Development of a New Method for Turbidity Measurement Using Two NIR Digital Cameras

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ABSTRACT: This paper proposes a new method of using two NIR digital cameras to measure water turbidity accurately and quickly. A measuring device based on an NIR camera and image processing software is designed. Two NIR cameras collect scattered and transmitted images when the NIR light is passing through the turbid solution. The average RGB values of 400 pixels in the central region of the image are obtained and converted into CIE Lab color space values. The water turbidity was measured by the functional relationship between turbidity and the corresponding color components (R, G, B, L, a, b, and grayscale). The results of comparison with a commercial turbidimeter show that this method has a high accuracy for the determination of standard solution with wider linear range and is consistent with the turbidimeter results for the measurement of real samples, which verifies the feasibility of this method.

1. INTRODUCTION

Water contains suspended and colloidal substances such as soil, dust, microorganisms, and zooplankton, which can make the water turbid. Turbidity refers to a solution’s degree of obstruction to light, which includes the scattering of light by suspended matter and the absorption of light by solute molecules. Turbidity is not only related to particulate matter in water but also to the particles’ size, shape, and surface area. Liquid turbidity measurement has a wide range of applications in water supply, brewing, pharmaceutical preparation, environmental protection, health and epidemic prevention, and many other industries. In water quality monitoring, turbidity is also an important parameter to characterize water quality, and turbidity measurement plays an important role in the turbidity control systems for industrial and drinking water.

Some turbidity measurement techniques are based on optical methods, including the visual turbidity, transmission light, scattering light, and ratio methods. A visual turbidimeter has poor accuracy and is only suitable for rough judgment of water turbidity. The transmission light, scattering light, and ratio methods that were based on the photoelectric detection have been developed and were utilized to measure the turbidity. The main difference among them is the different angles of photodetectors relative to incident light and the different number of photodetectors. The angle of the detector has a great influence on the measurement range and sensitivity of turbidity detection. As for the transmission light method, the angle between the photodetector and incident light is 180°. When the path length is determined, multiple light scattering events will occur among particles in high turbidity solution (>250 NTU), and the linear relationship between scattering light intensity and suspended particle concentration will be disturbed. Therefore, the transmission light method is always used to measure those high turbidity solutions, whereas the scattering method is suitable for the low turbidity measurements. In the ratio method, two detectors are utilized simultaneously. One detector for incident light, positioned at 90°, is used to measure the intensity of scattered light, and another detector, at 180°, is used to measure the intensity of transmitted light. Because the transmission and scattering light have the same transmission medium, the influence of the change of water color and light source on turbidity is the same, so this method can remove part of the interference and improve the sensitivity. However, the ratio of scattered light to transmitted light intensity is not strictly linear, although it is approximately linear within a certain range of turbidity, so the measurement range of turbidity has certain limitations.

Apart from the conventional turbidity detection methods as mentioned above, some new turbidity measurement methods have been developed, such as using the attenuation of signal

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intensity as a turbidity measurement when measuring depth with a lidar pulse signal. It is able to measure the turbidity within the range of 0–1000 NTU with improved accuracy and robustness compared to the existing turbidity sensors. Another type of detector, using a plastic fiber sensor, has also been studied. This type of detector uses multimode optical fibers, and the probe is immersed in the turbid solution to collect reflection signals and determine turbidity by using different reflection signals. In addition, there is a measurement method based on chromaticity coordinates based on transmission spectroscopy, which uses different absorbance of different turbid solutions to express the turbidity of solutions by chromaticity coordinates.

The above turbidity measurement methods are all based on the photoelectric detection technique. For them, it is necessary to design the optical path, photoelectric detection circuit, signal amplification and processing circuit, and A/D conversion circuit. Hence, the whole system is complicated and the cost is expensive. Additionally, a smartphone camera with the HydroColor was applied to measure the remote sensing reflectance and turbidity.

In this study, a simple device with low cost was designed to measure the turbidity. Two NIR cameras were used to obtain the transmitted and scattered light images of NIR light passing through a turbid solution, and the RGB values of images were obtained by image processing. Then, the CIE Lab and the grayscale values of the solution image are obtained by RGB values. Luminance refers to the brightness of a surface, expressed in L, that is, the light flux reflected from a surface. The intensity of light can be measured by the total amount of light illuminated on the plane, which is called incident light. If the intensity of light is measured by the amount of light reflected from the plane to the eyeball, then it is called reflection light or brightness. Under the same conditions, the greater the intensity of light, the brighter it will be. Among some color spaces, the CIE Lab is the most intuitive color space to express brightness. Moreover, it is found that the luminance (L) has a linear relationship with turbidity when the RGB color space is converted into Lab color space in our experiments. The variation trends of RGB, Lab, and grayscale values with a series of turbid solutions and modes of transmission, scattering, and ratio are analyzed and fitted, and the expressions of RGB, Lab, and grayscale values for turbidity are obtained. The real samples were measured and compared with turbidimeter data to verify the feasibility of this method for turbidity measurement.

2. RESULTS AND DISCUSSION

2.1. Experimental Data and Analysis. To test the performance of our device, some standard solutions with different turbidity values were prepared according to the international standard ISO7027. First, the distilled water was filtered at least twice by a microporous membrane with a pore size of 0.2 μm. Then, the filtrate was obtained as the zero turbidity water (means 0 NTU without sample). The other standard solutions with different turbidity values, such as 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, and 1000 NTU were prepared, referring to the ISO 7027 using the zero turbidity water, hydrazine sulfate, and hexamethylenetetramine.

The RGB values of transmitted and scattered light corresponding to different turbidities were measured and then converted to Lab and grayscale values, respectively. Note that each standard solution was measured five times to reduce the error. The standard deviation for each measurement was calculated using eq 1 as shown below

\[ \alpha = \sqrt{\frac{\sum_{i=1}^{n} (V_i - V_0)^2}{n - 1}} \]

where the α is the standard deviation, \( V_i \) is the measurement values, \( V_0 \) is the averaged value, and n is measurement amount. However, the calculated standard deviation values are rather small (~0.5) in comparison to the measured values. Hence, the standard deviation was not considered. The averaged value, which was calculated by the five measurements, was regarded as the experimental data in this study.

Figure 1 shows that the variation trend of G and R values is consistent with that of turbidity in the scattering and transmission modes. However, the B value in the scattering mode does not correspond to turbidity one to one, whereas the B value in the transmission mode is almost the same and hardly distinguished at a low concentration range. Hence, the B value is not suitable for the turbidity measurement under the current condition. One reason for this is the different spectral sensitivity of the red, green, and blue channels. The blue and the green channels have cross interference. Moreover, the blue channel has high sensitivity. Another reason is that the camera’s white balance setting affects the gain of the three-color channels.

Figure 2 shows the good corresponding relationship between the L value and turbidity, which means that the L...
value can be used to measure turbidity, while the values of \(a\) or \(b\) are not suitable for turbidity measurement because of the nonmonotonicity between turbidity and \(a\) or \(b\). According to the Beer–Lambert law, as shown in eq 2

\[
I_T = I_0 e^{-kdl}
\]

where \(I_T\) is the intensity of transmitted light, \(I_0\) is the intensity of incident light, \(k\) is the proportional constant, \(d\) is the turbidity of the sample solution, and \(l\) is path length; there is a negative exponential relationship between transmitted light intensity and turbidity. However, the relationship between luminance \(L\) and turbidity is approximately linear when the transmitted light is measured in this research. The reason is that the luminance \(L\) obtained by the imaging method is different from the light intensity obtained by the photocell of the turbidimeter.

By using the ratio between scattering and transmission data, the influence of light refraction, the color of turbid solution, aging, and instability of the LED light source on measurement can be eliminated. The ratios of \(R\), \(G\), and \(B\) are denoted as \(R', G',\) and \(B'\). As shown in Figure 3, the \(R', G',\) and \(B'\) values in the transmission/scattering mode have high sensitivity for low concentrations, whereas they become very low for the medium and high concentrations. The sensitivity of RGB in scattering/transmission mode is high for high concentration and low for medium and low concentrations.

The ratios of \(L\), \(a\), and \(b\) are denoted by \(L', a',\) and \(b'\), as shown in Figure 4. In this ratio mode, the effect based on the \(L'\) value is the best. Using either the ratio of scattering to transmission or transmission to scattering mode, the \(L'\) value has higher discrimination of changes in turbidity. However, the color components \(a'\) and \(b'\) are indistinguishable at the medium turbidity range and cannot be used for turbidity measurement.

2.2. Fitting Results of \(R, G, L\), and Grayscale Values to Turbidity. Through the analysis of experimental data, the trend of change between the \(R\) value, \(G\) value, \(L\) value, and turbidity shows good monotonicity, so \(R\), \(G\), and \(L\) values in the scattering, transmission, and ratio measurement modes are selected for turbidity measurement. The formulas of fitting curves and coefficient of determination are given in Figure 5. The fitted coefficients \(R^2\) are very close to 1, which means that the fitted formulas have a good fit with those curves. Using these fitted formulas, the turbidity of the solution can be calculated.

The grayscale of image also represents the turbidity of solution. It can be calculated using eq 3

\[
\text{grayscale} = R \times 0.299 + G \times 0.587 + B \times 0.144
\]

where \(R\), \(G\), and \(B\) means the RGB values of the turbid solution images. These grayscale values in scattering and transmission modes are also fitted, as shown in Figure 6.

2.3. Measurement of Standard Turbidity. To verify the performance of the turbidity measurement of our device, the turbidity of standard solutions and real samples were measured using the designed device and two commercial turbidimeters, namely, Turb-1 with the range of 0–200 NTU and Turb-2 with the range of 0–1000 NTU. The standard turbid solutions of 10, 20, 30, 40, 50, 60, 80, 100, 150, and 200 NTU were measured by our setup, and compared with Turb-1, the standard turbid solutions of 50, 100, 200, 300, 400, 500, 600,
700, 800, and 900 NTU were measured and compared with Turb-2. All of the turbidity data and standard turbidity value were analyzed by the independent sample t test. The detailed results are listed in Tables 1 and 2. As shown in the two tables, no matter the results of the one-sided test or the results of the two-sided test, the significance level are much greater than 0.05 in each set, indicating that there was no significant difference in data. These results show that the performance of our setup is comparable to that of commercial products.

The measurement accuracy was estimated by calculation of the deviation rate using eq 4 as shown below

$$D = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{V_i - V_0}{V_0} \right) \times 100 \%$$

(4)

where $D$ is the deviation rate, $V_i$ is the measurement values using the designed device and two commercial turbidimeters, $V_0$ is the corresponding standard turbidity values, and $n$ is measurement amount using the same method. The less $D$ value means the higher measurement accuracy.

Moreover, the accuracy was also calculated to estimate measurement accuracy using eq 5

$$A = \frac{\max(V_i - V_0)}{R} \times 100\%$$

(5)

where $A$ is the accuracy level, $\max$ means the maximum values that are measured, and $R$ is the measurement range of the instruments. The less $A$ value means the higher measurement accuracy.

All the calculated deviation rates and accuracy levels are listed in Tables 1 and 2. As shown in Table 1, the deviation rates under the Scat-R, Scat-L, Scat/Tran-L', Tran/Scat-G', Tran/Scat-L', and Scat-gray measurement modes are lower than those of the value measured by Turb-1, whereas the other deviation rates are higher than those of Turb-1. Additionally, the Scat-R, Scat-L, Tran-L, Scat/Tran-L', Tran/Scat-G', Tran/Scat-L', Scat-gray, and Tran-gray modes are more accurate due to their less A values. However, all the deviation rates and accuracy levels measured by Turb-2 are higher than those of the values measured by our designed setup, which means that our methods are more accurate for the measurement of high turbidity values.

Figure 4. Relationship between turbidity and $L'$, $a'$, and $b'$ ratio values. (a) Relationship in the ratio of scattering to transmission mode. (b) Relationship in the ratio of transmission to scattering mode.

Figure 5. Fitting curves in the scattering, the transmission, and the ratio measurement mode with their fitted formulas. (a) Fitting curve of the R value in scattering mode (Scat-R), (b) fitting curve of the L value in scattering mode (Scat-L), (c) fitting curve of the G value in transmission mode (Tran-G), (d) fitting curve of the L value in transmission mode (Tran-L), (e) fitting curve of the R' value in the ratio of scattering to transmission mode (Scat/Tran-R'), (f) fitting curve of the L' value in the ratio of scattering to transmission mode (Scat/Tran-L'), (g) fitting curve of the G' value in the ratio of transmission to scattering mode (Tran/Scat-G'), and (h) fitting curve of L' value in the ratio of transmission to scattering mode (Tran/Scat-L').
These 20 sample solutions were used as the current study’s solutions were randomly prepared with standard turbid water, wastewater, and production water, and the other 10 sample solutions were obtained from local rivers, industrial wastewater, and production water, and the other 10 sample solutions were obtained from local rivers, industrial wastewater, and production water. Tran-gray, were selected for turbidity measurement. Analyzed by one-way ANOVA (analysis of variance). Their turbidity measurement results using the new NIR digital camera device.

2.4. Contrastive Measurement of Real Samples. Ten sample solutions were obtained from local rivers, industrial wastewater, and production water. These 20 sample solutions were randomly prepared with standard turbid water. These 20 sample solutions were used as the current study’s real samples. The data of 20 real samples measured by Turb-1, Turb-2, and our chosen eight measurement models were analyzed by one-way ANOVA (analysis of variance). Their Pearson correlation coefficient $\gamma$ were also calculated. When the significance level $\alpha$ is 0.05, the critical value $F_{\text{crit}}$ (1, 38) is 4.0982.

The analysis results of real samples are shown in Table 3. The probability $P$-values of the eight groups of data are all greater than $\alpha$, whereas all $F$ values are less than $F_{\text{crit}}$. The Pearson correlation coefficients are very close to 1. These results indicate that there is no significant difference between the data of eight measurement modes and the Turb-1 and Turb-2 data. It also shows the practicability and consistency of measurement results using the new NIR digital camera device.

### 3. CONCLUSIONS

A turbidity measurement method based on the NIR camera is proposed. The turbidity measurement device and image acquisition software were designed. The transmission and scattering images of NIR light through solutions with different turbidity were obtained with the camera and used to obtain the fitting relations and correlation of turbidity values under transmission, scattering, and ratio modes for different color components. Data analysis verifies the feasibility of eight turbidity measurement methods: luminance $L$ and color $R$ in scattering mode, luminance $L$ in transmission mode, color $G$ in transmission/scattering mode, luminance $L$ in ratio (scattering/transmission and transmission/scattering) mode, and grayscale in scattering and transmission mode. Compared with two standard turbidimeters, our device and proposed methods have higher accuracy in the measurement of standard solutions. For the measurement of specific water samples, our model can provide more reliable and accurate data for turbidity analysis.

### Table 1. Comparison of Measurement Data between Our Setup and Turb-1

| measurement mode | sig. (one-sided) | sig. (two-sided) | deviation rate | accuracy level |
|------------------|-----------------|-----------------|----------------|---------------|
| Turb-1           | 0.905           | 0.918           | 3.56%          | 3.85%         |
| Scat-R           | 0.938           | 0.988           | 2.05%          | 0.65%         |
| Scat-L           | 0.986           | 0.991           | 0.95%          | 0.60%         |
| Tran-G           | 0.832           | 0.976           | 5.53%          | 0.95%         |
| Tran-L           | 0.842           | 0.998           | 5.47%          | 0.46%         |
| Scat/Tran-R'     | 0.184           | 0.934           | 56.42%         | 4.51%         |
| Scat/Tran-L'     | 0.977           | 0.994           | 3.48%          | 0.42%         |
| Tran/Scat-G'     | 0.946           | 0.970           | 1.48%          | 0.69%         |
| Tran/Scat-L'     | 0.985           | 0.998           | 1.21%          | 0.30%         |
| Scat-gray        | 0.960           | 0.988           | 1.32%          | 0.74%         |
| Tran-gray        | 0.985           | 0.979           | 4.35%          | 0.46%         |

### Table 2. Comparison of Measurement Data between Our Setup and Turb-2

| measurement mode | sig. (one-sided) | sig. (two-sided) | deviation rate | accuracy level |
|------------------|-----------------|-----------------|----------------|---------------|
| Turb-2           | 0.823           | 0.898           | 14.73%         | 7.79%         |
| Scat-R           | 0.973           | 0.979           | 1.17%          | 2.38%         |
| Scat-L           | 0.974           | 0.978           | 0.99%          | 2.47%         |
| Tran-G           | 0.965           | 0.995           | 2.21%          | 1.10%         |
| Tran-L           | 0.999           | 0.999           | 1.80%          | 0.64%         |
| Scat/Tran-R'     | 0.771           | 0.460           | 12.02%         | 4.45%         |
| Scat/Tran-L'     | 0.869           | 0.995           | 0.83%          | 0.76%         |
| Tran/Scat-G'     | 0.984           | 0.990           | 1.42%          | 3.78%         |
| Tran/Scat-L'     | 0.986           | 0.998           | 0.87%          | 0.76%         |
| Scat-gray        | 0.974           | 0.979           | 0.96%          | 2.52%         |
| Tran-gray        | 0.941           | 0.990           | 1.80%          | 1.43%         |

Figure 6. Fitting curves of the grayscale the in the scattering mode and transmission mode with their fitted formulas. (a) Scattering mode (Scat-gray), (b) Transmission mode (Tran-gray).

Table 3. Analytical Results of Real Samples

| group             | Turb-1 | Turb-2 |
|-------------------|--------|--------|
|                   | $F$    | $P$-value | $\gamma$ | $F$    | $P$-value | $\gamma$ |
| Scat-L            | 0.3656 | 0.5490  | 0.9988  | 0.0051 | 0.9433  | 0.9901  |
| Tran-L            | 0.9278 | 0.3415  | 0.9877  | 0.0924 | 0.7628  | 0.9898  |
| Scat-R            | 0.3500 | 0.5576  | 0.9956  | 0.0074 | 0.9317  | 0.9902  |
| Scan/Tran-L'      | 0.7159 | 0.4028  | 0.9992  | 0.0277 | 0.8687  | 0.9908  |
| Tran/Scan-G'      | 0.0895 | 0.3492  | 0.9990  | 0.0745 | 0.7864  | 0.9906  |
| Tran/Scan-L'      | 0.0232 | 0.8797  | 0.9989  | 0.0232 | 0.8797  | 0.9907  |
| Scat-gray         | 0.8082 | 0.3745  | 0.9988  | 0.0562 | 0.8139  | 0.9900  |
| Tran-gray         | 0.6525 | 0.4243  | 0.9952  | 0.0071 | 0.9333  | 0.9893  |
experimental results are consistent with those of the standard turbidimeters, which verify the practicability of our methods. Using the NIR camera instead of an optical detection system not only reduces the cost of the design but also improves the accuracy of the measurement. The method can also be applied to other NIR measurement fields.

4. MATERIALS AND METHODS

4.1. Measuring Device. Figure 7 shows the schematic diagram of the designed device. The system consists of an NIR light source, a sample cell, two NIR cameras, and a microcomputer. The NIR light source uses an 850 nm, 0.5 W LED, powered by the USB port from the camera, and driven by an adjustable current source circuit. The working current is about 15 mA. As reported by Omar and Matjafri, the NIR light source is less influenced by the color of the solution. Therefore, NIR light sources with a wavelength at 850 nm was used in this study. When the LED works in constant current, the current flowing through the LED can be kept within the rated working range to ensure the stability of the light source. One camera for the transmission mode is in line with the NIR light source (180°), and the other for the scattering mode is perpendicular to the NIR light source (90°). A black PVC tube is used to connect the camera and the sample compartment, and the inner diameter of this PVC pipe is 30 mm. The camera is connected to the microcomputer through a USB port. The acquired image is sent to the computer for further processing to obtain the required experimental data. The black cover and sample chamber form a closed space, which effectively avoids the interference of other light sources on the turbidity measurement.

4.2. The Function of the NIR Digital Camera. Two NIR cameras with the same type were used in the experiment. Both of them are 850 nm narrow-band filters combined with ordinary CMOS cameras. The CMOS sensor model is AR0130. The maximum resolution is 1280 × 960. The 850 nm narrow-band filter with a focal length of 3.6 mm can effectively eliminate the influence of other wavelengths and improve the sensitivity. To verify the experimental results, the camera can be manually adjusted in focus, white balance, tone, and other parameters.

The CMOS photosensitive elements used in digital cameras are semiconductor devices used to record the change of light. Each pixel of the camera is equivalent to a photoelectric detection element. After the light passes through the turbid solution and the 850 nm filter, in turn, the camera collects the incident light with a wavelength of about 850 nm. The camera’s photodiode detects the intensity of NIR light sensitively. The CMOS image sensor converts an optical image into an electrical signal, which is converted into a digital image signal after A/D (analog-to-digital conversion). Then, it is sent to the digital signal processing (DSP) chip for processing into raw RGB data and transmitted to the computer through the USB interface. For RGB cameras, the NIR light is equivalent to a white light source, and the result of camera imaging is a gray image. Therefore, the camera can take a clear NIR image and express it in RGB. In addition, using the camera can avoid the necessity of developing a photoelectric detection, signal processing, and A/D conversion circuit to allow visualization of the turbidity measurement process.

4.3. Design of Image Acquisition Software. The image acquisition software interface is shown in Figure 8. Using the Visual Studio platform, it was developed with C# language and
Camera_NET control, and the programming was relatively simple. "Camera selection" is used to select the experimental camera, and "camera settings" includes options to adjust the brightness, white balance, tone, saturation, and exposure settings of the camera. The software automatically saves the parameters of the previous camera settings. However, due to the different requirements of transmission and scattering for camera parameters, transmission and scattering need a set of fixed camera parameters. "Snapshot the frame" obtains a frame image and takes the average RGB value of 400 pixels in the central region of the frame image. In this way, the RGB value corresponding to the turbid solution can be obtained, and then, the corresponding Lab value of the turbid solution can be obtained by converting the RGB color space to the CIE Lab color space. In the CIE Lab color space, "L" represents the luminance of the solution through light, "a" represents the range from red to green, and "b" represents the range from yellow to blue. L ranges from 0 to 100, and a and b range from +127 to -128.

An approximate conversion algorithm is used to transform the RGB color space to the CIE Lab color space as follows. First, the RGB color space is converted to the XYZ color space

\[
\begin{align*}
X &= 0.412453 \times X + 0.357580 \times Y + 0.180423 \times Z \\
Y &= 0.212671 \times X + 0.715160 \times Y + 0.072169 \times Z \\
Z &= 0.019334 \times X + 0.119193 \times Y + 0.950227 \times Z
\end{align*}
\]  

(6)

\[
X = \frac{X}{255 \times 0.950456} \\
Y = \frac{Y}{255} \\
Z = \frac{Z}{255 \times 1.088754}
\]

(7)

Then, the XYZ color space is converted to CIE Lab color space

\[
\begin{align*}
L &= 116(Y - 16) \\
a &= 500(f(X) - f(Y)) \\
b &= 200(f(Y) - f(Z))
\end{align*}
\]

(8)

\[
f(t) = \begin{cases} 
\frac{1}{3} & \text{if } t > \left( \frac{6}{29} \right)^3 \\
\frac{1}{3} \left( \frac{29}{6} \right)^2 t + \frac{4}{29} & \text{otherwise}
\end{cases}
\]

(9)

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### Notes

The authors declare no competing financial interest.

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