Measurement Science and Technology

PAPER

Design and development of a quasi-digital sensor and instrument for water turbidity measurement

Recent citations

- Abdul Salam

To cite this article: Ramesh Sanga *et al* 2019 *Meas. Sci. Technol.* **30** 115106

View the article online for updates and enhancements.

This content was downloaded from IP address 131.104.97.86 on 18/04/2020 at 03:58

IOP Publishing

Measurement Science and Technology

Meas. Sci. Technol. **30** (2019) 115106 (8pp)

https://doi.org/10.1088/1361-6501/ab2b87

Design and development of a quasi-digital sensor and instrument for water turbidity measurement

Ramesh Sanga, M Sivaramakrishna and G Prabhakara Rao

Security and Innovative Sensors Division, Electronics and Instrumentation Group, Homi bhabha National Institute, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu 603102, India

E-mail: stram@igcar.gov.in

Received 8 March 2019, revised 18 June 2019
Accepted for publication 20 June 2019
Published 6 September 2019

Abstract

In this paper, the design, realization, fabrication and assembly of a prototype water turbidity monitoring instrument based on an opto-resistive quasi-digital sensor has been proposed. The turbidity sensor has been constructed with LED (590 nm) as the light source, a light-dependent resistor, fixed capacitor and logic gate inverter. The primary output signal from the sensor is in the form of a transistor–transistor-logic pulse stream with 50% duty cycle. This form of the output signal can be directly interfaced with the microcontroller. To process pulse stream from the sensor, to convert into turbidity value in NTU and to display on an LCD, a microcontroller (PIC18f4550)-based embedded system has been developed. The turbidity monitoring instrument has been constructed, calibrated and experimentally tested by measuring the turbidity of the water in the range of 0–1000 NTU. The turbidity of 0–1000 NTU corresponded to the output frequency of 40.6–18.8 kHz with sensitivity of 22 Hz/NTU. This is a high-precision, low-power, portable instrument with low manufacturing costs compared to commercial turbidity monitoring instruments.

Keywords: turbidity, pulse frequency, quasi-digital sensor, light-dependent resistor, LED, microcontroller

(Some figures may appear in colour only in the online journal)

1. Introduction

Turbidity measurement is one of the important parameters used to determine the quality of water. Poor water quality affects the health of humans, the environment, aqua life, and production in industries. The quantity of suspended particles present in water is an indication of the quality of the water [1]. Microorganisms, spores, mud, sand and chemical precipitates contribute to the turbidity of water. Scaling on metal surfaces of a boiler takes place gradually over a period of time due to the turbidity in the processed water of power plants, and consequently the life span and efficiency of the boiler decreases. Turbidity measurement and purification of water can prevent scaling on metal surfaces of the boiler and other components of the power plants.

Turbidity is optical clarity of liquid and it is indicative of the quality of the water. In general, the turbidity of water is measured with an optical principle such as transmission and scattering [2–10]. In most cases, the sensing element of the turbidity sensor is a photodiode. First of all, the photodiode transforms the optical energy signal into an electrical signal in the order of μA. Afterwards, a high-gain, low-noise transimpedance amplifier strengthens the electrical signal, followed by a low-pass filter to remove the noise and finally an analog-to-digital converter to interface with a microcontroller. These signal conditioning blocks rely on operational amplifiers. Finally, a microcontroller acquires, stores, communicates to the computer and displays the turbidity value on an LCD.

Figure 1(a) shows the conventional method of signal conditioning of the turbidity sensor. The advantage of these

 © 2019 IOP Publishing Ltd Printed in the UK

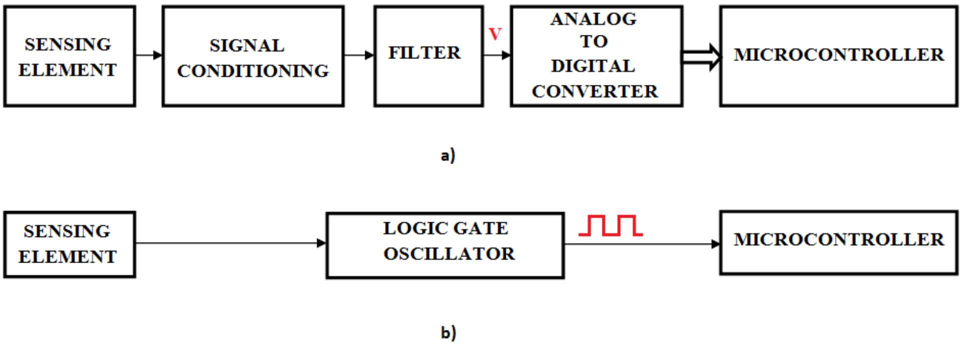

Figure 1. (a) Block diagram of conventional signal conditioning of the sensors, (b) block diagram of quasi-digital sensors.

methods is high accuracy. However, there are some obvious disadvantages. They require elaborate instrumentation, high cost, greater power consumption and more space. Direct digital readable sensors or quasi-digital sensors are highly precise with low power consumption, lower cost and are portable, making them suitable for the construction of instruments for industrial applications [11–13]. Figure 1(b) shows a diagram of the quasi-digital sensor. The sensing element (resistive, capacitive and inductive) is part of the timing circuit of the relaxation oscillator. Output from these sensors is quasi-digital (period or time interval) in nature. This kind of output is easy to interface to the microcontroller without using an analog-to-digital converter and other analog signal conditioning circuits. Quasi-digital signal can be directly measured in the digital domain using the timer/counter of the microcontroller.

This paper describes the design, realization, fabrication and assembly of a water turbidity monitoring instrument based on an opto-resistive quasi-digital sensor. Section 2 details the design, mechanical construction of the sensor, logic gate inverter-based signal conditioning circuit and working principle of the turbidity sensor. Section 3 explains the design and development of the embedded system to obtain the output from the sensor, measuring the pulse frequency, converting the sensor output into turbidity, displaying the turbidity value on an LCD, and communicating the turbidity values to the computer over RS232. Section 4 deals with the experimental setup to measure the turbidity, preparation of the turbidity standards, calibration of the instrument, an algorithm to measure the turbidity, measuring the turbidity of the unknown samples with the developed instrument and comparing it with that of a commercial instrument.

2. Sensor design

2.1. Construction of the sensor

In general, the turbidity sensors work on the principle of light absorption in the water or liquid. They require a light source (radiant energy) and sensing element to convert the unabsorbed radiant energy transmitted through the liquid into an electrical signal. Figures 2(a) and (b) show the schematic diagram of the opto-resistive sensing element and the photograph of the mechanical assembly of the prototype turbidity sensor.

The turbidity sensor was constructed with a cylindrical black-colored single-ended polyvinyl chloride plastic pipe 70 mm high and 30 mm in diameter. The black-colored pipe was chosen to avoid the interference of ambient light on the radiant energy of the turbidity sensor. This pipe was used to hold the sample bottle to measure the turbidity of the water or liquid. Light from an LED (590 nm wave length) of 5 mm diameter was chosen as radiant energy and a light-dependent resistor (LDR) of 5 mm diameter was chosen as a sensing element. These components were embedded in the walls of the PVC pipe exactly opposite each other. Any displacement of the LED and LDR due to vibration can result in a change in the radiant energy direction. Consequently, there is a shift of sensor output and calibration of the instrument. To avoid displacement, the LED and LDR were fixed on a plastic pipe with Araldite. The sample bottle made of quartz glass was used to test the turbidity of the water.

2.2. Design of the quasi-digital-sensor transduction circuit

The transmittance or absorption of radiant energy in the solution was adopted and deployed to design a quasi-digital sensor. The LED (590 nm) and LDR were used as radiant energy and sensing elements respectively. The LDR was part of the timing circuit of the relaxation oscillator. The logic gate oscillator (relaxation oscillator) consists of a fixed capacitor, variable resistor as the LDR and logic gate inverter. Figure 3 shows the schematic diagram of the quasi-digital sensor.

As per Beer–Lambert law, the amount of radiant energy absorbed by the liquid is an exponential function of the concentration of the absorbing particles present in the path of radiant energy [14–17].

$$I_T = I_0 e^{-\varepsilon c l}. \tag{1}$$

I_T = Intensity of the light transmitted through the solution
I_0 = Intensity of the light entering the solution
ε = Molar absorptivity (l/mole-cm)
c = Concentration (mole l^{-1})
l = Lightpath length (cm)

The relationship between the transmitted light and turbidity is given by [18]:

$$I_T = I_0 e^{-KT}, \tag{2}$$

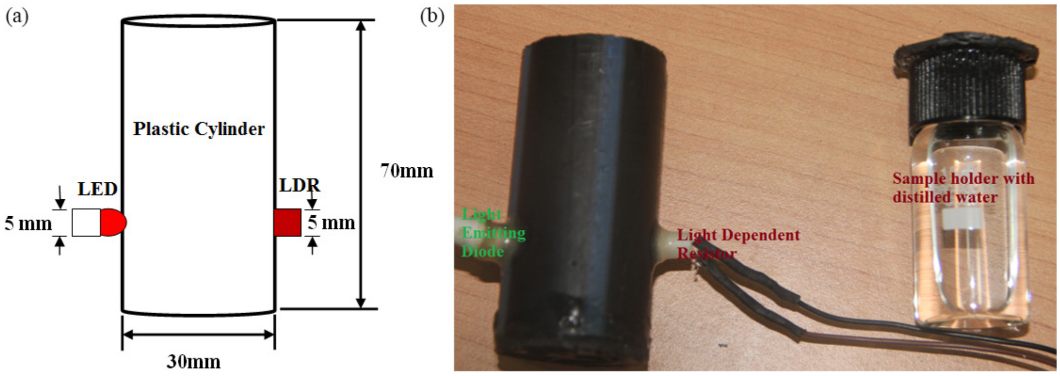

Figure 2. (a) Schematic diagram of the sensor assembly. (b) Photograph of the sensor assembly.

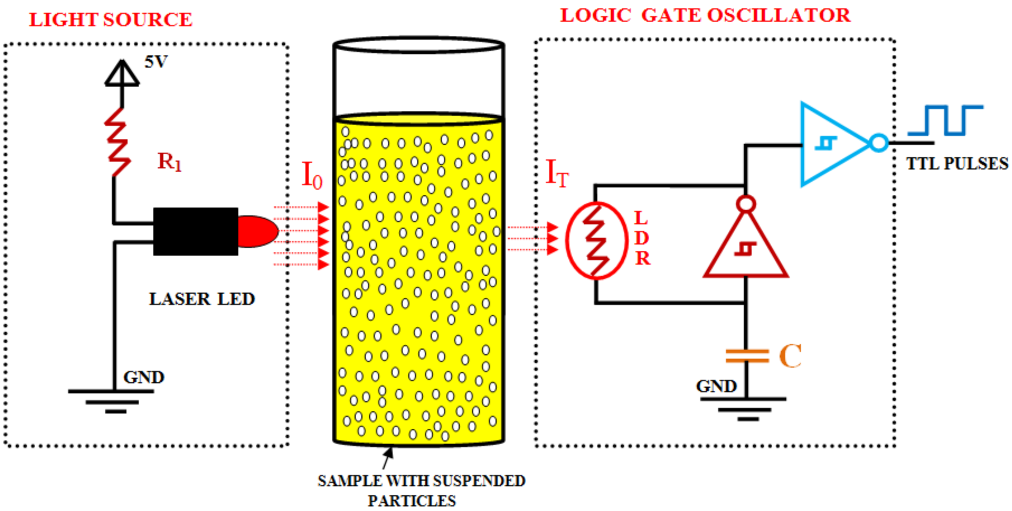

Figure 3. Schematic diagram of the quasi-digital sensor.

where K is the absorption coefficient and T is the turbidity of the test solution.

The LDR was used to detect the intensity of transmitted light (I_T) through the solution. The relationship between the LDR resistance (R_{LDR}) and intensity of the light (I_T) is given in equation (3) [19–22].

$$R_{LDR} = kI_T^{-\gamma}. \tag{3}$$

Here, k is constant and Υ is a parameter depending on the type of LDR material (in this work $\Upsilon = 0.7$).

By substituting equation (2) in (3),

$$R_{LDR} = k(I_o e^{-KT})^{-\gamma} = k\left(\frac{e^{0.7KT}}{I_o^{0.7}}\right) = k_1(e^{0.7KT}). \tag{4}$$

Here, k_1 is constant. From this equation, the resistance of LDR varies with the concentration, path length and molar absorptivity. The path length and molar absorptivity are constants. Finally, the increase in the concentration of liquid causes turbidity. Thus, there is a change in resistance of the LDR. This resistance is the active part of the timing circuit of the logic gate oscillator. The frequency of the RC logic gate oscillator is given in equation (5).

$$f = \frac{1}{2.2R_{LDR}C} = \frac{1}{2.2 * k_1(e^{0.7KT}) * C}. \tag{5}$$

R_{LDR} = resistance of the LDR in (Ω), the dark resistance of the LDR is 100 kΩ, C = capacitance of the fixed capacitor (5 nF) and f is the pulse frequency of the logic gate oscillator in (Hz).

$$f = \frac{e^{-0.7KT}}{k_2} = \frac{e^{-T}}{k_3}. \tag{6}$$

By applying a logarithm, equation (6) becomes,

$$T = -\ln(k_3 * f) = -\ln(k_3) - \ln(f). \tag{7}$$

From equation (7), the turbidity of the solution is obtained as,

$$T = 0.5f^2 - 2f + k_4. \tag{8}$$

k_2, k_3 and k_4 are constants. Thus, the theoretically calculated pulse frequency of the logic gate oscillator with dark resistance is 910 Hz. Due to variation in the turbidity of the water, the absorbance of light varies. Thus, there was a shift in transmitted light and a corresponding sensitive shift in the LDR resistance. Hence, there was a sensitive variation in the pulse

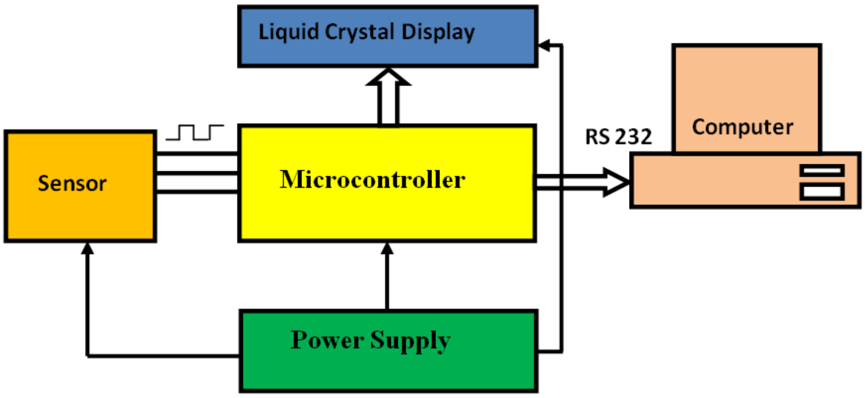

Figure 4. Block diagram of the embedded system.

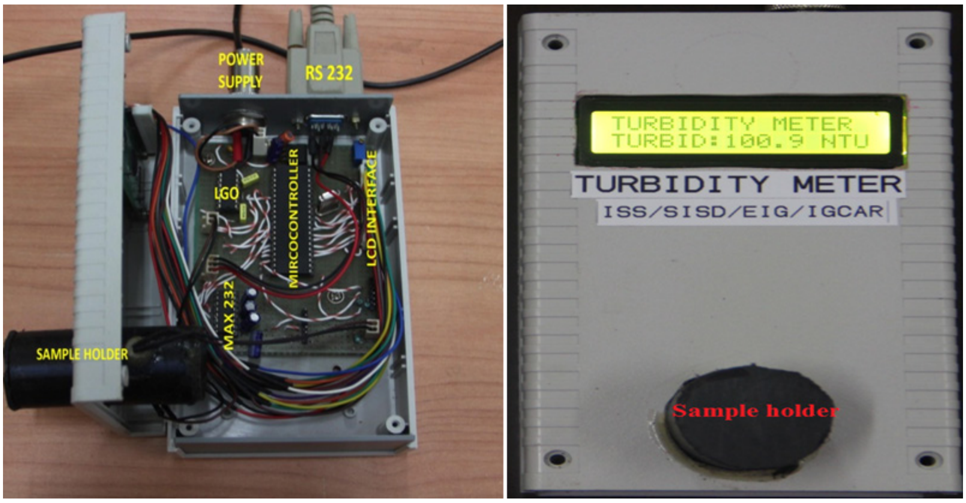

Figure 5. In-house-developed turbidity meter.

frequency of the logic gate oscillator. Therefore, it is clear that the pulse frequency carries the turbidity information of the water.

3. Instrumentation

The pulse frequency of the quasi-digital sensor carries the turbidity information of the water sample. To obtain the turbidity from the sensor, an instrument is required with features enabling it to measure pulse frequency, convert frequency into turbidity, display on an LCD and communicate to the computer. To perform these operations, a microcontroller-based pulse counter with data acquisition capability was developed in-house. This device mainly consists of a power supply, pulse shaping circuit, microcontroller, LCD and RS232 serial communication. Figure 4 shows the block diagram of the developed embedded system.

To calculate the turbidity-sensitive pulse frequency from the quasi-digital sensor, two timers/counters of the microcontroller T0 and T1 were used. T0 was used for setting the 1 s time period and Timer T1 was used to count the pulses from the sensor. Here, the 16-bit timer (T1) is allowed to count the pulses up to 1 s. An interrupt method was used to count the pulses in 1 s and the number of overflows multiplied by 65 536 plus count of the timer (T1) that register within this period gives the pulse frequency of the sensor. The LCD was interfaced with the microcontroller to display the pulse frequency.

Figure 6. Prepared standard turbidity samples.

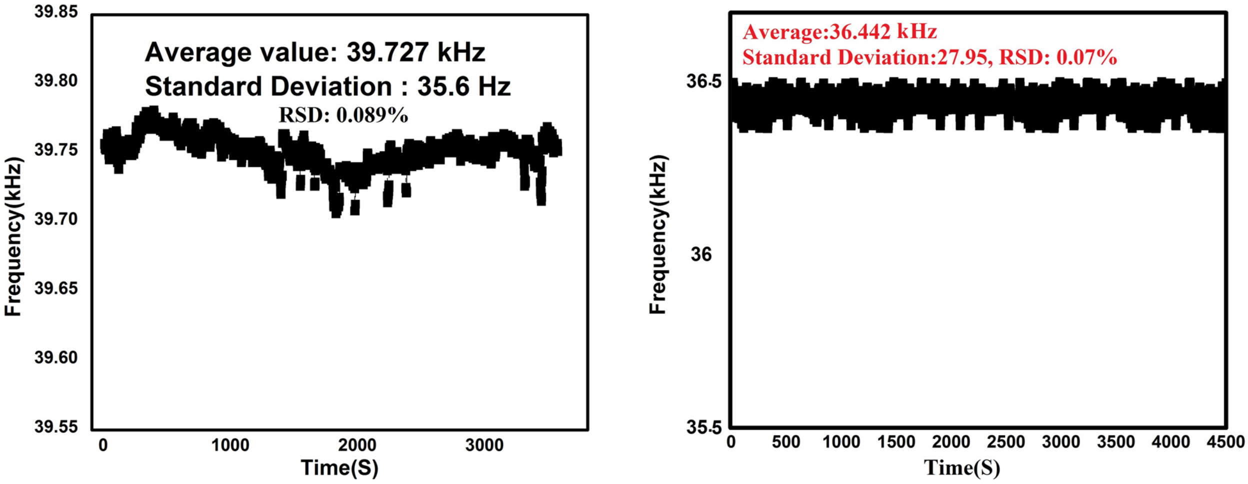

Figure 7. Stability test of the sensor and instrument with 5 and 80 NTU turbidity standards.

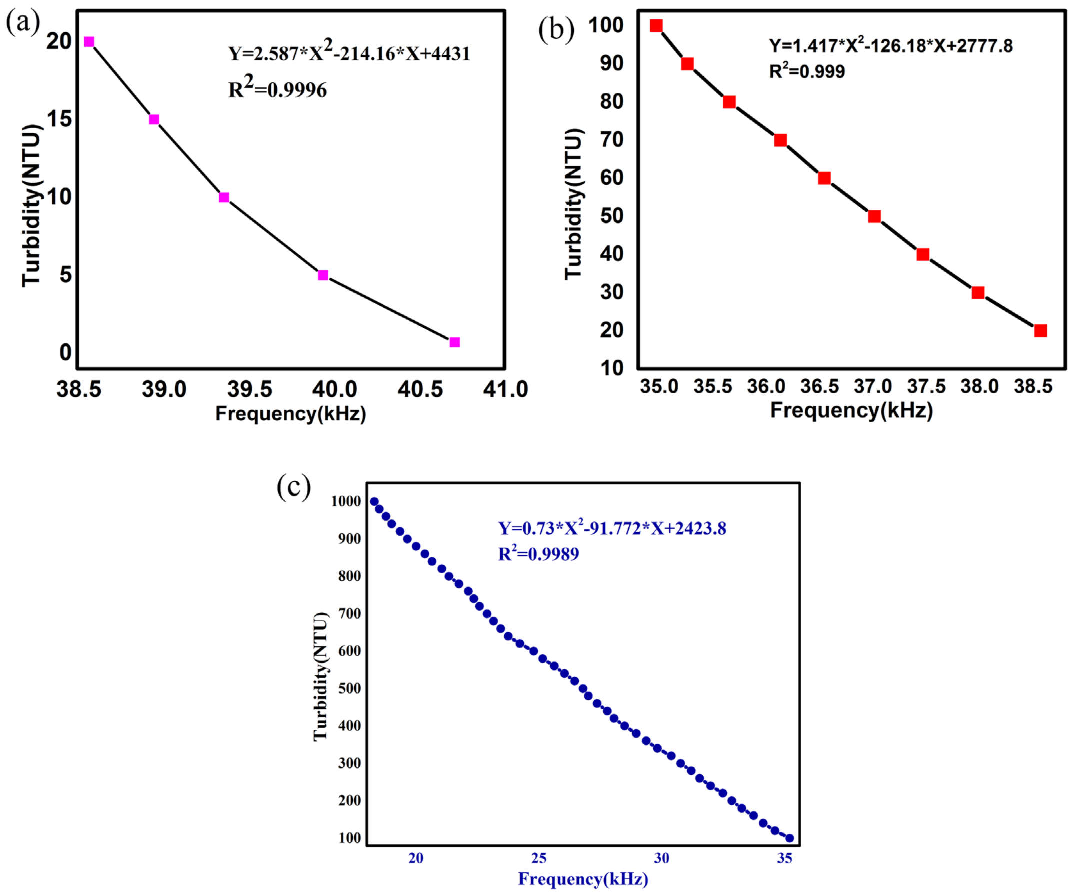

Figure 8. (a) Plot between turbidity (0–20 NTU) and pulse frequency (kHz). (b) Plot between turbidity (20–100 NTU) and pulse frequency (kHz). (c) Plot between turbidity (100–1000 NTU) and pulse frequency (kHz).

A serial communication port was provided to store the data in the computer for calibration. An algorithm was developed in embedded *C* to count the pulse frequency, convert into turbidity value and display on an LCD and to communicate to the computer. The PCB was fabricated and assembled with the necessary components. An enclosure was fabricated to mount the PCB, LCD, power supply and RS232 DB 9 connector. The sensor assembly was firmly fixed inside the enclosure with Araldite to avoid the displacement of the sensor due to vibration. The photograph of the in-house-developed microcontroller-based turbidity monitoring device with quasi-digital sensor is shown in figure 5.

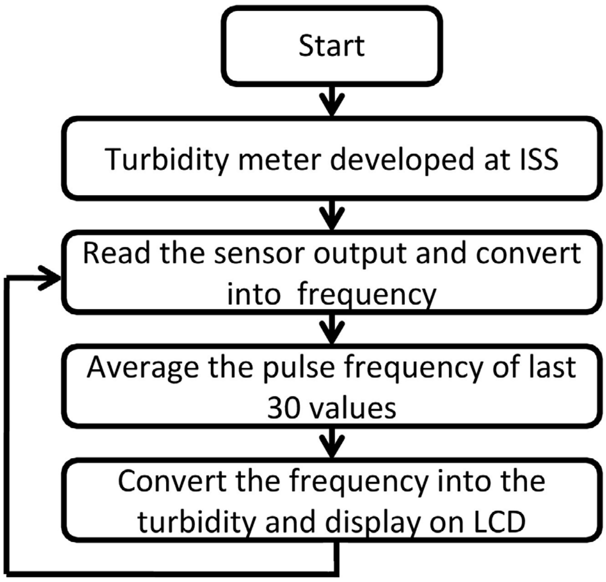

Figure 9. Flow chart for measuring the turbidity.

4. Experimental results and discussion

4.1. Experimental setup

An experimental setup was constructed in the laboratory to test the performance of the developed opto-resistive quasi-digital sensor and instrument to measure the turbidity of the water. In this experiment, an assembled turbidity monitoring device, known turbidity standards, power supply and computer were used. A 12 V adapter was used as the power supply and a 7805 regulator was used to convert 12 V voltage into 5 V. Standard samples with known turbidity values were prepared in the laboratory as per the established guidelines.

4.2. Preparation of standard turbidity values

To calibrate the developed turbidity meter, standard solutions that have known turbidity values in the range of 0–1000 NTU were prepared and used in the experiment. Towards this, chemicals such as hexamethylene Tetramine (CH2CL4) and Hydrazine Sulphate (N2H4H2SO4) were used. After preparation of the standards, each standard solution was filled in a quartz glass bottle to calibrate the turbidity meter. Figure 6 shows the photograph of the prepared standard turbidity values filled in the quartz glass sample bottles in the laboratory.

4.3. Stability in frequency measurement

The standard samples (turbidity value of 5 and 80 NTU) were used to test the stability in the measurement of pulse frequency by the instrument. The sample is filled in a quartz glass bottle and kept in the closed sample holder containing the sensing element. The pulse frequency measurement was carried out for 1 h continuously. Figure 7 shows the stability test of the turbidity monitoring instrument with the quasi-digital sensor with 5 and 80 NTU turbidity standards. The average value of the pulse frequency is 39.727 and 36.442 kHz, the standard deviation is 35.6 and 27.95 Hz and the relative standard deviation is 0.089% and 0.07%.

4.4. Calibration of the turbidity meter

To calibrate the developed turbidity meter, a set of known turbidity samples of 0–1000 NTU were used. The corresponding turbidity-sensitive pulse frequency values were recorded in the computer. For 0 NTU standard, distilled water was used. From the analytical equation it is observed that the relationship between the pulse frequency and turbidity is nonlinear in nature. As the error in the lower range of the turbidity is greater, the calibration was carried out with a subsection curve fitting up to 100 NTU; (i) calibration with 0–20 NTU turbidity standards with a 5 NTU interval, (ii) calibration with 20–100 NTU turbidity standards with a 10 NTU interval and (iii) calibration with 100–1000 NTU turbidity standards with a 20 NTU interval. The sensor output was recorded in the computer with each sample and a relationship between the pulse frequency and turbidity was established. The graph between the turbidity and pulse frequency of the sensor was plotted. From the plots, it is observed that the relationship between the pulse frequency and turbidity is polynomial in nature. This is due to the nonlinear relationship between the absorbance of light due to variation in the turbidity of the water.

Figure 8 shows the plots between the turbidity and pulse frequency. The evolved quadratic equation from the experimental data is $Y = A * X^2 + B * X + C$, where Y is the turbidity in NTU and X is the pulse frequency in kHz. A, B and C are the coefficients determined experimentally by curve fitting. These equations were embedded in the firmware and loaded into the flash memory of the microcontroller to measure the turbidity of the unknown samples.

4.5. Algorithm to measure the turbidity

To measure the turbidity of the water samples, an algorithm was developed and embedded in the firmware of the microcontroller. An embedded C code was developed to program the microcontroller. The pulses from the sensor were counted and the frequency was calculated by the microcontroller and converted into the turbidity. Here, the pulses were counted for 1 s and stored in a variable. To improve the accuracy, the last 30 frequency values were averaged and stored in a variable, and the average value of the pulse frequency was substituted in the quadratic equation to obtain the unknown turbidity of the water. Figure 9 shows the flow chart of the embedded system to measure the turbidity of the water.

4.6. Measurement of the turbidity of unknown samples and comparison with a Hach turbidity meter

A turbidity monitoring device was used to measure the unknown turbidity of samples in the range 0–1000 NTU and

Table 1. Comparison between the Hach turbidity meter and developed instrument.

S. no	Turbidity value with the Hach instrument (NTU)	Turbidity value with the developed instrument (NTU)	% error
1	5	3.5	30
2	32	35.4	10.62
3	45	48.7	8.2
4	100.05	108.3	8.3
5	200.02	206.9	3.45
6	400.05	404.5	1.125
7	500.06	503.2	0.64
8	800	797.5	0.312
9	1000	997.1	0.29

Figure 10. Comparison between the Hach turbidity meter and developed turbidity meter.

compared with the values of a Hach turbidity meter. Readings were recorded from the in-house-developed turbidity meter and Hach turbidity meter, simultaneously, by loading the unknown turbidity samples. Figure 10 shows the photograph of the experimental setup for measuring the unknown turbidity values. Table 1 shows the comparison between the commercial instrument (Hach) and developed turbidity meter. From these results, it is observed that the accuracy of the developed instrument falls within ±8 NTU.

5. Conclusion

In this paper, a low-cost quasi-digital sensor-based turbidity meter has been presented. The structure, basic working principle of the sensor, logic gate oscillator, experimental results and in the end the comparison between the commercial turbidity meter and quasi-digital-sensor-based turbidity meter were discussed. The developed instrument is low-cost, portable, simple in construction, and able to provide high-precision measurement. The measurement results of the prototype instrument have shown that the system is capable of measuring turbidity in the range of 0–1000 NTU with significantly higher sensitivity of 21 Hz/NTU. The accuracy of the instrument is within ±8 NTU. The presented sensor and instrument measures the turbidity with a scanning time of 30 s. Even though many commercial instruments with better accuracy are available in the market, the cost of the instruments is more than €2500, whereas the developed instrument cost falls between €100 and €120.

Acknowledgments

The authors are extremely grateful to Dr A K Bhaduri (Director), IGCAR, Kalpakkam and Dr B K Panigrahi (Director), Electronics and Instrumentation Group, IGCAR, for their whole-hearted support and constant encouragement throughout this work.

ORCID iDs

Ramesh Sanga https://orcid.org/0000-0003-4624-0686

References

[1] Downing J 2005 Turbidity monitoring *Environmental Instrumentation and Analysis Handbook* (Hoboken, NJ: Wiley) pp 511–46
[2] Lambrou T P, Anastasiou C C, Panayiotou C G and Polycarpou M M 2014 A low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems *IEEE Sens. J.* **14** 2765–72
[3] Attivissimo F, Carducci C G C, Lanzolla A M L, Massaro A and Vadrucci M R 2015 A portable optical sensor for sea quality monitoring *IEEE Sens. J.* **15** 146–53
[4] Garcia A, Perez M A, Ortega G J G and Dizy J T 2007 A new design of low-cost four-beam turbidimeter by using optical fibers *IEEE Trans. Instrum. Meas.* **56** 907–12
[5] Wang Y, Rajib S M S M, Collins C and Grieve B 2018 Low-cost turbidity sensor for low-power wireless monitoring of fresh-water courses *IEEE Sens. J.* **18** 4689–96
[6] Samah A H A, Rahman M F A, Omar A F, Ahmad K A and Yahaya S Z 2017 Sensing mechanism of water turbidity using LED for *in situ* monitoring system *2017 IEEE 7th Int. Conf. on Underwater System Technology: Theory and Applications (Kuala Lumpur)* pp 1–6
[7] Azman A A, Rahiman M H F, Taib M N, Sidek N H, Bakar I A A and Ali M F 2016 A low cost nephelometric turbidity sensor for continual domestic water quality monitoring system *2016 IEEE Int. Conf. on Automatic Control and Intelligent Systems (Selangor)* pp 202–7
[8] Arifin A, Irwan I, Abdullah B and Tahir D 2017 Design of sensor water turbidity based on polymer optical fiber *2017 Int. Seminar on Sensors, Instrumentation, Measurement and Metrology (Surabaya)* pp 146–9
[9] Prerana D, Shenoy M R, Pal B P and Gupta B D 2012 Design, analysis, and realization of a turbidity sensor based on collection of scattered light by a fiber-optic probe *IEEE Sens. J.* **12** 44–50
[10] Komiyama R, Kageyama T, Miura M, Miyashita H and Lee S 2015 Turbidity monitoring of lake water by transmittance measurement with a simple optical setup *2015 IEEE Sensors (Busan)* pp 1–4
[11] Ramesh S, Rajiniganth M P and Sahoo P 2016 Deployment of inductance-based pulsating sensor toward the development of measurement technique for ovality in the pipe *IEEE Trans. Instrum. Meas.* **65** 1443–9
[12] Ramesh S, Srinivasan V S, Sivaramakrishna M and Prabhakara Rao G 2018 Deployment of an inductance-based quasi-digital sensor to detect metallic wear debris in lubricant oil of rotating machinery *Meas. Sci. Technol.* **29** 075102
[13] Ramesh S, Sourabh A, Sivaramakrishna M and Prabhakara Rao G 2018 Deployment of the quasi-digital sensor for high-temperature molten salt level measurement in pyroprocessing plants *Rev. Sci. Instrum.* **89** 045007
[14] Rouessac F and Rouessac A 2007 *Chemical Analysis: Modern Instrumentation Methods and Techniques* 2nd edn (New Jersey: Wiley) pp 187–8
[15] Khandpur R S 2006 *Handbook of Analytical Instruments* 2nd edn (New Delhi: Tata McGraw-Hill) pp 40–1 ISBN 0-07-060460-6
[16] Dias Tavares A and Muramatsu M 2008 Some simple experiments in optics using a photo-resistor *Int. J. Hands-On Sci.* **1** 84–8 ISSN (print): 1646-8937; (online): 1646-8945
[17] Skoog A, West D M, Holler F J and Crouch S R 2004 *Fundamentals of Analytical Chemistry* 8th edn (Thomson-Brooks/Cole)
[18] Wang H *et al* 2019 A wide dynamic range and high resolution all-fiber-optic turbidity measurement system based on single photon detection technique *Measurement* **134** 820–4
[19] Circuits Today 2018 *LDR-Light Dependent Resistors* http://circuitstoday.com/ldr-light-dependent-resistors (Accessed: 10 November 2018)
[20] All About Circuits *Design a Luxmeter Using a Light Dependent Resistor* https://allaboutcircuits.com/projects/design-a-luxmeter-using-a-light-dependent-resistor (Accessed: 10 November 2018)
[21] EMANT 2019 *Measure Light Intensity using Light Dependent Resistor (LDR)* http://emant.com/316002.page
[22] CascAID+ 2017 *Fluorescence Detector (Lightbringer)* http://2017.igem.org/Team:Munich/Hardware/Detector (Accessed: 5 March 2019)