Study on engineering module design for liquid macromolecular ingredient content detection

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Abstract: The liquid milk with the main ingredients of protein and fat was used as the research background for liquid macromolecular ingredient content detection in this paper. A model for the protein and fat ingredient content was established with the theory of scattered through ratio. Based on this, the photoelectric detection module was designed. Multiple photoelectric detection module circuit boards had been tested, the average error of the scattered light direction photoelectric detection circuit was 0.0072 and the average error of the photoelectric detection circuit in the direction of transmission light was 0.0094. The correlation coefficient of the established model can reach 0.97 and the system measurement uncertainty is about 0.078. The above test results show that the design meet the engineering application indicators basically. The detection module designed in this paper had the convenience, fast and efficient real-time performance, the reproducibility and stability was satisfactory.

Keywords: ingredient content detection; liquid macromolecular; engineering; module design; scattered through ratio.

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1 Introduction

Dairy product content measurement is one of the most typical liquid ingredient content detection. The main nutritional contents of dairy products are fats and proteins which are more and more important in people's eating life (Szwarcman et al., 2016). Macromolecular refers to more than 5,000 of relative molecular mass, or even more than a million biological substances, such as proteins, nucleic acids, polysaccharides, etc. Protein and fat in milk belong to macromolecular. For the detection of proteins, Kjeldahlnitrogen method (Hong-Liang et al., 2010) is used universally and the two parallel determination of the difference between the results did not exceed twice the average of 1.5%. Fat detection is using the Rhodes-Gothic method and the mass fraction can be accurate to 0.01% (Campinsfalco et al., 2008). However, chemical methods are expensive and time-consuming, requiring skilled operation, consuming large amounts of chemical reagents and water and producing waste emissions (Szwarcman et al., 2016). In recent years, some non-chemical methods have been studied to detect protein and fat ingredient content, such as single-wavelength method, dual-wavelength method, photo resist method, on these basis, a multi-wavelength method is developed to measure the relationship between particle concentration and distribution (Wu et al., 2008a, 2008b; Heussen et al., 2007). As the progress of science and technology, especially the rapid development of electronic computer technology and laser technology, there have been some new methods of milk rapid detection. In which the ultrasonic detection method (Bordin et al., 2001) and infrared spectroscopy method (Feng et al., 2011) are more mature and commonly used. Ultrasonic method is subject to the stability of the emission source and the detection accuracy of the constraints, which needs multiple correction of the instrument, may not achieve long-term high-precision detection (Wang et al., 2006). Recently, some companies have developed milk detection devices based on ultrasonic detection technology, such as Unconstitutional Zhejiang University, LACTOSCAN series in Bulgaria and LACTICHECK series in the USA (Bordin et al., 2001). With the continuous maturity of spectroscopy method, a number of enterprises have begun to apply this method for the detection of milk components. The Baudong company developed a 8,620-type milk testing equipment and measured 55 different sources of milk powder with this device, obtained their diffuse reflectance spectra and the use of the relevant algorithm to establish a protein model, which has a 0.96 correlation coefficient, SEC value of 0.196% (Sirisomboon et al., 2012). Another available method is HPLC/ESI-MS tests which are simple, rapid and suitable used in the laboratory. But it may not be widely used for the milk detection of the small and medium farm with characteristics of high cost and huge volume (Chen et al., 2004). However, with the

continuous development of photovoltaic technology, light scattering technology began to be studied to the detection of milk ingredient content, has gradually become a hot research (Xin et al., 2006).

The method of laser light scattering is mainly used to capture optical signal intensity ratio of scattered light intensity to characterise the optical parameters and then measure milk samples content of fat and protein, has a certain practicality. In recent years, the group headed by Professor Zhou Zhen of Harbin University of Science and Technology has conducted a large number of experimental studies on the milk composition by using this method (Zhou et al., 2006, 2008). By combining the law of conservation of energy with the least square method, a correlation model, not only verified the feasibility of the method, but also determined the best experimental conditions and designed the experimental prototype. At present, although some research results have been obtained, the correlation coefficient of the model is low and it restricts the accuracy of the test results. Some key units need to be improved and the analysis and evaluation of the overall device testing level is lacking. There is no engineering design for the device based on this method, which makes it difficult to get out of the laboratory and limit its application.

In this paper, the design based on the principle of laser scattered through ratio, is applied to the detection module of dilute milk photoelectric signal, which plays an important role in suppressing the instability of the emission source. Based on the previous research, the detection system module is designed and the model was established between the scattered through ratio and the ingredient content of milk by the view of engineering practical.

According to the relevant provisions of the country as well as the requirements of various aspects (Ministry of Health in People's Republic of China, 2010a, 2010b), the model of the association and the system designed to achieve the technical indicators are as follows. The system designed in this paper requires that the correlation coefficient of the correlation equation is not less than 0.95, the system precision is about 5% and the measurement uncertainty of the whole system is not larger than 0.1.

2 Principle and modelling of scattered through ratio method

2.1 Scattered light reception angle selection

In this paper, the basic method of milk ingredient content detection is scattering ratio method which is used to detect the light information in the scattering direction and the light information in the transmission direction. Scattered light is a parameter that mainly reflects the information of the particles. The stronger the scattered light is, the more information it carries. However, the light intensity around the light-emitting utensil is not evenly distributed. Therefore, the angle of strongest scattered light is necessary to be found to place photoelectric sensors. Below, we used five sets the same concentration of dilute milk for experiments, tested the intensity of the angle every 15° from –90° to 90°. The scattered light intensities obtained from each angle are shown in Table 1 partially.

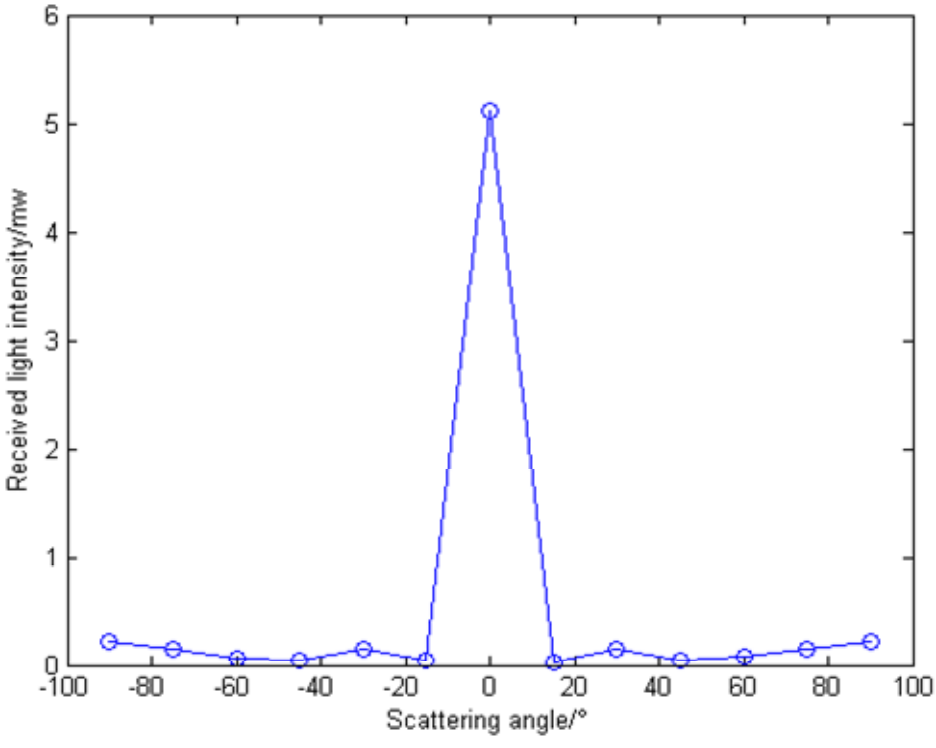
Table 1 Data of scattering angle – scattered light intensity

Scattering angle (°)	*Scattering light intensity(μW)*				
	No. 1	*No. 2*	*No. 3*	*No. 4*	*No. 5*
–90	216.2	216.1	215.8	215.7	216.1
–45	40.0	40.2	39.8	39.6	40.1
–30	143.5	143.7	144.0	143.6	144.4
0	5,110.2	5,110.0	5,110.2	5,109.4	5,109.7
30	154.7	154.8	154.0	155.0	154.6
45	44.2	44.4	44.6	44.1	44.8
90	215.5	215.7	215.4	216.0	215.8

Taking the average of the measured data, the relationship between the scattered light intensity and the scattering angle can be obtained, as shown in Figure 1.

Figure 1 show that the strongest light is in transmissive direction and the weakest light in 45° direction is due to two walls of the utensil being in 45° direction. Followed by +90°, –90° and –30°, +30° angle of the light intensity is relatively large, in this paper, we chose the 90º angle to place photoelectric detection device.

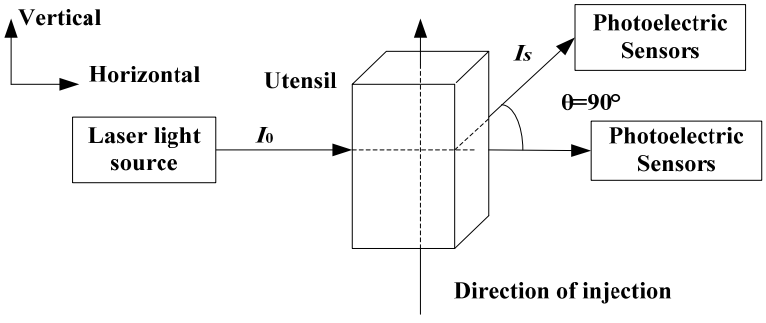
Figure 1 The received intensity of light for different scattering angle (see online version for colours)



2.2 Scattered through ratio principle

The scattered through ratio method is to measure the transmitted light intensity at 0° and the intensity of the scattered light at 90° in the incident plane of the light and use their ratio to characterise the optical parameters of the milk protein and fat content, as shown in Figure 2 (Biswas et al., 2008). This method which is applied to milk ingredient content detection can also solve the problem of stability of the emission source, that is, the fluctuation of the light intensity of the emission source can be effectively eliminated by the ratio of the transmitted light intensity to the scattered light intensity.

Figure 2 The detection scheme



Using the theoretical basis of the scattered through ratio method, the measured liquid can be seen as separate pure fat thin solution and the same concentration of pure protein solution to study. So it can be seen as the laser was injected into the same concentration of pure fat dilute solution and the same concentration of pure protein solution (Zhou et al., 2006). According to Lambert's Law:

$$I_{t1} = I_0 e^{-\mu_{s1}\xi_1 d} \tag{1}$$

$$I_{t2} = I_{t1} e^{-\mu_{s2}\xi_2 d} \tag{2}$$

where I_{t1} is the transmitted light intensity from the fat emitted; I_0 is the intensity of the incident light; μs_1 is the macroscopic scattering constant of the fat; ξ_1 is the concentration of fat; d is the channel length of the sample box; I_{t2} is the total transmitted light intensity; μs_2 is the macroscopic scattering constant of the protein; ξ_2 is the protein concentration. Then the total transmitted light intensity I_{t2} becomes:

$$I_{t2} = I_0 e^{-(\mu_{s1}\xi_1 + \mu_{s2}\xi_2)d} \tag{3}$$

As described of formula (3), when the value of the incident light intensity I_0 is kept constant, the pure fat solution is obtained by passing the protein dissolution EDTA (ethylenediamine tetra acetic acid) and the light intensity I_{t1} after the injection of the pure fat dilute solution is measured. Then, the fat concentration ξ_1 can be obtained by using the formula (1). Therefore, the total transmitted light intensity I_{t2} is measured. The concentration ξ_2 of the protein can be calculated from the value of ξ_1. It can be seen that the protein concentration ξ_2 corresponds to the total transmitted light intensity I_{t2}.

2.3 Model establishment

By using formulas equations (1) and (2), the equation can be derived as:

$$I_0 S_0 = \sum I_{si} \Delta S_i + \sum I_{sj} \Delta S_j + I_{t2} + I_a S_0 \tag{4}$$

where S_0 is the cross-sectional area of the incident beam; I_0 is whole incident light intensity; I_a is purely whole absorbed light. I_{si} is the scattered light intensity of the fat on its scattering per surface ΔSi; I_{sj} is the scattered light intensity of the protein on it's per scattering surface ΔSj and the equation (4) becomes:

$$I_s S_R = \sum I_{si} \Delta S_i + \sum I_{sj} \Delta S_j \tag{5}$$

I_s is the scattered light intensity of the incident light. S_R is a virtual sphere with radius R, its centre is at the centre of the specimen through the beam. And on the S_R, I_s is equal everywhere. It is a size associated with the size of the milk fat particles and the protein particles. The equation can be given as:

$$I_0 = mI_S + I_{t2} + I_a \tag{6}$$

where $m = S_r / S_0$. It is proved by experiment that it is a constant in dilute solution. $I_a = e^{d(k1\xi1+k2\xi2-c)}$, where k_1, k_2 is the pure absorption coefficient, c is a constant, then the equation about scattered through ratio Y can be described as:

$$mY = e^{(\mu_{s1}\xi_1+\mu_{s2}\xi_2)d} - e^{(k_1\xi_1+k_2\xi_2-c)d} - 1 \tag{7}$$

The values of ξ_1 and ξ_2 are small, because it is a dilute milk solution. Equation (7) is calculated for Taylor expansion. The equation becomes:

$$\begin{aligned} mY = &-\left(k_1^2/2+\mu_1 K_1\right) d^2 \xi_1^2 - \left(K_2^2/2+\mu_2 K_2\right) d^2 \xi_2^2 \\ &+ \left(d_2 k_1 c + d^2 \mu_1 c - d k_1\right) \xi_1 + \left(d^2 K_2 c + d^2 \mu_2 c - d k_2\right) \xi_2 \\ &- \left(K_1 K_2 + K_1 \mu_2 + K_2 \mu_1\right) \xi_1 \xi_2 - \left(c_2 d_2/2 - cd + 1\right) \end{aligned} \tag{8}$$

The equation can be given as:

$$Y = A_1 \xi_1^2 + A_2 \xi_2^2 + B_1 \xi_1 + B_2 \xi_2 + M \xi_1 \xi_2 + N \tag{9}$$

where A_1, A_2, B_1, B_2, M, N are constants.

From equation (8), we can see that $Y = f(\xi_1, \xi_2)$. After conversion by computer, $\xi_2 = f(Y, \xi_1)$ can be obtained. Then scattered through ratio Y can be measured directly. And the mass fraction ξ_1 of the fat can be obtained by the aforementioned equation $\xi_1 = f(Y_1)$. As the above process, the mass fraction ξ_2 of the protein can be obtained.

3 Modular design

3.1 Photoelectric conversion system and the overall system design

The design of the detection system is shown in Figure 3. The following is the detailed description of the system.

1 Light source. In photoelectric conversion systems, light carries information. Common light sources are solar light, incandescent, gas discharge light, semiconductor light-emitting devices, laser light sources. In this paper, a laser was chosen for the light source.

2 The formation of the measured optical signal. When the light source irradiates the object to be detected, it will produce a certain optical effect. After a series of scattering, transmission and absorption process, the optical signal which needs to be detected and processed is finally formed. In order to obtain an optical signal which carries enough characteristic information of the measured object, optical devices such as an optical filter can be used.

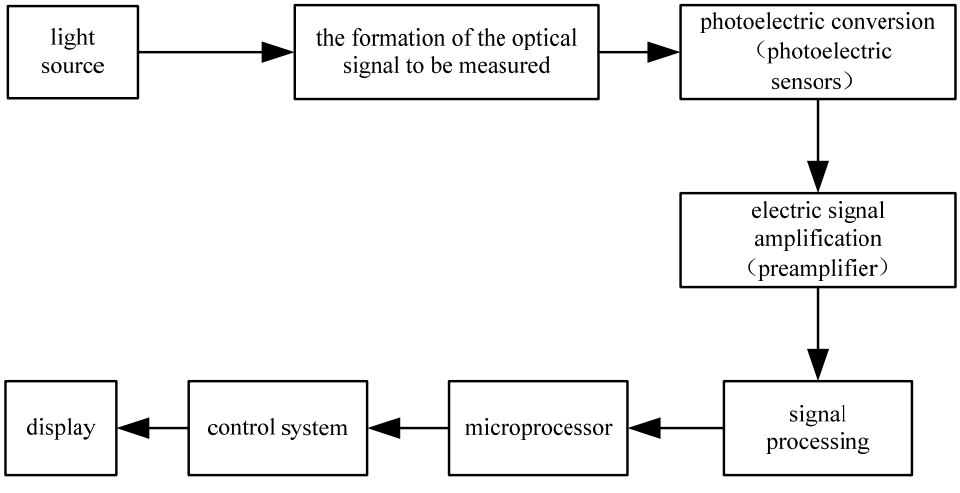
3 Photoelectric conversion. The photoelectric conversion is to achieve the signal of light-to-electricity conversion, the quality of its conversion has a direct impact on the overall accuracy of the system. Once the conversion is completed, the signal can be amplified, filtered and other processing. In this article, we chose silicon photovoltaic cells for photoelectric conversion.

4 Amplification and processing of electrical signals. This part is mainly to make some electronic circuits, the converted electrical signal amplification, computing and processing, in order to achieve the system's detection function. It is easy to get the information carried in the electrical signal.

5 Microprocessor and control system. This part not only can carry on the intellectualised control to the whole system operation, but also can carry on the necessary processing to measured value, finally obtains the satisfactory test result, sends to the display part.

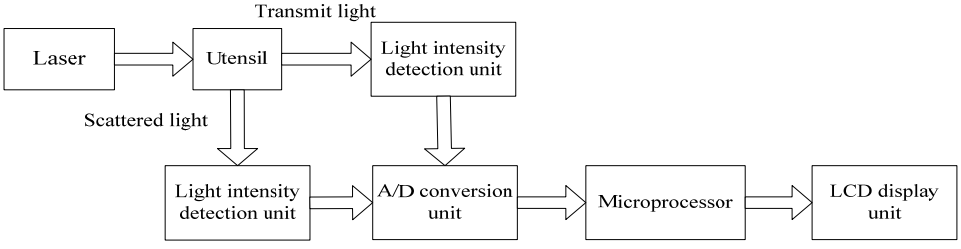
6 The display. The complete photoelectric detection system needs an intuitive exposition of the test results. The information of the final measurement can be displayed by using the display element and the test personnel can evaluate the test results by the man-machine interface.

Figure 3 The component of photoelectric detection system



This paper carried out a detailed design of the system, the overall structure of the block diagram shown in Figure 4. It can detect the content of milk in real time. In the light source part, a 650 nm wavelength semiconductor laser was chosen. The position and height of the light source is adjusted, so that it can just irradiate the detection utensil. Then the photoelectric detection unit along the light transmission direction and its vertical direction were placed. The detected light scattering and transmission of photoelectric signal is amplified and sent to the A/D conversion. After the final calculation of its microprocessor, the content of milk ingredients was shown by LCD.

Figure 4 The overall structure diagram of milk ingredients system



3.2 Selection of laser

The wavelength and intensity of the light source are two important parameters for selecting the laser. First of all, because the physical or chemical properties of the substances to be detected are multifarious, the different wavelengths have different effects on substances. Therefore, it is important to select the appropriate wavelength for different substances. In the detection of liquid macromolecules content should also pay attention to the choice of wavelength. Second, appropriate light intensity should be chosen. And the selection of light intensity range is mainly decided by the composition of the concentration, photoelectric conversion range and A/D conversion module.

For different concentration milk solutions, the absorption at different wavelengths is not the same. Therefore, the most suitable for the wavelength of the device should be found. The higher the absorbance band indicates that the higher the wavelength of the solute.

This article used a spectrophotometer to select the best wavelength. By observing the spectrum as shown in Figure 5, we can observe the light intensity absorption of different concentrations in different wavelength. In the range of 700 nm to 850 nm, the peak value is significantly larger than the other peaks and there is less glitch in this range. The water in this range has more interference with this wave band, so we did not choose this range (Pegau et al., 1997; Karoui et al., 2006). And the range of 550 nm to 700 nm was selected for initial determination. (The occurrence of the minus absorbance indicates is caused by the difference between two test utensils of spectrophotometer or deviation of operation. And it does not interfere with finding the result of the feature absorption peak.)

Since milk contains large amounts of water, therefore, the influence of water on light absorption should be eliminated. So liquid water is analysed. As shown in Figure 6, spectra of water is in order to further determine the laser wavelength range. Observations can be found that the absorbance of liquid water before wavelength 700 nm is small, so the impact on the results is almost negligible. Then considered with the commonly used

laser wavelength, price and other factors, we chose the Sanyo DL-3147-065 laser for milk composition detection system. Its wavelength is 650 nm, the minimum spot diameter of 0.5 m is about Φ0.5 mm and its external dimension is Φ16 mm × 60 mm. It can work for more than 12 hours continuously and its working life can reach about 20,000 hours.

Figure 5 The spectra of casein solution of different concentrations

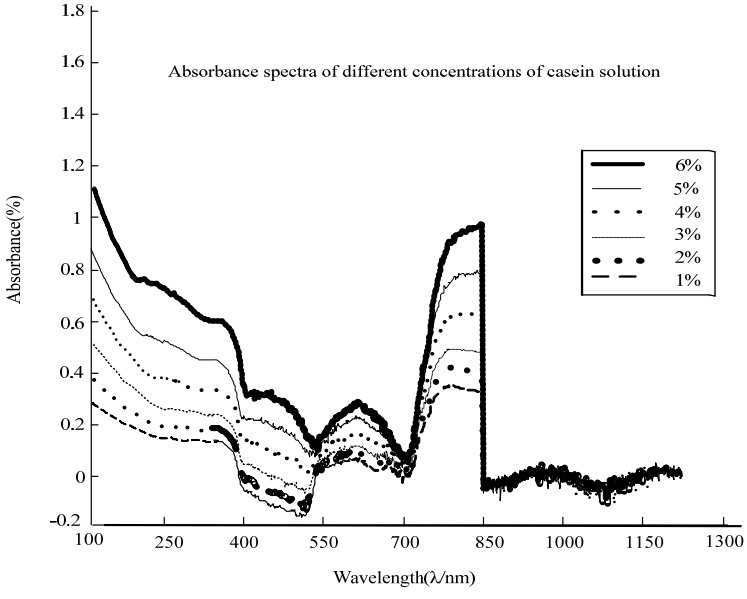
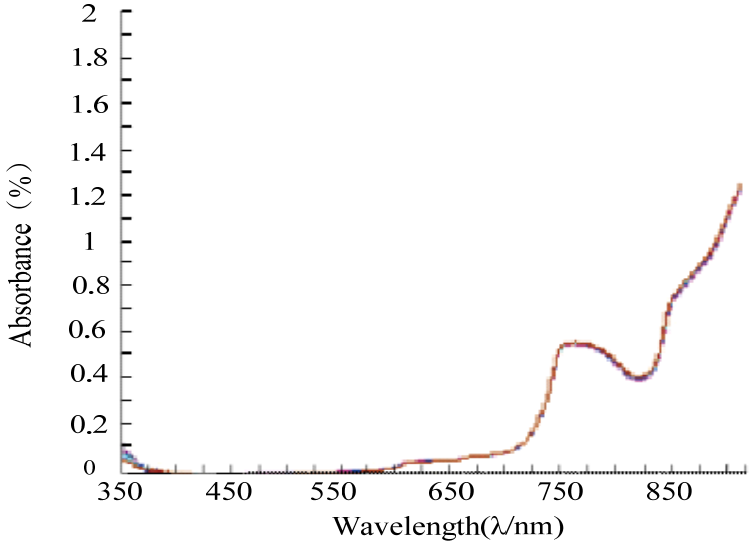


Figure 6 Spectra of water in the visible (see online version for colours)



Then the laser light intensity had to be chosen. The A/D input measurement range is 0–2 V, so the laser light after the dilute milk solution of scattered light and transmitted light into the voltage range cannot exceed the range. And then after several tests, 500 μW can well meet the requirements.

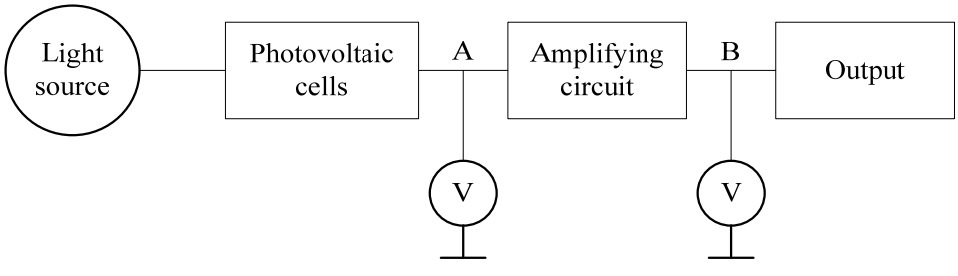
3.3 Photoelectric conversion module design

Photoelectric conversion device is photoelectric sensor. Its principle is to use the photoelectric effect to convert optical signals into electrical signals. In general, photoelectric conversion device can be used as a power device or a detection device. In many photoelectric conversion devices, silicon photovoltaic cells have been a great application in the energy and detection. It has some advantages such as conversion speed, wide spectral range, good stability and others. So the silicon photovoltaic cells were used as the sensors of photoelectric conversion module in this paper.

The circuits used a second-order low-pass filter design, to avoid the high-frequency electrical signals on the detection results. Since the detected signal was a weak electrical signal, it would be 100 times magnified after filtering, to make the observation more convenient. The circuit diagram of the photoelectric conversion module is shown in Figure A1 (Appendix).

From Figure A1 in Appendix, we can see that R6, R7, R8 and R9 are the resistors which directly affect the magnification. They are the key resistors, so the precision of these resistors needs to be improved. Therefore, these resistors are all used 0.1% precision metal film resistors to reduce the error of amplification circuit. The voltage converted by light is very small, so the amplifier circuit must be used to amplify the electrical signal. OP77 chip was selected as the photoelectric conversion module amplification calculator. The gain is maintained at 10,000,000 or higher over the entire ±12 V output range, which shows that it has very good gain linearity. It can correct for non-linearity errors that many other chips cannot correct, greatly improving its performance in closed loop gain. And the OP77 has a significant improvement in initial VOS drift, settling time and power consumption with not only low drift and fast settling characteristics but also a power dissipation of only 50 mW. In addition, the device features excellent TCVOS (only 0.3 μV/°C maximum) and low VOS (25 μV maximum), eliminating the need for external VOS adjustments and improving system accuracy over the full temperature range. The maximum supply rejection ratio of 3 μV/V (110 dB) and the maximum common-mode rejection ratio of 1.0 μV/V are almost completely eliminating the errors caused by power-supply drift and common-mode signals.

Figure 7 The photo detector conversion test circuit



In the design of this module, the amplification part of the photoelectric detection circuit was tested and two photoelectric detection circuit boards were required due to receiving two signals of scattered light and transmitted light. So the two circuit boards were tested respectively. The test circuit is shown in Figure 7.

The result is measured by using Aglient34401A digital multimeter, with high accuracy. The voltage at the point A is the measured preamplifier stage input voltage. The theoretical output voltage is the preamplifier stage output voltage. And the point B is the actual measured output voltage. The experimental data are shown in Table A1 and Table A2 (Appendix) partially.

The average error of the photoelectric detection circuit in the direction of the scattered light is 0.0072 and the average error of the photoelectric detection circuit in the direction of the transmitted light is 0.0094. It can be seen that these two photoelectric detection circuit boards' replication is good, they can meet the needs of this article.

3.4 Microprocessor design

The enhanced STC89C58RD+ was selected as the system microprocessor. The advantages of STC89C58RD+ microcontroller are superior anti-interference ability, ultra-low power consumption, excellent encryption, making its application more flexible. In addition, it has a hardware watchdog, which makes the program crashes and other issues have been well resolved. It compares with the 8,051 microcontroller has more storage space, to a certain extent, makes up for the shortcomings of the 51 microcontroller memory is too small. And it has compatible with the 51 SCM command system and pin, making the programming and debugging are more portable and flexible. So the chip is well suited to control program and data processing functions.

The accuracy requirements of microprocessor control section are not high, so based on the cost and other considerations, the device can be used to select low-precision devices. The control of the whole machine, man-machine interface display, A/D conversion is achieved by the preparation of the program. The program flows are shown in Figures A2 and A3 (Appendix).

3.5 A/D conversion module design

The system requires high conversion accuracy for the analogue-digital converter and the conversion speed is not rigid requirements. ICI7135 is a 4-bit dual-integrated A/D conversion chip that can convert ±20,000 digital outputs, with STB gated control BCD code output and the computer interface is very convenient. The ICL7135 has the advantage of high accuracy (equivalent to 14 A/D conversion) and low price. The conversion speed is related to the clock frequency. Each conversion cycle consists of four phases: self-calibration (zeroing), positive integration (measured analogue voltage integration), reverse integration (reference voltage integration) and zero-crossing detection. Among them, the self-calibration time is 10,001 pulses and the positive integration time is 10,000 pulses. Reverse integration will stop when voltage reaches zero, stop counting. A number of pulses are to be subtracted by 10,000, that is, to get the corresponding analogue. The timing diagram is shown in Figure A4 (Appendix). It can be

seen from the figure, positive integration starts when BUSY goes high, while BUSY goes low when reverse integration reaches zero, so BUSY can be used to control the start/stop of the counter. This article used a serial transmission mode, which greatly saved the microcontroller I/O port occupancy. Figure A5 (Appendix) is ICL7135 microcontroller interface circuit.

A/D converter converted to the digital volume cannot be converted with the previous simulation is exactly the same, there must be some deviation. Agilent 34401A digital multimeter was used to correct the A/D module. Engineering not just refers to the hardware circuit components of engineering, which also includes the commissioning of the process for engineering, experimental process of engineering. The calibration steps are as follows:

1 Connect A/D circuit, check the correct A/D conversion circuit board power (±12 V) and the smallest single-chip system board power supply (+5 V).

2 Adjust the reference voltage of the A/D conversion board to 1 V, short the analogue input and eliminate the offset of the zero voltage with software.

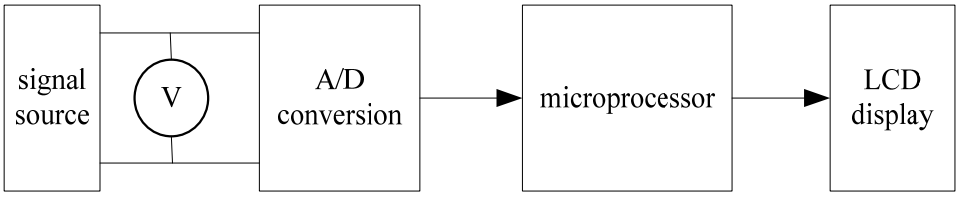
3 Adjust the analogue input to 1.656 V and adjust the A/D conversion value, meanwhile the potentiometer is calibrated, to minimise the error between these two values.

4 The analogue to digital conversion test of the calibrated A/D conversion circuit board is carried out and the test data are recorded.

5 Do A/D conversion of 1.656 V analogue input voltage for many times, record conversion data.

6 The partial pressure of the reference voltage is measured by several times to determine the stability.

Figure 8 The A/D conversion test circuit



The test circuit is shown in Figure 8. According to the above operation flow, three A/D conversion circuit boards were tested, debugged in accordance with the above debugging steps. The test results are shown in Table A3 (Appendix) partially.

Three analogue-to-digital conversion circuit boards were tested. And relative errors of the circuits were 0.156%, 0.148% and 0.152%. Therefore, the analogue-digital conversion module can be a well copy, error controllable A/D conversion module. This design can meet requirements and the needs of engineering which is under normal circumstances can be less than the overall error of 1/10.

4 Experiments

4.1 Experimental condition

In order to ensure that the photoelectric signal detection system designed can complete the detection of milk ingredient content in this paper, it is necessary to determine an appropriate experimental condition. Through a large number of experiments that the experiment should be homogeneous pressure 18 MPa, the temperature should be maintained at 40°C. It must ensure that the milk sample concentration invariance, because only in this way, can get a unique surface equation.

The experimental equipment required by the design of the milk ingredient content detection instrument designed in this article, HJ-4 long magnetic stirrer (self-heating function), high pressure homogeniser and test tube, beaker, liquid pipe and so on.

4.2 Experimental procedure

The engineering design of a detection system is sometimes not only the engineering design of the hardware such as the circuit boards, but also the engineering design of the key part of the experiment process so as to improve the experiment accuracy and repeatability.

1 We selected the pasteurised milk that has been calibrated, with a protein content of 6% and a fat content of 5%. Because pasteurisation is low-temperature sterilisation, the impact on the content of milk is small. The pasteurised milk samples were taken from ten groups and each sample was subjected to the operations numbered 1 to 10.

2 Turn on the power source and preheat the circuit and the laser about 90 minutes. The circuit and the laser can be maintained in a more stable working condition after 90 minutes, it is helpful to improve the accuracy of the result.

3 After homogenising the milk with a homogeniser, 1 mL of milk and 9 mL of physiological saline were taken with a burette (buret precision is 0.5 mL), the milk and the physiological saline were sufficiently stirred. After that, the mixture was introduced into a detection plate No.1 and the detection plate was placed in closed detection device with the lid covered to prevent external light interference. The scattering voltage and transmission voltage values were recorded in per 5 minutes.

4 Repeat the above three steps, the solution was 2 mL milk and 8 mL water.

5 Repeat the above steps, the solution was 3 mL milk and 7 mL water.

6 Repeat the above steps, the solution was 4 mL milk and 6 mL water.

7 Repeat the above steps, the solution was 5 mL milk and 5 mL water.

8 Repeat the above steps, the solution was 6 mL milk and 4 mL water.

9 Repeat the above steps, the solution was 7mL milk and 3 mL water.

10 Repeat the above steps, the solution was 8 mL milk and 2 mL water.

11 Repeat the above steps, the solution was 9 mL milk and 1 mL water.

12 Repeat the above steps, the solution was 10 mL milk and 0 mL water.

13 Record the result, analyse the conclusion.

The scatter ratios obtained for the five tests are reported in Table 2.

Table 2 Scattered through ratio five times the measured data

No.	*Fat (%)*	*Protein (%)*	*Test 1*	*Test 2*	*Test 3*	*Test 4*	*Test 5*
1	0.6	0.5	1.2710	1.2711	1.2873	1.2721	1.2871
2	1.2	1.0	1.4656	1.4847	1.5111	1.5109	1.5065
3	1.8	1.5	1.5850	1.5452	1.6055	1.5577	1.5936
4	2.4	2.0	1.5730	1.5563	1.5384	1.5967	1.6161
5	3.0	2.5	1.5355	1.5482	1.5563	1.6561	1.6150
6	3.6	3.0	1.5676	1.5517	1.6802	1.5706	1.5903
7	4.2	3.5	1.4950	1.4760	1.5975	1.6072	1.5359
8	4.8	4.0	1.6612	1.5919	1.6800	1.6331	1.6611
9	5.4	4.5	1.6084	1.6445	1.6374	1.6858	1.6664
10	6.0	5.0	1.6749	1.6859	1.5863	1.6458	1.7065

4.3 Data analysis

The data obtained in the experiment are shown in Table 2. The results of the scattering ratio recorded as Table 2, plotted as a graph, as shown in Figure 9.

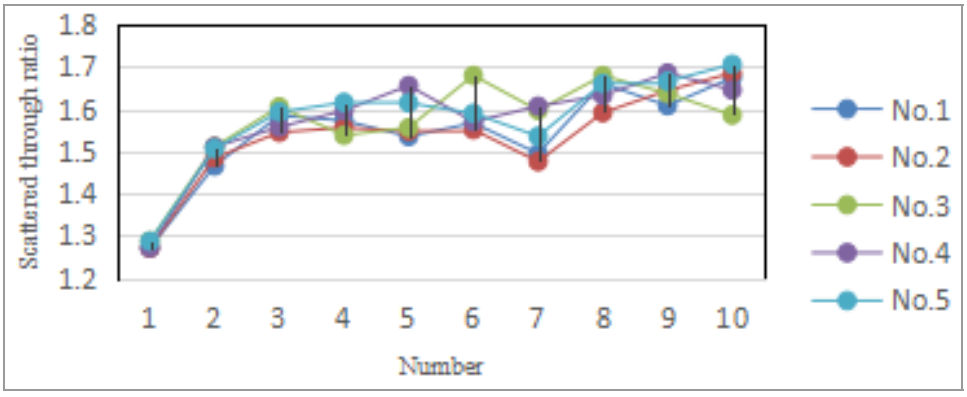
It can be seen from Figure 9 that this method does not apply when the milk protein or fat content is relatively high. The high concentration of milk samples is not conducive to the transmission of light, making the transmission signal more weak and not easy to measure, it often makes large deviations for detection results. Besides, the reason for the large deviation of the high concentration samples is the complex refraction of the light. In addition, the higher light intensity will lead to higher heat carried by the incident light, which will affect the detection results. Therefore, this method has a protein range of 0% to 1.5%, which can be measured by this method when the concentration of fat is 0% to 1.8%. It can be seen from Figure 9 that in every situation where the measurement is the same, the system precision is about 5%.

Based on the research on the establishment of relevant models in Section 2.2 and experimental data, the multiple linear regression theory is used to do the regression analysis of the multiple milk samples in same concentration. The correlation standard between scattered through ratio and the concentration information was obtained. The model equation was:

$$\begin{aligned} Y = & -17.9711\xi_1^2 - 87.6896\xi_2^2 - 32.5489\xi_1 \\ & -7.7555\xi_2 + 170.4241\xi_1\xi_2 + 9.2963 \end{aligned} \tag{10}$$

The correlation coefficient of this regression equation was 0.96, which can meet the design requirements of this paper, can well characterise the relationship between the scattered through ratio and the main ingredient contents of milk.

Figure 9 The ratio of scattered light and transmitted light multiple test results (see online version for colours)



As we all know, the measurement error objectively exists and is inevitable. If only with the traditional perspective of error analysis, there will often be many imperfections. In this paper, the uncertainty of the measurement results to be analysed, due to it is easy to operate, easy to quantify and other advantages, the results obtained can be more complete analysis. Measurement uncertainty is a parameter used to indicate the dispersion of a measured value, usually representing an estimate of the true value (Mandavgade et al., 2012; Lanza and Viering, 2011). In other words, uncertainty is expressed as a degree of dispersion in the measurement result. It can be seen that when uncertainty is used to measure the outcome of a system, the result is not a fixed value, but rather a discrete interval that contains an infinite number of possible values.

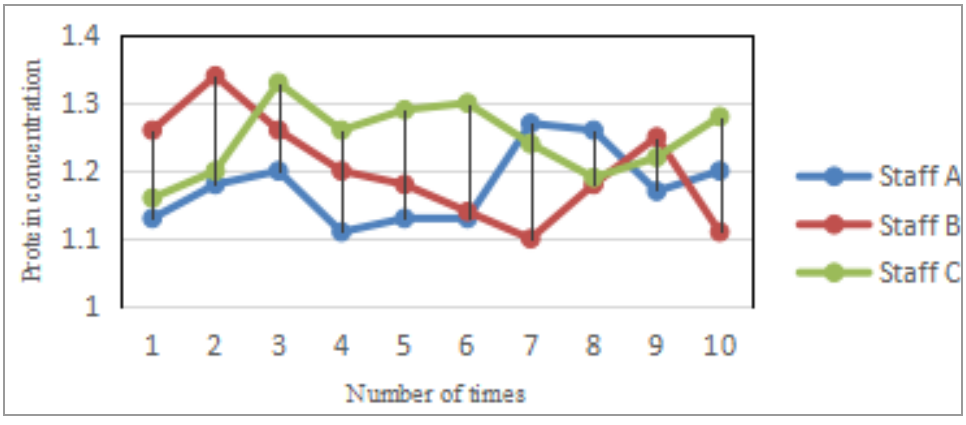
Table 3 Protein concentration test results for different operators (%)

Number	*Staff A*	*Staff B*	*Staff C*
1	1.13	1.26	1.16
2	1.18	1.34	1.20
3	1.20	1.26	1.33
4	1.11	1.20	1.26
5	1.13	1.18	1.29
6	1.13	1.14	1.30
7	1.27	1.10	1.24
8	1.26	1.18	1.19
9	1.17	1.25	1.22
10	1.20	1.11	1.28

In order to make a more complete measurement of the whole system, by the view of uncertainty analysis, the milk detection system designed is analysed in this paper. The experimental steps are as follows. Take a sample of the milk that has been subjected to calibration and detect the milk sample by the three systems of A, B and C, respectively. The three samples each received the same milk sample that had been calibrated and the value of the calibrated protein was 1.20%. This value can serve as a reference for the

following experiments. Table 3 shows the measurement results and for more intuitive observation, the data is charted as shown in Figure 10.

Figure 10 Comparative measurements of different people (see online version for colours)



An analysis of multiple measured data yielded a measured concentrations average of A is 1.178, B is 1.212 and C is 1.247. After getting the average, we conduct uncertainty analysis of the results from multiple perspectives.

1 The data observed in the Table 3 can be drawn, each time a different experiment regardless of whether the operator is the same person, the results will be relative to the calibration value of a certain deviation and this deviation is uncorrected. Therefore, the component u_1 caused by the deviation and the linearity is as follows.

$$u_1 = \frac{\text{The biggest deviation}}{\sqrt{3}} = \frac{1.247 - 1.2}{\sqrt{3}} \approx 0.0271 \tag{11}$$

2 As can be seen from the data, the offset of Staff C data are the largest, so the uncertainty component u_2 caused by repeatability is as follows.

$$u_2 = \sigma = \sqrt{\frac{\sum v^2}{n-1}} = \sqrt{\frac{0.03339}{9}} \approx 0.0609 \tag{12}$$

3 Observed by the data in the Table 3 shows that the operator's replacement will have a certain impact on the results. Therefore, the uncertainty component u_3 caused by reproducibility can be obtained.

$$u_3 = \sigma_0 = \frac{\max \overline{x_i} - \min \overline{x_i}}{d_m} = \frac{\overline{C} - \overline{A}}{d_3} = \frac{1.247 - 1.178}{1.69} \approx 0.0408 \tag{13}$$

Comprehensive analysis of the above data, we can draw the system's synthesis of standard uncertainty as shown below.

$$u_3 = \sqrt{u_1^2 + u_2^2 + u_3^2} = \sqrt{0.0271^2 + 0.0609^2 + 0.0408^2} \approx 0.078 \tag{14}$$

In summary, the overall system uncertainty is 0.078, indicating that the value of the uncertainty is not large, the system's detection accuracy can satisfy design requirements.

5 Summary

With the background of milk, this paper mainly studied on engineering module design for liquid macromolecular ingredient content detection, based on the theory of scattered through ratio. Firstly, a model for protein and fat ingredient content was established with the theory of scattered through ratio. Then the modular design, engineering exploration of each module were carried out. The average error of the two photoelectric conversion circuit boards were 0.0072 and 0.0094 respectively and the relative error of the three A/D conversion circuit boards were 0.156%, 0.148% and 0.152% respectively. The design can meet the engineering application indicators basically. After several experiments and comparative analysis, when the modular instrument in the experimental conditions were the same, we obtained the relation of scattered through ratio and the main ingredient contents of milk by experiment data. Finally, the correlation coefficient of the established model can reach 0.97, the system measurement uncertainty is about 0.078, so the reproducibility of the system designed in this paper is well. It may provide a basis for reference to the detection of milk ingredient content. In addition, protein and fat particles are used as experimental objects to represent a class of macromolecules in this paper. The universality of scattered through ratio method measurement in other such macromolecules will be a future study.

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Appendix

Figure A1 Overall circuit diagram of photo detector

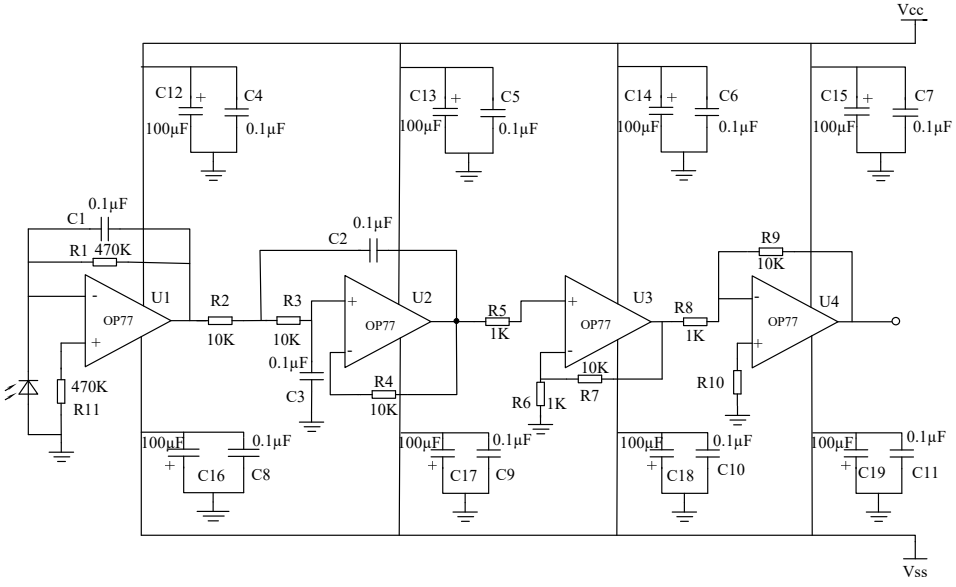

Figure A2 The main program flow chart

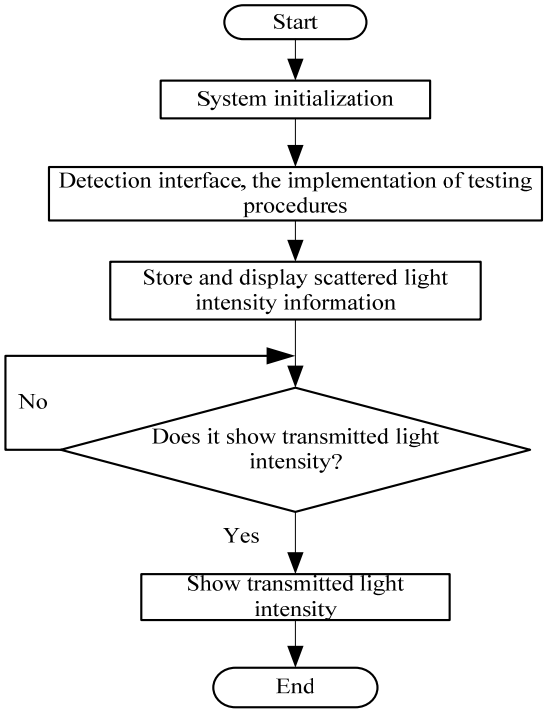

Figure A3 The a/d conversion flow chart

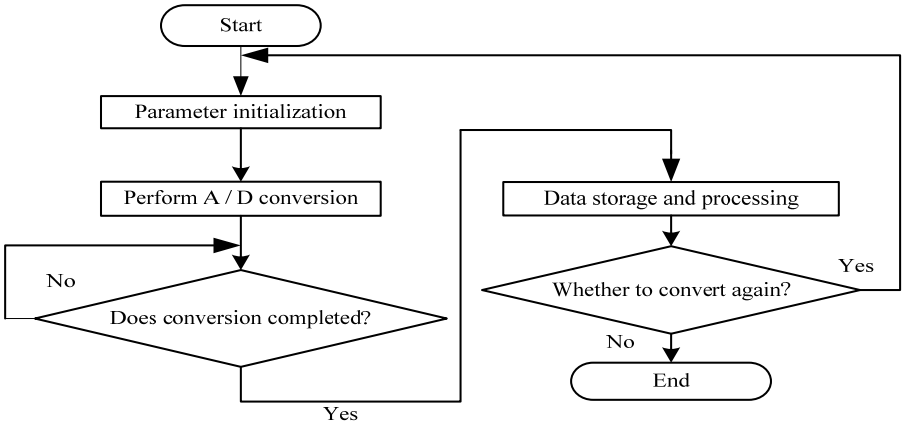

Figure A4 The conversion diagram of ICL7135

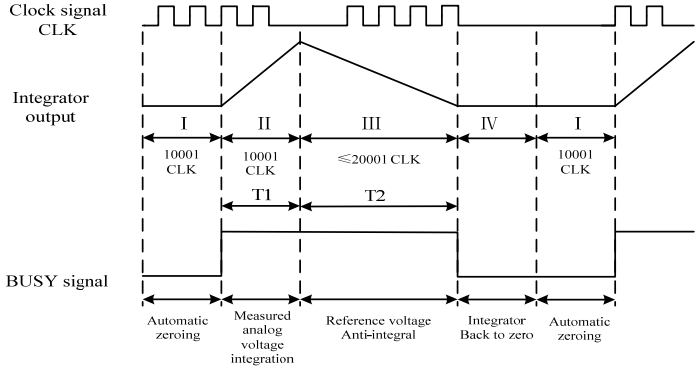

Table A1 Scattered light measurement data of the direction of the photodetector circuit

Preamplifier stage output voltage (V)	*Theoretical output voltage (V)*	*Actual output voltage (V)*
0.006832	0.6832	0.6897
0.009168	0.9168	0.9224
0.011071	1.1071	1.1073
0.013186	1.3186	1.3257
0.014977	1.4977	1.5113

Figure A5 The A/D conversion and its interface circuit

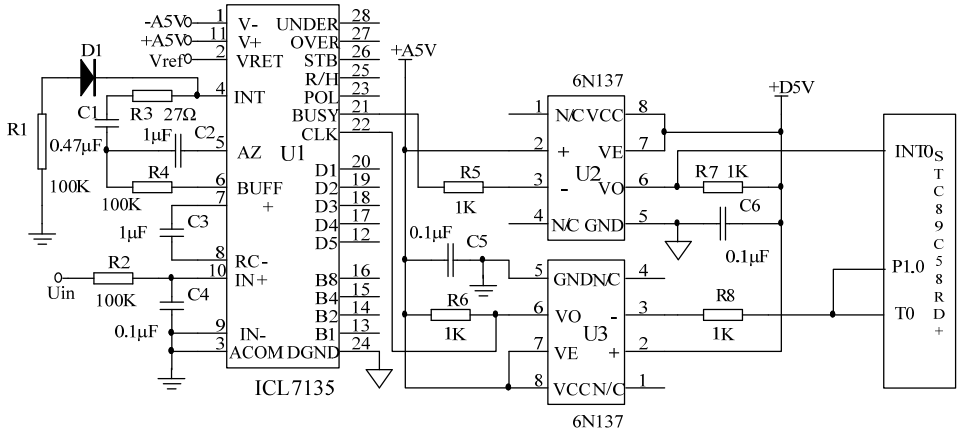

Table A2 Transmitted light measurement data of the direction of the photoelectric detection circuit

Preamplifier stage output voltage (V)	*Theoretical output voltage (V)*	*Actual output voltage (V)*
0.006186	0.6186	0.6246
0.009237	0.9237	0.9326
0.010382	1.0382	1.0484
0.013462	1.3462	1.3591
0.014498	1.4498	1.4641

Table A3 The digital calibration test data of ICL7135

Serial number	*Enter the value (V)*	*A circuit display value (V)*	*B circuit display value (V)*	*C circuit display value (V)*
1	0.0032	0.0031	0.0031	0.0031
2	0.0953	0.0952	0.0952	0.0952
3	0.5960	0.5961	0.5961	0.5961
4	0.9959	0.9961	0.9960	0.9960
5	1.1968	1.1969	1.1969	1.1969
6	1.5966	1.5966	1.5967	1.5966
7	1.8963	1.8964	1.8964	1.8964
8	1.9959	1.9958	1.9958	1.9958