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Design and characterization of a smart turbidity transducer for distributed measurement system

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ABSTRACT

This paper presents the design and characterization of a turbidity transducer, intended for measuring water turbidity in distributed measurement system (DMS). The design of the transducer based on IEEE 1451 standard focus on the networking capability in distributed measurement applications. The design of Smart Transducers Interface Module (STIM), Transducers Electronic Data Sheets (TEDS), self-recognition of STIM and temperature self-compensating are presented. The electrical characterization and fabrication of the transducer are also investigated. The Transducer Independent Interface (TII) has been replaced with a more conventional and widely used RS-485. The turbidity transducer proposed suitable for continuous monitoring of water turbidity, and the prototype developed is appropriate for turbidity measurement in the range of 0–100 NTU. The transducer described here has the characteristics of good linearity, high reproducibility, high accuracy, low power dissipation and no significant temperature effect on the turbidity transducer.

1. Introduction

Turbidity is regarded as a key technical parameter in water quality measurement, and the turbidity transducer as an instrument for measuring water turbidity has been applied widely in water quality monitoring [1–3]. There are two main types of turbidity transducer. Common turbidity transducers measure light attenuation and nephelometric turbidity transducers measure scattered light at an angle of 90° to the incident beam. The latter has been adopted by Standard Methods as the preferred method of turbidity measurement [4]. Previous studies of turbidity transducers are comprised of the following parts: light source (light emitting diode), detector (photodiode), signal processing circuit and microcontroller unit or microprocessor. The microcontroller performs the software and sends the resulting signal via USB [5] or RS-232 [6] to the data recording device to display or store the results, such as LCD and PC [7–9]. These transducers capable of measuring a wide range of turbidity, has good sensitivity, high accuracy and precision. Moreover, embedded with a microcontroller unit or microprocessor, the transducers can perform more powerful functions such as self-calibration [10].

However, as to the distributed measurement applications, the most attractive advantage that a smart transducer offers is the networking capability [11–13]. Previous studies can be used for laboratory measurements using desktop computer, or as a portable instrument for field measurements using laptop computer or basing turbidity meter, few studies has been focused on the networking capability of turbidity transducer in distributed measurement applications. At the lowest level of a distributed measurement system (DMS), smart transducers are interfaced to the network node to sense environmental conditions [14]. Turbidity transducers suitable for continuous operation in remote field sites ideally require the additional design features of durability, low power consumption, minimal electronic drift, automatic temperature compensation and a means of overcoming the problem of window fouling due to algal growth.

In order to achieve the above additional design features, the IEEE1451 standard could be an interesting solution and selection. The sensor networking and DMS design are regulated by the IEEE1451 smart transducer interface standards [15]. The standard IEEE 1451 [16,17] intends to normalize and simplify the interconnection between transducer systems using networks. Standardization of interface makes interconnection of transducers to instruments and networks easy and standard [18,19]. This standard is divided in two parts: in the first part, the smart transducer interface module (STIM) to interface transducers and carries out all the functions related with the transducers, and holds their Transducer Electronic Data Sheet (TEDS); in the second part, the Network

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Capable Application Processor (NCAP) communicates with the STIM via the Transducer Independent Interface (TII), reads the TEDS from the STIM and transmits processed measurement data to a high-level network server. The standard IEEE 1451 has been applied in designing of other sensors [20–22] or systems [23,24]. However, few researchers have been done on turbidity transducer based on IEEE 1451 for DMS.

Furthermore, the turbidity transducers obtainable in the market produce their outputs (4–20 mA, frequency output, voltage output, etc.) in many different ways, and the types of interface differ between each turbidity transducer. As a result, the development of turbidity transducer becomes complex and expensive which causes many disadvantages for designers, turbidity transducer manufacturers and final users. Compatibility problems are a key reason for standardizing the interface at the hardware interconnection level. The STIM and the NCAP are linked by a Transducer-Independent Interface specified in this standard, a 10-wire bus designed for feeding the STIM and for exchanging information [25]. The TII is a superset of Serial Peripheral Interface (SPI); a transfer protocol is specified to allow data transmission across the TII. However, the TII has been replaced with UART and USB interfaces because of the complexity and unpopularity of the TII definition, so that popularly accepted RS-232, RS-485, and USB serial communication protocols can be directly used in smart turbidity transducers [18,19].

In this paper we describe a smart turbidity transducer designed based on IEEE1451 standard for distributed measurement system. The transducer embedded with a microprocessor can embed local intelligence to support features such as self-recognition, automatic temperature compensation, and can perform self-declaration to the network based on TEDS designed in this paper. This self-declaration feature allows turbidity transducer devices to be connected to the network in a true "plug-and-play" fashion. Besides, the design of a Smart Transducers Interface Module that meets the IEEE 1451 normative has been presented. The STIM provide signal conditioning and processing functions to sensor. Thus, output of the sensor is digital signal with physical unit. The TII has been replaced with a more conventional and widely used RS-485 for remote transmission and easier interface design. The transducer also features a power voltage decrease from standard voltage 12–24 V to 2.7–3.3 V for realizing low power dissipation.

2. Principle of operation

The turbidity is the reduction of the transparency of a liquid due to the presence of non-dissolved materials. When light is passed through a water sample, particles in the light path change the direction of the light, scattering it and decreasing the incident radiation to the detector. If the turbidity is low, most of the light will continue in the original direction. Light scattered by particles allows the particles to be detected in water [26]. In all cases, light scattering leads to (a) an angular distribution of scattered light, and (b) a reduction in intensity of transmitted light. Both of these effects can be exploited to measure turbidity. It is possible to measure the amount of light transmitted through the sample or the light scattered at one or more angles to the incident beam. Difficulties exist in transmitted light measurement: (1) turbidities less than about 10^{-4} cm^{-1} cannot be easily measured; (2) transmitted light measurements essentially give the extinction, and there may be a contribution from absorption as well as turbidity. For colored waters this can be a significant problem. These problems can be avoided by measuring scattered rather than transmitted light [27].

The scattered light can be measured by one or more photodetectors positioned at $\alpha = 90^\circ$ (nephelometric scattering), $\alpha < 90^\circ$ (forward scattering) or at $\alpha > 90^\circ$ (back scattering) to the direction of the incident beam [2]. The scattered light measured at an angle of 90° to the incident beam is not sensitive to particle size, and has less influence of stray light [28–30]. So the transducer we developed measures scattered light at an angle of 90° to the incident beam.

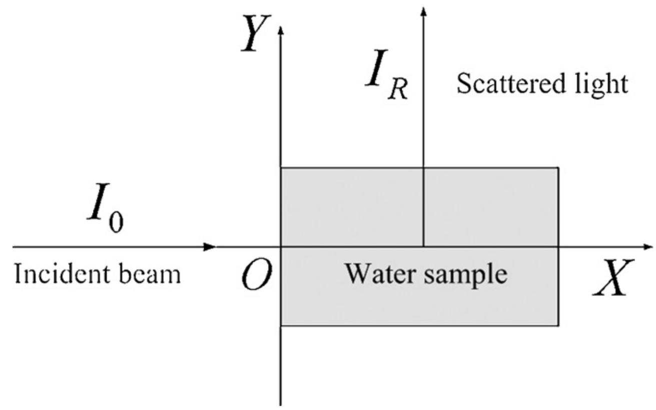

Fig. 1. Principle of operation.

A basic light scattering set-up is shown schematically in Fig. 1. In the figure, an incident beam passed through a suspension. When particle size less than light wavelength, the intensity of scattered light is then given by (often known as the Rayleigh scattering law):

$$I_R = \frac{24\pi^3 NV^2}{\lambda^4}\left(\frac{n_1^2 - n_2^2}{n_1^2 + 2n_2^2}\right)^2 I_0 \tag{1}$$

where I_0, is the incident light intensity, and I_R is the scattered light intensity at the scattering angle of 90° to the incident beam, N is the number of particles per unit volume, and V is the particle volume, λ is the incident light wavelength, n_1 and n_2 are refractive index of water and particle respectively.

Under given circumstances, λ and V are assumed to be constant, $(24\pi^3 NV^2)/(\lambda^4)((n_1^2 - n_2^2)/(n_1^2 + 2n_2^2))^2$ is in direct proportion to the sum of particle number per unit volume as well as total volume. Then I_R is given by

$$I_R = K_R T I_0 \tag{2}$$

where T, is turbidity, $K_R = (24\pi^3 V^2)/(\lambda^4)((n_1^2 - n_2^2)/(n_1^2 + 2n_2^2))^2$ is scattering coefficient. Under the circumstances of I_0 remain unchanged, I_R is in direct proportion to T.

When particle size is equal or greater than light wavelength, the intensity of scattered light is then given by (often known as the Mie scattering law):

$$I_M = K_M A T I_0 \tag{3}$$

where A, is particle surface area, I_M is the coefficient. Under the circumstances of A remaining unchanged, I_M is in direct proportion to T. Based on Rayleigh scattering law or Mie scattering law, scattered light intensity is in direct proportion to turbidity, and the measurement of turbidity was changed into the measurement of the intensity of scattered light.

3. Design of the transducer based on IEEE1451

3.1. STIM software design

The STIM program flow is shown in Fig. 2. The STIM working procedure starts with an initialization process of loading TEDS information; finishing self-configuring of STIM Module; setting various special register; initializing work mode for UART; setting working mode for timer and correlative variables and defining STIM channel. After initialization, the STIM checks whether there is a

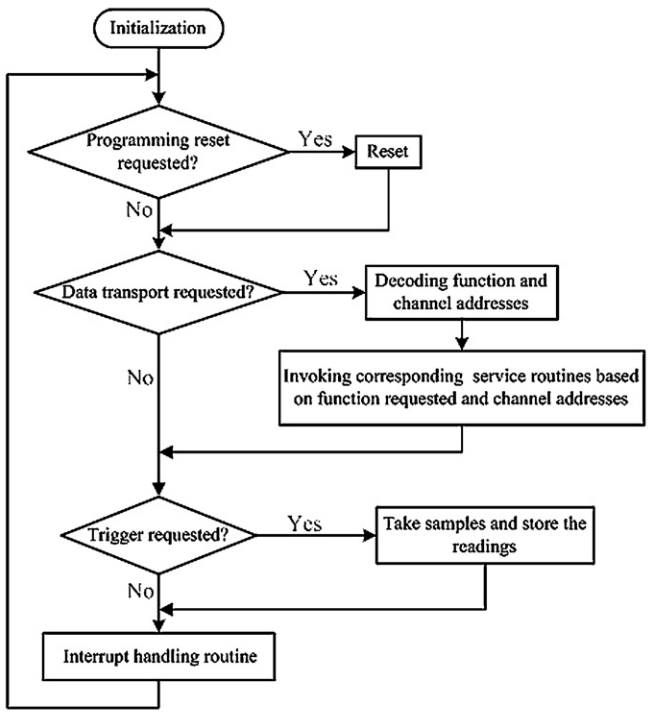

Fig. 2. Flowchart of software for STIM.

software reset request, to reset software or not. Then it checks the RS-485 interface for either a data transport request or a transducer trigger request from the NCAP. For a data transport request, the STIM decodes the function address, which indicates the type of function requested and the channel address. Commonly used functions include reading channel transducer data, reading various types of TEDS data, and reading channel status. Based on the function requested and the channel address, the STIM invokes corresponding service routines. For a transducer trigger request, the STIM takes a sample measurement in a specified channel, which was previously determined through the data transport request.

If, during the service, an error is detected on any of the transducer channels, the STIM invokes the corresponding interrupt handling routine, and asserts the interrupt signal line of the RS-485 interface to inform the NCAP. If no error is detected, the STIM would check the RS-485 interface again and the execution returns to the waiting loop.

3.2. TEDS design

The Transducer Electronic Data Sheet (TEDS) is a set of non-volatile memory locations used to store the information about the type, operation, and attributes of the transducer. In IEEE 1451.2, eight different TEDS sections are defined. Only two of them (Meta-TEDS and Channel-TEDS) are mandatory and remain with the STIM for the duration of its lifetime, and the other six are optional. The Meta-TEDS provides the interface with all of the information needed to gain access to any channel, plus information common to all channels. The Channel-TEDS supplies all of the information concerning the channel being addressed to enable the proper operation of the channel [17].

In this paper, the TEDS consists of Meta-TEDS, Channel-TEDS and Calibration-TEDS. Meta-TEDS describes the general characteristics of the transducer, including data structure and information of channels group. Information of channels group contains number of channels which the transducer supports, channel limited time and so on. When the transducer starts to work, the terminal identifies the transducer by reading Meta-TEDS, so the transducer can realize the plug-and-play function. Channel-TEDS describes the channel characteristics of the transducer, including measurement parameters, time parameters, physical units, measuring range, sensitivity and so on.

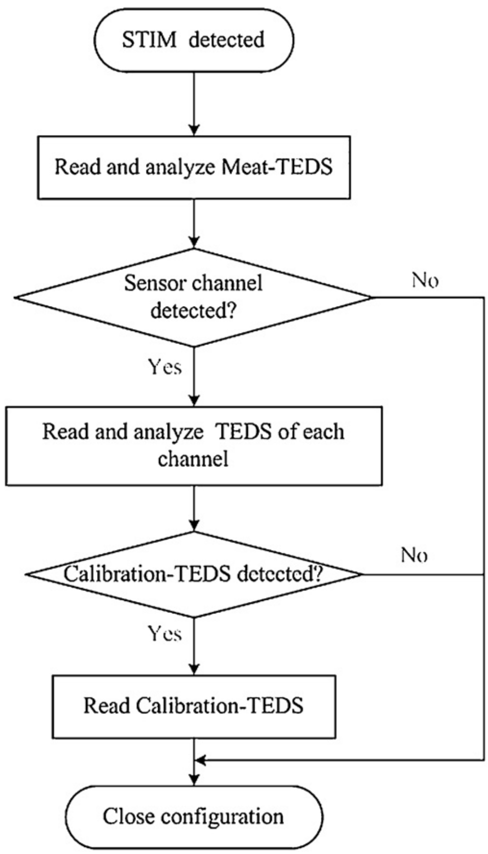

Fig. 3. Flow chart of self-recognition.

Calibration tables are stored in Calibration-TEDS and the transducer calibrates the turbidity sensor according to these tables. These sheets contain the latest calibration date, calibration cycle and all the other calibration parameters. The temperature of water is the main factor which influences the turbidity of water. So the Calibration-TEDS contains the temperature parameter tables and the relationship table of the temperature and the turbidity.

3.3. Self-recognition of STIM

Self-recognition is an important characteristic of intelligent sensor based on IEEE1451 standard, the TEDS in the STIM provides the capabilities of self-recognition for a smart transducer. NCAP can recognize the functions, usages, and specifications of the transducer, including software revision level, number and type of sensors, channel addresses, data types, physical units, signal ranges, calibration models, and time when last calibration was conducted, by reading its TEDS. All the information of STIM channel can be recognized by analyzing all the parameters, the self-recognition feature would allow easy implementation of plug-and-play for the smart transducers based on IEEE1451 standard. Flow chart of self-recognition is shown in Fig. 3. STIM can be detected by NCAP in the process of using, and then NCAP read and analyze the information stored in Meat-TEDS. If there is sensor channel detected, read and analyze the TEDS of each channel, else close configuration. If there is Calibration-TEDS detected, read Calibration-TEDS and close configuration, else close configuration directly.

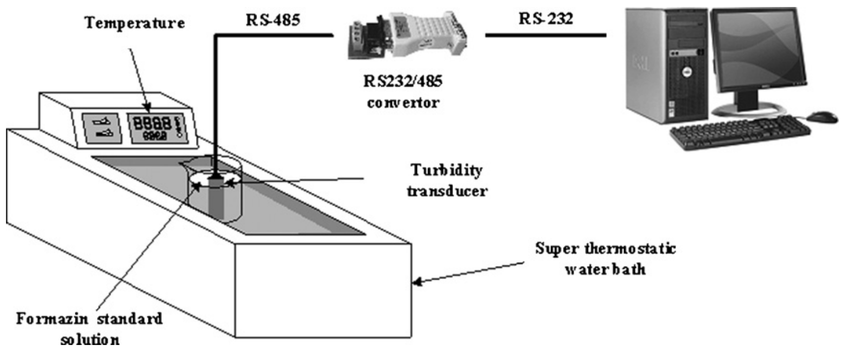

Fig. 4. Experimental device.

3.4. Temperature self-compensating

Turbidity transducer for water treatment applications is based on scattered light measurement. When a light beam from the light emitter passed through a water sample, particles in the light path will change the direction of the light and scatter it, scattered light received by the detector. The electro optical characteristic of the light emitter and detector has a close relationship with the temperature. Fluctuations in water temperature can potentially affect electronic components and cause output signal errors in turbidity transducers [31].

N different gauge point in the range of the turbidity sensor electronic scale were defined, and M different gauge point in the range of the temperature were defined, standard input value of each gauge point come from standard value generator of turbidity (Y_i) and temperature (T_j) respectively as following:

$$Y_i : Y_1, Y_2, \ldots, Y_N$$

$$T_j : T_1, T_2, \ldots, T_M$$

Read the corresponding output values U and U_T that correspond to standard input value of each gauge point above mentioned. In this way, the turbidity sensor calibrating in static states was done at M different temperature states, M different corresponding input and output character cluster (Y_i–U) were obtained. At the same time, N different input and output character cluster (T_j–U_T) of temperature sensor corresponds to different turbidity states were obtained too.

The correction coefficient of the two character cluster above mentioned was calculated by the least square method, which deduce the correction equation for the intelligent turbidity sensor, and the correction equation will be stored in Calibration-TEDS. Turbidity value and temperature signal voltage converts into turbidity project value after collected by the microcontroller by using the correction equation, which will finish the real-time self-compensating of turbidity and temperature sensor signal measurement errors.

4. Experimental details

4.1. Materials and equipment

The objective of the experiment was to evaluate the characteristics of the turbidity transducer design for distributed measurement system before use in the field. The experiment was carried out in a laboratory, and features such as linearity, reproducibility, accuracy, temperature effects and Method Detection Limit (MDL) were evaluated. Each feature was evaluated by monitoring Formazin standard suspension.

4.1.1. Turbidity standard solution

All solutions were prepared with filtered water and analytical grade chemicals. A 400 NTU Formazin standard suspension was prepared by mixing equal volumes of 100 mg/mL hexamethylenetetramine; $(CH_2)_6N_4$ and 10 mg/mL hydrazine sulfate solution $N_2H_4H_2SO_4$, after that, the mixture was let to stand for 24 h at 24–26 °C in a topaz bottle before the measurements. Filtered water was used as a carrier.

4.1.2. Measuring equipment for experiment

Fig. 4 shows an outline of the experimental equipment used in this study. In this work, measuring cylinder and Bunsen beaker were used to dilute Formazin standard solutions, and prepare the water samples. A fridge used to cool the water samples, and a super thermostatic water bath was used to change the temperature of water samples. In order to meet the market demand, and the requirement of remote transmission and networking, the transducer uses RS-485 field bus to make connection. Because the computer cannot connect with RS-485 interface directly, a RS-232/RS-485 converter was used to achieve the communication between computer and turbidity transducer.

4.2. Electrical characterization of the transducer

According to ISO 7027 light with $\lambda > 800$ nm can minimize interferences caused by the presence of dissolved light-absorbing substances (substances imparting color). Since colored organic substances are often present in surface water and drinking water from surface sources, it should be assumed that instruments using the longer wavelength will produce better turbidity measurements [32]. The use of high wavelength LED and especially that of IR emitting light were recommended [26] to avoid interferences for the water color.

The transducer is based on a high-power infrared light emitting diode (LED). The detector is a matching, high sensitivity Silicon Photoelectric Generator. Both the emitter and detector provide a narrow and closely matched spectrum. Hardware structure of the transducer is shown in Fig. 5. The transducer is primarily composed of a signal conditioning model, power source model, IR LED, Silicon Photoelectric Generator, constant-current source, temperature sensor, RS-485 field bus, microprocessor and FRAM.

Conversion of the Silicon Photoelectric Generator current and amplification of the voltage is achieved by using one wide range of input offset, low offset voltage drift, high input impedance, extremely low power, and high gain quad operational amplifiers (TLC27L4) – the gain can be adjusted according to the actual requirement. Constant-current source is consisted of operational amplifiers and triode. Take a 16 K bit Ferroelectric Nonvolatile RAM FM24CL16 as a storage space for TEDS. Temperature measurements by using a thermistor, temperature signal voltage converts into

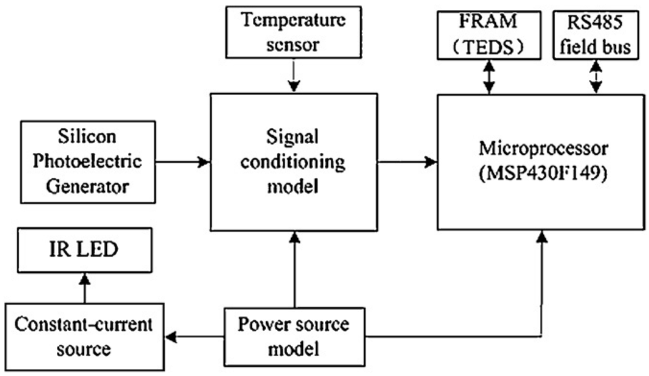

Fig. 5. Hardware structure of the transducer.

project value after collected by the microcontroller. The transducer requires a 3.3 V DC power source for the microprocessor, operational amplifiers, FM24CL16 and thermistor. A full circuit diagram is shown in Fig. 6.

4.3. Fabrication

An important design criterion for the transducer was that the casing will be rugged enough to withstand use for extended periods of time. The transducer contains three parts: external casing, foundation and shield. Black ABS plastic tubing was used for the three parts. Water outlet ports were set into the side face of the foundation, and water inlet ports were set into the bottom of the shield. Both the external casing and the shield have internal screw thread, and the foundation has external screw thread. The infrared emitter and the photodiode were fixed to the foundation with resin. The circuit board was set into the external casing. External casing connects to the foundation by means of screw thread and seal ring. Power, ground and output wiring were packaged in cable which is tightened to the external casing by cable seal gland. The shield connects to the foundation also by means of screw thread and seal ring. The black ABS shield ensured that no extraneous infrared light could be refracted through the casting to interfere with the turbidity signal received by the photodiode. The exploded view of the transducer is shown in Fig. 7. Fig. 8 shows the picture of the transducer.

4.4. Experimental set-up and results

4.4.1. Calibration curve

Calibration experiments were carried out at room temperature. In order to measure the response of the transducer to different solution concentrations, turbidity standard solutions of Formazin were adjusted with filtered water into water samples of 0–100 NTU

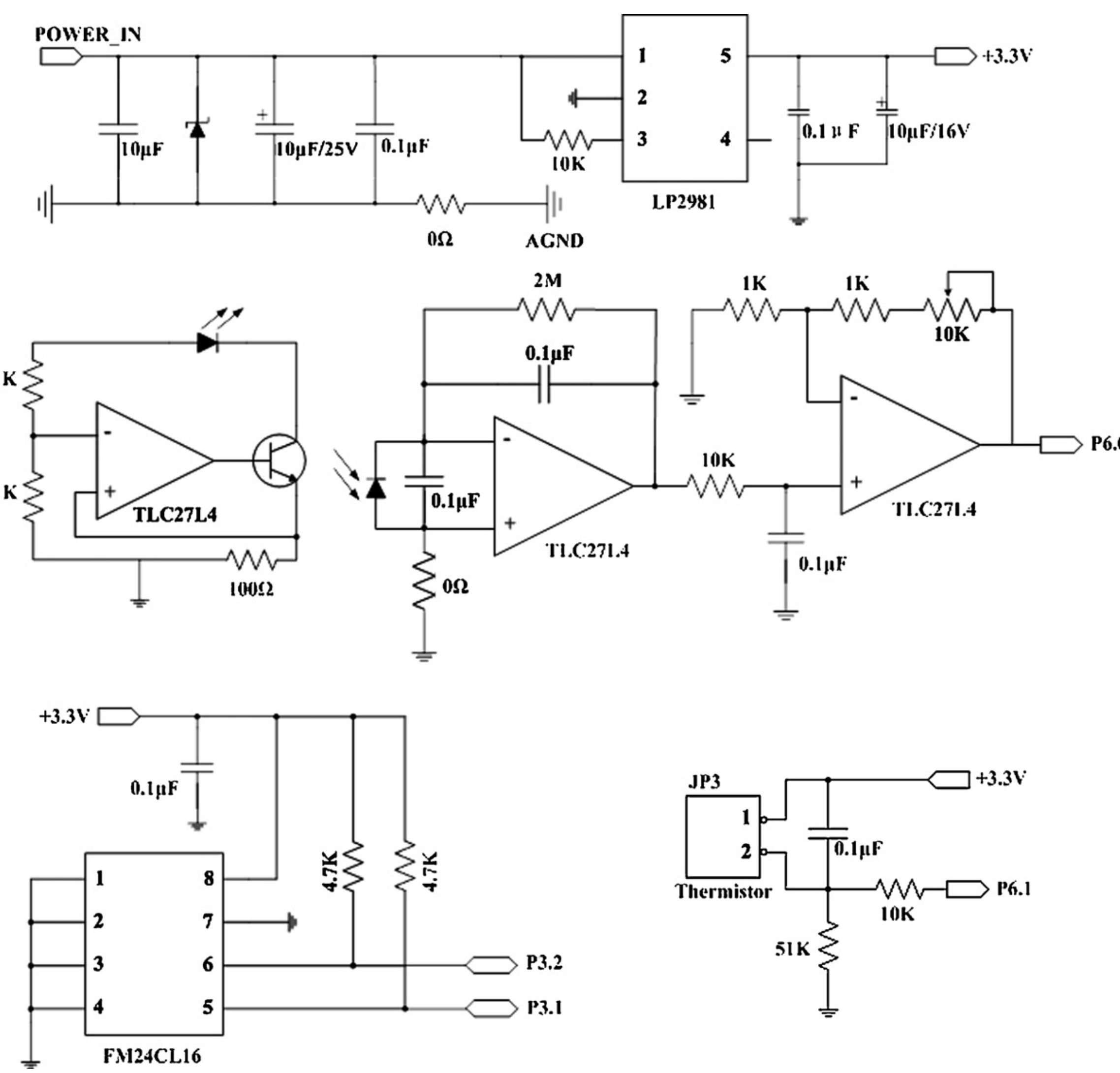

Fig. 6. Circuit diagram for the transducer.

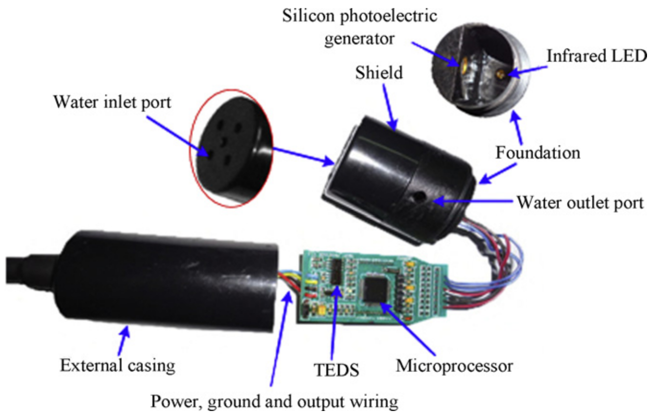

Fig. 7. Exploded view of the transducer.

Fig. 8. Picture of the transducer.

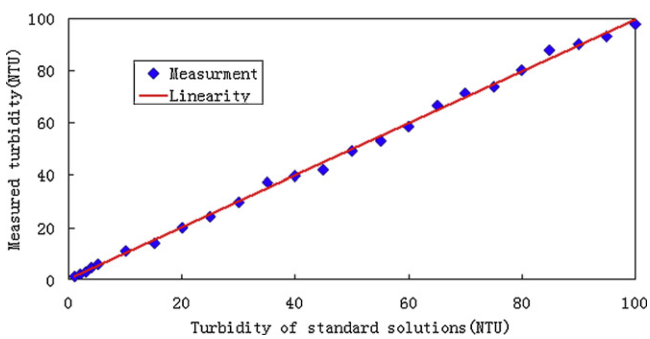

Fig. 9. Calibration results of the transducer.

and their turbidities were measured by the transducer to evaluate the linearity of the measured values. Twenty measurements at 5 s intervals were recorded for each concentration after the suspension had mixed for 1 min, complete disaggregation of the sample was assumed. Different concentrations were measured, ranging from 0 to 100 NTU. The measuring time was set to two minutes for the evaluation of linearity and the transducer was completely submerged under water.

Table 1 shows the results of measuring of different Formazin standard solutions with the transducer which was completely submerged under the solution. Fig. 9 shows the relationship between the turbidity of sample water prepared by diluting turbidity standard solutions of Formazin and the values measured by the transducer. Calibration curve of the probe was fitted according to the principle of least square which is $y = 0.9937x + 0.1182$, and the correlation coefficient is $R^2 = 0.9983$. Results show all the solutions measured gave nearly linear relations between the concentration of the standard solutions and the measured turbidity.

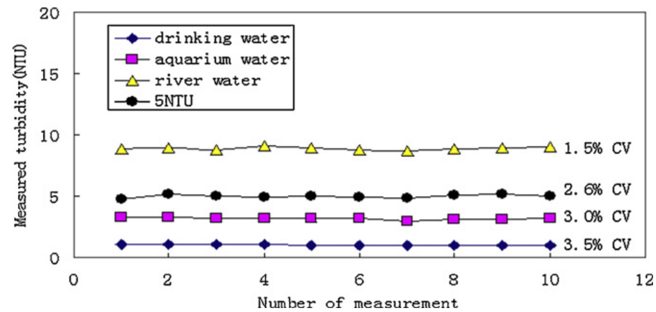

Fig. 10. Reproducibility of measured turbidity.

4.4.2. Reproducibility of the transducer

Adjusting turbidity standard solutions of Formazin by filtered water into water sample (5.00 NTU), a Bunsen beaker was filled with the water sample, and the transducer was completely submerged under water. Standard solutions were measured repeatedly 10 times; and the measuring time was set to two minutes for each test. Moreover, aquarium water, drinking water and river water were measured in the same way. Fig. 10 shows the results of repeatedly measuring the turbidity of Formazin standard solution (5.00 NTU), aquarium water, drinking water and river water samples 10 times each using the transducer. As the figure shows, the measurement reproducibility is very high and the coefficient of variation (CV) is within 5% for all these samples.

4.4.3. Accuracy analysis

Measurement accuracy reflects the closeness between the measurement result and the true value of the measure. Accuracy is measured in error – the smaller the error, the higher the accuracy. A measurement error can be expressed in absolute or relative form. The error expressed in the absolute form is called the absolute measurement error. The error expressed in relative form is called the relative measurement error. Table 2 shows the results of continuous monitoring of Formazin standard solutions (5.00, 10.00, 20.00, 50.00 and 100.00 NTU) with the transducer which was completely submerged under the solution. As the figure shows, the measurement accuracy is very high and the relative measurement error is within ±2% for all these samples.

4.4.4. Temperature effects

Turbidity standard solutions of Formazin were adjusted by filtered water into water samples of 0–100 NTU to measure the response of the transducer to different temperatures. Different concentrations were measured, ranging from 0 to 100 NTU. A Bunsen beaker was filled with Formazin standard solution, and the solution was cooled to 0 °C, and then the transducer was immersed in the solution. The Bunsen beaker and transducer were placed in a super

Table 1
The results of measuring of Formazin standard solutions.

Water sample/NTU	Measurements/NTU	Water sample/NTU	Measurements/NTU	Water sample/NTU	Measurements/NTU
1	1.17	25	24.15	65	66.83
2	2.26	30	29.62	70	71.21
3	2.81	35	37.28	75	73.94
4	4.45	40	39.47	80	79.96
5	6.09	45	42.21	85	87.62
10	11.02	50	49.32	90	90.36
15	13.75	55	53.15	95	93.09
20	19.77	60	58.62	100	98.02

Table 2
The results of accuracy testing.

Water sample/NTU	Measurements/NTU								Average value/NTU	Absolute measurement error	Relative measurement error
	1	2	3	4	5	6	7	8			
5.00	4.74	5.13	5.02	4.91	4.96	4.91	4.85	5.07	4.95	−0.05	−1.00%
10.00	10.05	10.11	10.32	10.27	10.02	10.02	10.03	9.98	10.10	0.10	1.00%
20.00	19.96	20.01	19.88	19.82	19.85	19.90	19.80	20.30	19.94	−0.06	−0.30%
50.00	49.61	49.21	49.82	50.02	50.43	50.23	49.41	49.43	49.77	−0.23	−0.46%
100.00	100.58	101.30	100.94	99.86	99.86	100.28	101.09	101.24	100.64	0.64	0.64%

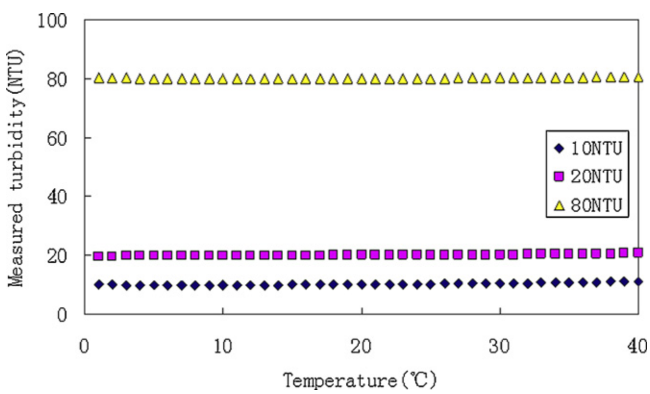

Fig. 11. The results of temperature compensation.

thermostatic water bath filled with an ice water mixture. Solution in the Bunsen beaker was gradually heated to 40 °C and output of the transducer recorded at 5 s intervals. The experimental set-up in this study is shown in Fig. 4. Trace bubbles will be produced in the heating process, so a glass rod washed by filtered water was used to agitate the standard solution of Formazin which was measured, for the purpose of avoiding influence of the trace bubbles to measured results.

The effect caused by temperature was measured by using Formazin standard solution of 10.00 NTU, 20.00 NTUand 80.00 NTU under the range of 0–40 °C and the results are shown in Fig. 11. Results show no significant temperature effect in the three output signals.

4.4.5. Method detection limit

Seven different zero turbidity water samples were measured by the transducer and the Method Detection Limit was analyzed according to EPASW-846 of USA. Table 3 shows the results of measuring of the seven different zero turbidity water samples.

The MDL is given by

$$\mathrm{MDL} = S \times t_{(n-1,0.99)} \tag{4}$$

where S, is standard deviation of the seven measured results, and $t_{(n-1,0.99)}$ is the value of t when the confidence is 99% and freedom is $n-1$, n is sample number. The MDL is calculated as following:

$$S = \sqrt{\frac{\sum_{i=1}^{7}(X_i - \overline{X})^2}{6}} = 0.0048795 \tag{5}$$

$$\mathrm{MDL} = S \times t_{(6,0.99)} = 0.015 \tag{6}$$

Table 3
The results of measuring of zero turbidity water samples.

Number of water samples	1	2	3	4	5	6	7
Measured results/NTU	0.01	0.01	0.00	0.01	0.01	0.00	0.01

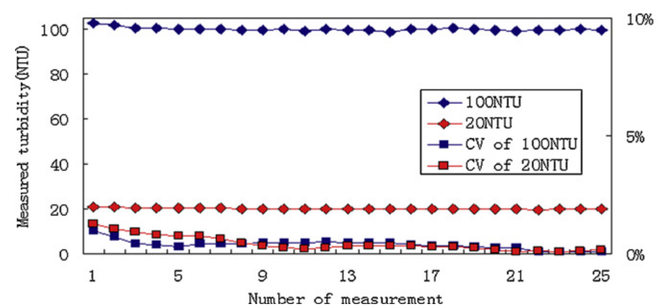

Fig. 12. Experimental results of Stability.

4.4.6. Stability test

Generally stability refers to the ability of metrological characteristics of the measuring instrument does not change with time. For measuring instrument, stability is one of the important metrological performances, and the stability of the indicated value is the foundation of guarantying the accuracy of measurement result. Adjusting turbidity standard solutions of Formazin by filtered water into water samples (20.00 NTU, 100.00 NTU), Bunsen beaker was filled with the water sample, and the transducer was completely submerged under water. Twenty-five measurements at 5 s intervals were recorded for each concentration. Fig. 12 shows the results of measuring the turbidity of Formazin standard solution (20.00 NTU, 100.00 NTU) using the transducer. Results show no significant change and the coefficient of variation (CV) is within 5% for each samples. The transducer gives a stable output value within 5 s.

5. Conclusion

In this paper, a smart turbidity transducer design based on IEEE1451 devoted to the distributed measurement system has been described. We conducted basic experiments to evaluate the characteristics of the turbidity transducer. By this experiment, the following results were obtained:

(1) The proposed turbidity transducer appears to be suitable for continuous monitoring of water quality. The prototype developed is appropriate for turbidity measurement in the range of 0–100 NTU. An almost linear relationship was found between the turbidity of each standard solution measured by the turbidity transducer and the concentration for all samples. The transducer has high reproducibility. Low power dissipation realized by decreasing power voltage, and no significant temperature effect on the turbidity transducer. These features basically meet of the additional design features mentioned above.
(2) The turbidity transducer is integrated with a standardized RS-485 interface and possesses self-recognition capability provided by its TEDS. Intelligent sensor interface module based on IEEE1451 standard achieving plug-and-play functionality.
(3) It should be noted that this study has been conducted in a laboratory, and the field measurements will be carried out in

the future for testing the networking capability of the transducer we have designed. The proposed turbidity transducer is not equipped with a self-cleaning mechanism. Further work is required to study how to clean the transducer from the impurities deposited during the measurements. Ultrasonic cleaning could be a good solution.

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