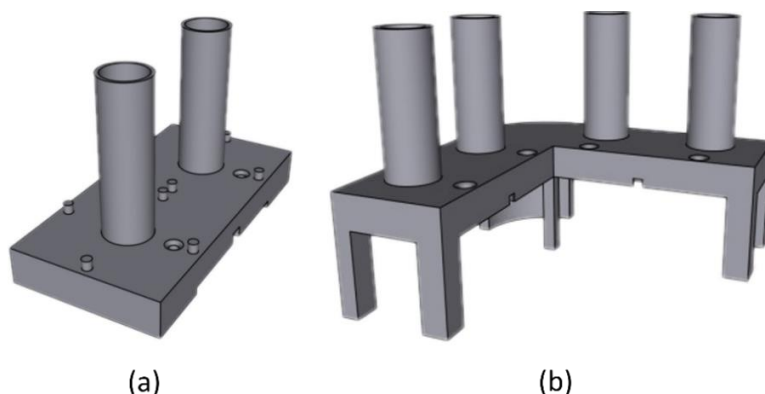


Figure 3. 3D model of capacitive sensors. (a) Dual-channel capabilities. (b) Four-channel capabilities.

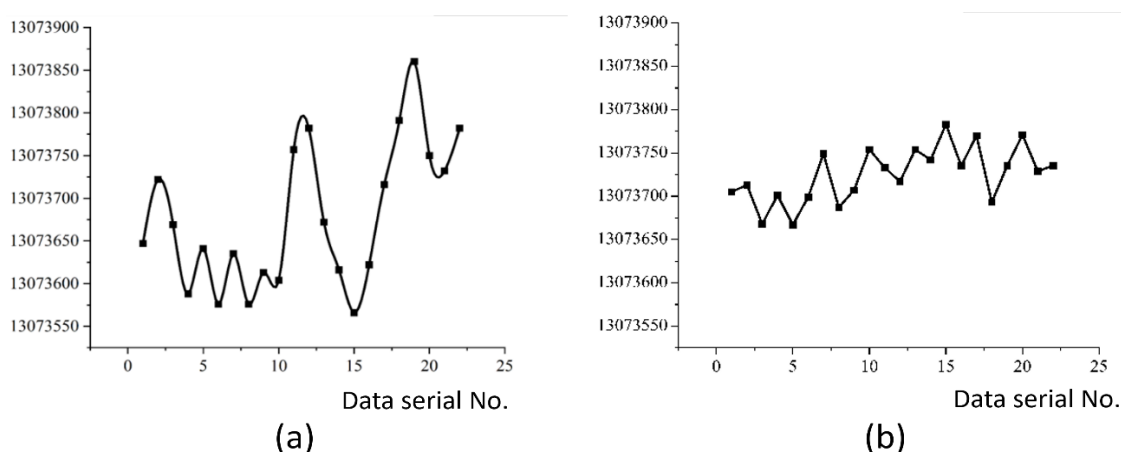


Figure 4. Comparison of single-channel reading and dual-channel reading. (a) Single-channel reading data. (b) Dual-channel reading data.

Additionally, for the sake of operational convenience during detection and to avoid potential residual effects from the previous solution on the accuracy, a different approach was adopted compared to the typical method of directly injecting the test solution into the capacitor. In this study, the test solution was injected into a glass bottle, and then the glass bottle was placed inside the cylindrical capacitive sensor for detection. This design ensures the isolation between the test solution and the capacitor, provides a sealed environment for the test solution, free from external air influences.

It also ensures consistent solution volume for each detection, rapid replacement, and other advantages, laying the foundation for the rapid measurement of small sample volumes.

The glass bottles used in the system are required to hold 25 ml of solution, with an outer diameter of 2.2cm. The internal diameter of the cylindrical capacitor is designed to match this requirement [8], and efforts are made to ensure a close fit between the glass bottle and the inner wall of the capacitor, as illustrated in Figure 5.

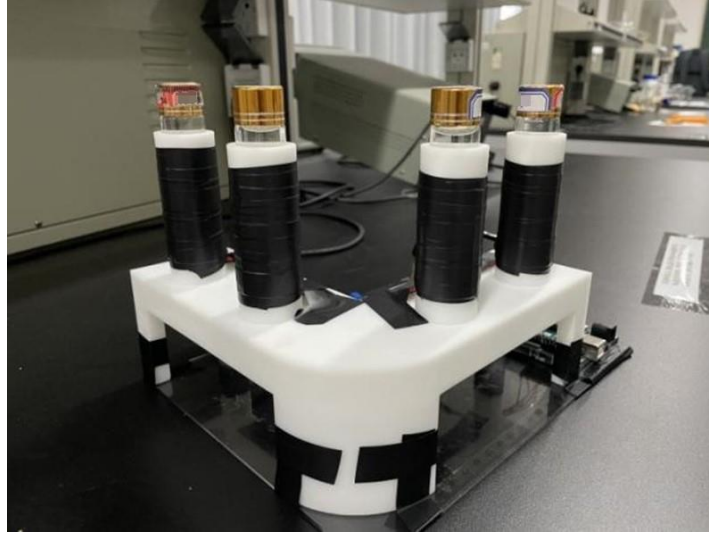


Figure 5. Cylindrical capacitors that match the inner diameter of glass bottles.

2.3. Design of FDC2214 capacitor detection circuit

In this system, capacitance detection is a crucial step, and one of the most challenging aspects of accurate acquisition of capacitance is addressing various interference issues. Therefore, this device utilizes a capacitance detection module based on Texas Instruments' FDC2214 chip as its core to achieve capacitance acquisition. This module features four transmission channels, each with a maximum transfer rate of 13.3 Kb/s. Under ideal conditions with 10 kHz frequency and 1 mH inductance, the maximum input capacitance for each channel is 250 nF. The signal transmission is carried out using the IIC communication protocol, and the maximum resolution is 28 bits in binary format [9]. By leveraging the outstanding performance of FDC2214, high-resolution capacitance acquisition, resistance to interference, and non-contact features have been achieved.

The circuit schematic and the actual module are shown in Figure 6. In practical use, a circuit module with peripheral interface circuits connected to the chip has been employed. In the actual circuit, the inductance $L=18\mu\text{H}$, the capacitance $C_0=33\text{pF}$, and the unknown capacitance (C_x) is combined with C_0 to form the front-end parallel LC resonant circuit for detecting unknown capacitances C_x . The internal main clock frequency of the module is generated by an external 40MHz crystal oscillator, effectively enhancing operational stability.

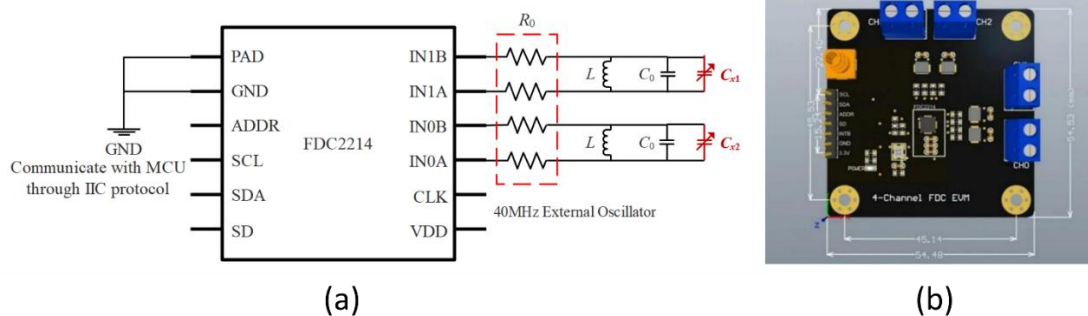


Figure 6. Schematic and actual module diagram of the detection circuit. (a) Simplified wiring schematic for the FDC2214. (b) The FDC2214 module used in the system, which includes the necessary components for operation such as external oscillators, resistors and capacitors.

The front end of the FDC2214 comprises a resonant circuit driver. In the input terminals of each detection channel of the chip, an inductor and capacitor form an LC circuit. The capacitance sensor under measurement is connected in parallel with the LC circuit, resulting in an oscillation frequency denoted as f_s . Subsequently, a multiplexer is employed, sequentially routing each channel through the main channel and connecting them to the core unit, where the digitization of the measurement frequency takes place. This core unit utilizes the reference frequency f_{REF} to measure the sensor frequency, with f_{REF} derived from either an internal reference clock (oscillator) or an externally provided clock source [10]. The digitized output of each channel is proportional to the measurement frequency f_s , and its value is designated as Data. The IIC interface is utilized to facilitate device configuration and transfer the digitized Data to the host processor for further processing.

Given the practical configuration and connection method of the system, the data resolution for the conversion channel is set to 28 bits. Consequently, representing the ratio as a 28-bit binary number facilitates computer readability. When displayed on a computer, this 28-bit binary number is converted into a decimal number. Therefore, the output Data should be:

$$\text{Data} = \frac{f_s}{2f_{REF}} \cdot 2^{28} = \frac{2^{28}}{f_{REF} \cdot 2 \cdot 2\pi\sqrt{LC}} \quad (1)$$

Considering the presence of the inherent capacitance C_0 and additional capacitance C_{Add} in the FDC2214, the calculation of the sensor capacitance is as follows:

$$C_x = C - C_0 - C_{Add} = \frac{2^{56}}{(4\pi \cdot f_{REF} \cdot \text{Data})^2 \cdot L} - C_0 - C_{Add} \quad (2)$$

Hence, by retrieving the readings from the FDC2214, the calculation of the sensor capacitance value C_x can be determined.

2.4. Design of data pre-processing and display system

The system employs Arduino as the lower-level microcontroller to facilitate data acquisition, preprocessing, and transmission. In the system, Arduino receives data (Data) and controls the FDC2214 to conduct multiple detections on a solution of the same concentration, calculating the average as processed data. The processed data is then forwarded to the upper-level controller (PC). Data reception and visualization on the PC are implemented using LabVIEW. Leveraging a serial communication protocol, LabVIEW can directly read the serial port data transmitted from Arduino to the PC.

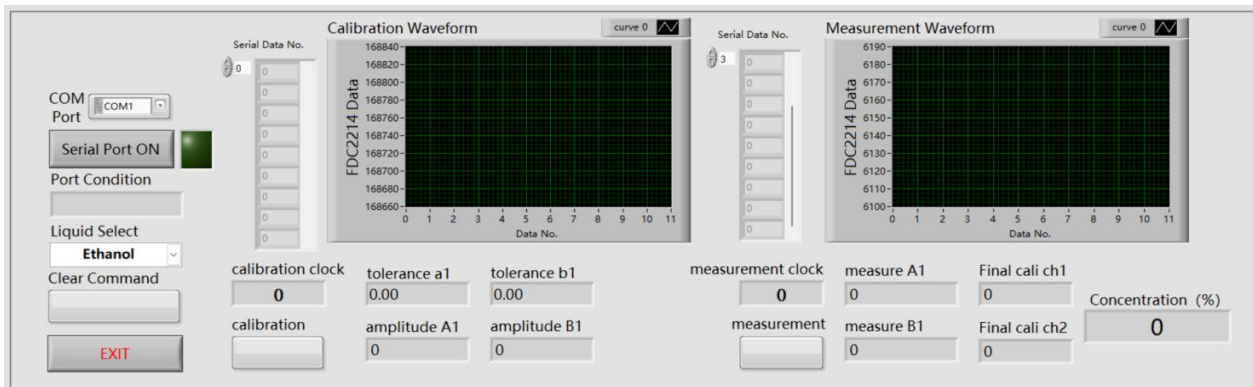


Figure 7. Graphical interface for LabVIEW host computer.

The LabVIEW interface is divided into calibration and measurement sections, emphasizing the necessity to calibrate before conducting measurements when utilizing the system. To provide real-time monitoring of the system's operational status and the measured solution, the upper-level controller features a serial port status monitor and a solution selection menu. The serial port status monitor displays prompt signals during serial port operation, facilitating users in real-time monitoring of the serial port communication status. The solution selection menu allows users to choose the solution to be measured, enabling timely adjustments to the measurement system. Refer to Figure 7 for the interface layout.

3. System debugging and testing

Before the practical application of this detection system, it should undergo debugging and testing. the system calibration section should be under assessment firstly, followed by the determination of calibration curves and standard curves. Finally, a simulation of actual usage detections for the device was conducted.

3.1. System calibration module

Due to the prolonged system powering, heat generation affects the detection of capacitance values. We conducted measurements to assess the impact of the duration of power-on time on the system readings, using glucose solutions as the medium, as shown in Figure 8. The curve equation (3) was obtained through Taylor expansion for curve fitting.

$$\text{Data}(t) = -0.0007t^3 + 0.2363t^2 - 33.935t + 152345 \quad (3)$$

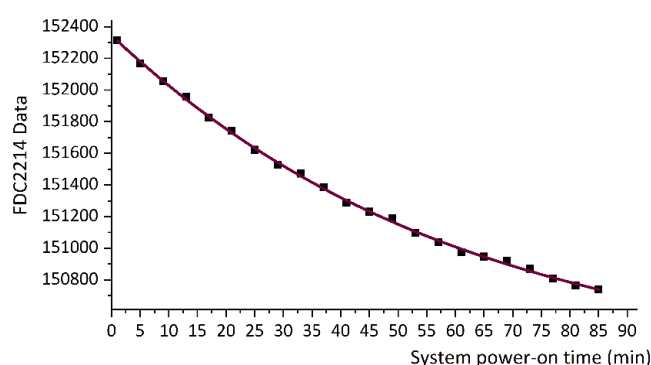


Figure 8. Effect of power-on time on system readings

The calculated R^2 value is 0.9993, indicating a fitting degree that aligns with expectations. This curve, obtained through Taylor expansion, can serve as the calibration curve for LabVIEW. Through the aforementioned calibration algorithm, the impacts of power-on time and temperature on the entire measurement system have been effectively addressed. A notable improvement is observed as the measurement of a 25% glucose solution, initially at 26.10%, is refined to 25.38% post-correction, demonstrating enhanced precision.

To further assess the accuracy of this calibration algorithm, a comparative analysis of results before and after correction was conducted for eleven sets of solutions, as presented in Table 1. The data reveals that, particularly under conditions of low to medium concentration test solutions, the correction algorithm exhibits favorable effects, leading to higher detection accuracy, while improvement is sought for solutions of higher concentrations.

Table 1. Results before and after calibration for each concentration gradient glucose solution

0	Before calibration	After calibration	R. E. R.	A. E.
4%	6.13%	4.72%	23.0%	0.72%
6%	7.94%	6.72%	15.5%	0.71%
10%	11.42%	10.65%	6.7%	0.65%
13%	14.35%	13.64%	4.9%	0.64%
16%	15.53%	16.87%	3.8%	0.87%
21%	22.74%	21.56%	5.2%	0.56%
25%	26.10%	25.38%	2.8%	0.38%
28%	29.78%	28.21%	5.3%	0.21%
32%	34.26%	32.95%	3.8%	0.95%
37%	39.28%	38.32%	2.4%	1.32%
42%	45.70%	43.97%	3.8%	1.97%
Mean absolute error				0.82%

Here G. S. C. refers to Glucose Solution Concentration, R. E. R. refers to Relative Error Reduce and A. E. refers to Absolute Error.

3.2. Detection and data fitting of standard curves

Determining a standard curve involves preparing standard solutions with known concentrations of solutes. The fundamental steps for measuring the standard curve using glucose and ethanol as solutes in this study are outlined as follows:

- 1) Prepare a 40ml solution of saturated glucose (or ethanol). After allowing it to equilibrate, use a syringe to extract 28ml and transfer it to measurement tube one.
- 2) Clean the syringe and use it to extract 28 ml of distilled water. Transfer the water to measurement tube two in the experimental setup. Initiate the system for data measurement and record the results.
- 3) Gradually dilute the solution in measurement tube one with a 5% concentration gradient while maintaining the total volume. Restart the program for each gradient and record the data.
- 4) Average the data obtained for each concentration gradient. Repeat the above steps for a total of five sets of data. Calculate the average for each concentration to obtain the table.
- 5) Utilize OriginPro to plot the "Glucose Solution Concentration-FDC2214 Data" table and perform a polynomial fit using a third-degree polynomial. This yields the analytical expression for the standard curve of glucose concentration versus FDC2214 readings, denoted as the standard curve.

The standard curves for glucose and ethanol solutions, determined using this method, are depicted in Figure 9. Curve fitting was applied to derive Equation (4) for each curve. These two curves are then recorded as the standard curves for concentration measurement in LabVIEW, thus completing the system calibration process.

$$\begin{cases} \text{Data}_{\text{glucose}}(c) = 74020c^3 - 34198c^2 + 33912c + 136820 \\ \text{Data}_{\text{ethanol}}(c) = 151326c^3 - 92196c^2 + 80932c + 136955 \end{cases} \quad (4)$$

Where c represents the solution concentration.

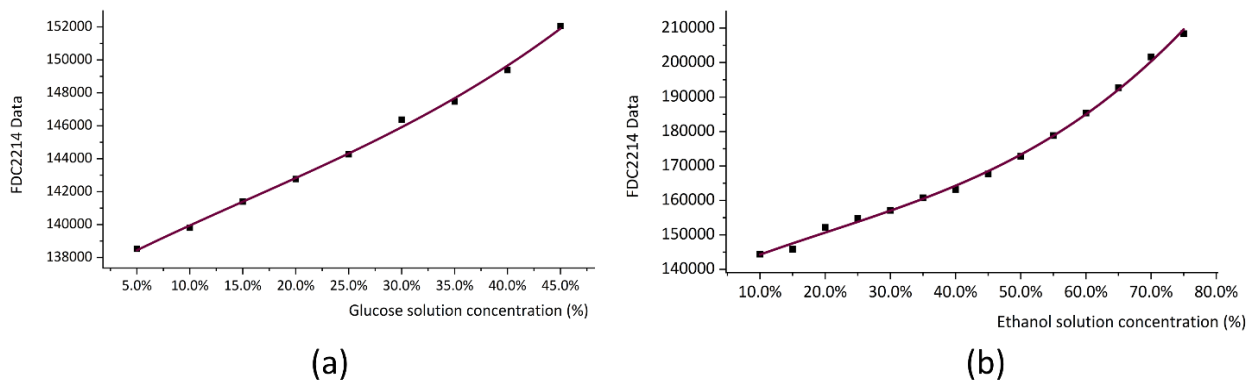


Figure 9. Standard curves for glucose and ethanol solutions. (a) The standard curve of glucose solution. (b) The standard curve of ethanol solution.

3.3. Test of the concentration of unknown transparent solutions

By preparing a glucose solution with a concentration of 18.8% as an unknown solution and measuring it after calibrating with 25% glucose solution, the result obtained was 19.73%. Subsequently, a solution with a concentration of 6% glucose was prepared as another unknown solution. After calibration with the appropriate calibration solution, it was measured in the device, yielding a result of 6.7%. Table 2 further presents a series of simulated detected results for ethanol and glucose concentrations. The data indicates that results exhibit a small absolute error compared to the known concentrations, confirming the precision of detections.

Table 2. Simulated detections of ethanol and glucose solutions

G. S. C.	Result	A. E.	E. S. C.	Result	A. E.
6%	6.7%	0.7%	14%	15.2%	1.2%
12.7%	12.2%	0.5%	28%	27.2%	0.8%
18.8%	19.7%	0.9%	37%	37.6%	0.6%
23.6%	24.0%	0.4%	49%	50.1%	1.1%
35.4%	34.8%	0.6%	55%	54.1%	0.9%
42.5%	42.8%	0.3%	64%	65.7%	1.7%
Mean absolute error		0.56%	Mean absolute error		1.05%

Here G. S. C. refers to Glucose Solution Concentration, E. S. C. refers to Ethanol Solution Concentration and A. E. refers to Absolute Error.

3.4. Analysis of system characterization indicators and detection results

(I) Accuracy, error, and uncertainty assessment

The errors occurring during the usage of this device primarily stem from environmental factors such as temperature and humidity, the duration of system powering, and external signal interference [9], including random errors introduced by electrical equipment like powered wires and air conditioning [11].

The variation in environmental temperature and prolonged system powering lead to circuit heating, causing a decrease in the insulation resistance value of the C capacitor in the LC oscillating circuit corresponding to the chip's oscillation frequency (f_s) [12]. This, in turn, results in an increase in leakage current and a reduction in the charge retained on the electrode plates, leading to a decrease in capacitance values and an increase in f_s . Consequently, the measured Data of the test solution increases with time. The difference in Data between the test solution and water decreases with an increase in powering time, giving rise to system errors.

In the data calibration and correction section, the system has implemented a calibration algorithm to correct for system errors. Therefore, the errors during the final detection primarily stem from random errors induced by interference from noise signals.

For a given detection method, errors inevitably exist, as elucidated in the previous sections regarding the random errors of this system. Therefore, uncertainty assessment is necessary [13]. Uncertainty indicates the reliability of results and serves as a metric for the quality of results. The smaller the uncertainty, the higher the quality, and the greater the value of the result. Conversely, higher uncertainty indicates lower quality, lower reliability, and reduced value of the measurement result.

Assessment based on the statistical distribution of detection data yields the Type A uncertainty of test results. It can be represented by the standard deviation as indicated in Equation (5), and the results are depicted in Figure 10(a). It is evident that the measurement data exhibit good repeatability, with a small uncertainty, indicating higher value and reliability of the detections.

$$S_n = \sqrt{\frac{\sum_{i=1}^n (N_i - \bar{N})^2}{n(n-1)}} \quad (5)$$

From Figure 10(b), it can be observed that after calibration, the absolute error of the tested results for solution concentration ranges from a maximum of 1.97% to a minimum of 0.21%. The average absolute error is 0.82%, with an uncertainty of 0.0014. The final average absolute error is $(0.82 \pm 0.14)\%$. When the solution concentration is below 30%, the absolute error is consistently less than 1%.

As for Figure 10(c), it can be concluded that during the simulation of actual usage, the absolute error of glucose solution ranges from a maximum of 0.9% to a minimum of 0.3%, with an average of 0.56%. The uncertainty is 0.0007, resulting in a final average absolute error of $(0.47 \pm 0.07)\%$. For ethanol solution, the absolute error ranges from a maximum of 1.7% to a minimum of 0.6%, with an

average of 1.05%. The uncertainty is 0.0016, resulting in a final average absolute error of (1.05±0.16)%.

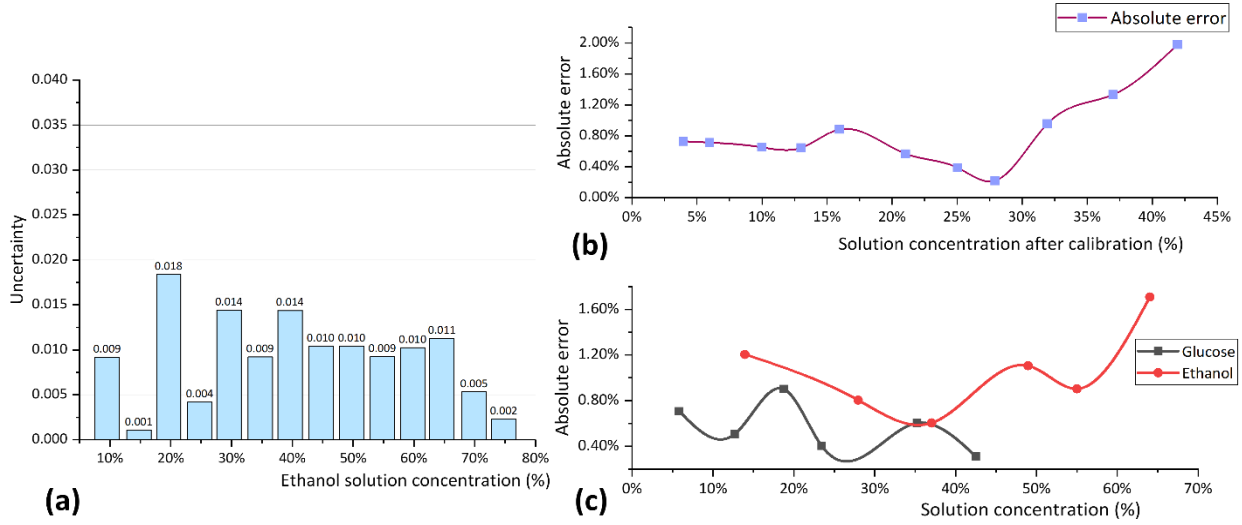


Figure 10. Uncertainty and absolute error in system test results. (a) Uncertainty assessment of measurement data for ethanol solutions. (b) Absolute measurement error for each concentration gradient after system calibration. (c) Evaluation of absolute errors in random concentration measurements of glucose and ethanol solutions.

(II) System minimum resolution

The detection system's resolution primarily depends on the measurement accuracy of FDC2214. When calculating the accuracy of capacitance measurements, the following considerations apply:

$$\Delta C_{\text{SENSOR}} = \left[\frac{1}{L \cdot \left(2\pi \cdot \frac{2 \cdot f_{\text{REF}} \cdot \text{Data}}{2^{28}} \right)^2} - C \right] - \left[\frac{1}{L \cdot \left(2\pi \cdot \frac{2 \cdot f_{\text{REF}} \cdot (\text{Data} + \Delta \text{Data})}{2^{28}} \right)^2} - C \right] \quad (6)$$

The magnitudes of the coefficients in the equation are on the order of 10^8 . Upon computation, the sensor capacitance (C_{SENSOR}) and the corresponding Data values exhibit an approximate linear relationship.

In theoretical analysis, the smallest variable value for FDC2214 reading is 1, which means $\Delta \text{Data} = 1$. Consequently, the change in capacitance (ΔC_{SENSOR}) is 0.00001pF, indicating that the theoretical resolution of the detection system is 0.00001pF. In the actual detection environment, signal noise interference is inevitable, resulting in a magnitude of $\Delta \text{Detection}$ on the order of 10^2 . Calculating from this, $\Delta C_{\text{SENSOR}} = 0.001\text{pF}$, indicating that the practical resolution of the detection system is 0.001pF. This implies that in actual detections, the system can effectively discern changes in the tested concentration of over 1%.

4. Conclusions

In summary, this LabVIEW-based detection system possesses characteristics such as simple structure, small size, non-contact operation, high precision, and low cost. It not only meets the requirements for small-sample detection of transparent solutions in laboratories and on-site settings but, with appropriate modifications, can also fulfill continuous detection of solution concentrations in industrial pipelines. Additionally, when integrated with LabVIEW software and a microcontroller, it can achieve automatic control. The versatility of the device extends to measuring both transparent and non-transparent solutions, making it suitable for a wide range of applications. Therefore, this device can be developed into a desktop liquid concentration detection instrument, widely applicable in laboratory, household, and industrial settings, enabling the measurement of various concentrations of liquids. It holds significant value for broad practical applications.

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