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Ultrasonic microcontroller device for distance measuring between dustcart and container of municipal solid wastes

***Abstract**. In the paper structural diagram of the device and block scheme of microcontroller control algorithm for measuring distance have been proposed. The main characteristics of the proposed device are provided. The results of experimental tests are shown for measuring distance with consideration of environmental parameters. The results of experimental studies, presented in the work, confirm reliability of the parameter being measured.*

***Streszczenie.** W artykule przedstawiono schemat konstrukcyjny urządzenia oraz schemat blokowy algorytmu sterowania mikrokontrolerem do pomiaru odległości. Podano główne cechy proponowanego urządzenia. Wyniki badań eksperymentalnych przedstawiono dla pomiaru odległości z uwzględnieniem parametrów środowiskowych. Przedstawione w pracy wyniki badań potwierdzają wiarygodność mierzonego parametru. (**Ultradźwiękowy mikrokontroler do pomiaru odległości między śmieciarką a pojemnikiem odpadów komunalnych**).*

Keywords: measuring, low cost, Arduino, distance, environmental parameters,
Słowa kluczowe: pomiar, niski koszt, Arduino, odległość, parametry środowiskowe

Introduction

Relevance of study of municipal solid wastes (MSW) management lies in the fact that it is included into one of the clauses of the Association Agreement between Ukraine and the European Union [1]. The MSW annual amount in Ukrainian localities constitutes more than 46 million m^3 [2]. Among the technologies for MSW management in Ukraine, the most widespread is burial in landfills and garbage dumps (96.5%), incineration at incineration plants (2.2%) and recycling (1.3%). Collection and transportation of MSW to landfills and waste incinerators is carried out by body-equipped dustcarts in the quantity exceeding 4100 vehicles [2], which have the following methods of loading solid waste into the body: rear (70%), lateral (25%) and front (5%) [3]. To position accurately the dustcart within the range of gripping MSW container with manipulator, driver-operator should know the exact distance between the dustcart and container. Therefore, in our opinion, it is expedient to install in the dustcart a device for measuring the distance with possibility of displaying the distance in the driver-operator's cabin. This is especially important for rear and lateral MSW loading, being most common in use.

According to Decision of the Cabinet of Ministers of Ukraine No. 265 [4], ensuring use of modern highly efficient dustcarts in the country's communal services as the main element in the structure of vehicles for collecting and initial treatment of municipal solid wastes, is a relevant scientific and technical problem. Development of instruments for measuring distance between the dustcart and municipal solid wastes container with consideration of environmental parameters is one of the important objectives for solution of this problem.

The purpose of the study is development of a device for measuring distance between the dustcart and municipal solid wastes container as based on the study of existing signal processing methods and measuring of physical quantities with consideration of environmental parameters.

As a result of the analysis of literary sources it has been established that many studies are focused on use of sensors and data recording systems in many fields of science and technology. Lately, Arduino microcontrollers [5] have become popular for development of digital measuring instruments, which along with many other well-known brands such as BeagleBone and RaspberyPi, belong to a class of small, low-cost, single-board computers, whose programming and applications' development are supported by a large group of developers and users who provide various open code libraries, examples of solutions, forums that cover various thematic and additional aspects [6]. The advantages of Arduino microcontrollers are low project cost, interconnection with sensors and expansion boards for tackling more complex tasks, self-sustainability, low power consumption, low installation requirements and small dimensions. The work [7] is dedicated to a low-cost device for mobile determination of parameters of atmospheric electric field, relative humidity and air temperature on the basis of Arduino Uno with GPS function. Alongside with the widespread method of putting measured data through user's graphical interface to the personal computer screen, there has been added capability to watch measurement results with use of LCD display and a laptop computer. A general data logger for Arduino Mega 2560-based photo electricity monitoring system, which can store large amounts of data on SD card from input channels, is proposed in article [8]. The work [9] describes a scanning system for nondestructive control, based on Arduino. Monograph [10] has developed methods and created on their basis means of continuous control of moisture content of powder-like materials under conditions of engineering process of their production. Paper [11] has proposed an instrument to permit rapid analysis for measuring relative humidity during experimental studies on MSW dewatering.

Methods

To convert digital signal value of ultrasonic sensor into a distance value, the following conversion equation is used [12]:

(1) $$l = \frac{\Delta\tau \cdot c}{2 \cdot 10^4} \text{ [cm]},$$

where $\Delta\tau$ – pulse width [µs], c – sound speed in the environment [m/s].

Sound speed in the air environment depends on its temperature [13, 14]

(2) $$c = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{\gamma R(273.15 + t)}{M}} \text{ [m/s]},$$

where: γ – adiabatic index (for air γ = 7/5), R = 8.31441 – universal gas constant [J/(mole • K)], T, t – air temperature, [K, ºC] respectively, M – molar mass of air [kg/mole].
Molar mass of the air in its turn depends on its relative humidity [15]

(3) $$M = M_v r_v + M_d\left(1-r_v\right) = M_d - \left(M_d - M_v\right)\frac{\phi p_s}{100 p_a}$$ [kg/mol],

where: M_v = 0.018 – molar mass of water vapor [kg/mole], r_v – volume fraction of water vapor in air, M_d = 0.029 – molar mass of dry air [kg/mole], φ – air relative humidity [%], p_s – pressure of saturated vapor [Pa], p_a = 101325 – atmospheric pressure [Pa].

Pressure of saturated vapor depends on its temperature per such empirical dependence [16]

(4) $$p_s = 611.2e^{\frac{17.62t}{243.12+t}}$$ [Pa].

After substituting expressions (2) – (4) into equation (1) we obtain the final equation for converting the value of digital signals of ultrasonic sensor and temperature and humidity sensor into the distance value:

(5) $$l = \frac{\Delta\tau}{2\cdot 10^4}\sqrt{\frac{\gamma R\left(273.15+t\right)}{M_d - \left(M_d - M_v\right)\dfrac{\phi}{p_a}6.112e^{\frac{17.62t}{243.12+t}}}}$$ [cm].

To convert the value of digital signals of air temperature and relative humidity sensor into the values of air temperature and relative humidity, the following conversion equation may be used:

(6) $$t = \frac{1}{\dfrac{1}{T_0} + \dfrac{1}{B}\ln\left(\dfrac{N_t}{2^n - 1}\right)} - 273.15$$ [°C],

(7) $$\phi = \frac{100}{\sigma_H - \sigma_D}\left[\frac{I\left(2^n - 1\right)}{U_b N_\phi l_t} - \sigma_D\right]$$ [%],

where Nt, $N\varphi$ – values of digital temperature and relative humidity signals, respectively, n – capacity of analog-to-digital converter (ADC), bit, T_0 – room temperature [K], B – coefficient which depends on the thermistor used, I – current strength [A], U_b – base voltage [V], σ_H – specific electrical conductivity of humidity in the air [Sm/m] σ_D – dielectric specific electrical conductivity [Sm/m], l_t – thickness of dielectric layer [m].

After introducing expressions (6), (7) into equation (5) we obtain a complete equation for converting the value of digital signals of ultrasonic sensor and air temperature and humidity sensor into distance value [cm]:

(8) $$l = \frac{\Delta\tau}{2\cdot 10^4}\sqrt{\frac{\gamma R\left[\dfrac{1}{T_0}+\dfrac{1}{B}\ln\left(\dfrac{N_t}{2^n-1}\right)\right]^{-1}}{M_d - \dfrac{M_d - M_v}{p_a\left(\sigma_H-\sigma_D\right)}\left[\dfrac{I\left(2^n-1\right)}{U_b N_\phi l_t}-\sigma_D\right]611.2e^{\left\{\frac{13.8\left[\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{N_t}{2^n-1}\right)\right]}{1-273.15\left[\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{N_t}{2^n-1}\right)\right]}+0.05675\right\}^{-1}}}}$$

The total error of reproduction of the real value of the distance is composed of systematic and random errors in the elements of the measuring channel and can be determined by the quadratic dependence.

(9) $$\delta_\Sigma = \sqrt{\delta_{in}^2 + \delta_{dn}^2 + \delta_{qe}^2 + \delta_{ce}^2 + \delta_{ze}^2}$$ [%],

where δ_{in} – integral nonlinearity [%], δ_{dn} – differential nonlinearity [%], δ_{qe} – quantization error [%], δ_{ce} – conversion factor error [%], δ_{ze} – zero bias error [%].

In the documentation on the microcontroller [17] the values of the individual parameters of accuracy are given. Integral nonlinearity characterizes the deviation of the real characteristic of the ADC from the ideal in the middle of the quantization step and is no more than 0.5 units of junior grade, that is, 0.05%. Differential nonlinearity characterizes the deviation between the centres of neighbouring steps of quantization on real and ideal characteristics and is no more than 0.25 units of junior grade, that is 0.025%. The error of the conversion factor shows how the slope of the line between the first and the last point of the actual conversion characteristic corresponds to the ideal value and is not more than 2 units of junior grade, that is, 0.2%. The bias error of zero indicates the value of the signal at the input of the ADC at the source code equal to 0 and is not more than 2 units of the junior grade, that is, 0.2%.

After the mathematical transformations of expression (1), the quantization error of the ultrasonic device for measuring distance with consideration of environmental parameters is estimated as [%]:

(10) $$\delta_{\varphi} = \frac{100\%}{\Delta\tau_{\min}} = \frac{1}{200 l_{\min}}\sqrt{\frac{\gamma R\left[\dfrac{1}{T_0}+\dfrac{1}{B}\ln\left(\dfrac{N_t}{2^n-1}\right)\right]^{-1}}{M_d - \dfrac{M_d - M_v}{p_a\left(\sigma_H-\sigma_D\right)}\left[\dfrac{I\left(2^n-1\right)}{U_b N_\phi l_t}-\sigma_D\right]611.2e^{\left\{\frac{13.8\left[\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{N_t}{2^n-1}\right)\right]}{1-273.15\left[\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{N_t}{2^n-1}\right)\right]}+0.05675\right\}^{-1}}}}$$

Using expression (10), we determine that maximum quantization error of the ultrasonic device for measuring distance with consideration of environmental parameters does not exceed 0.85%.

Introducing the known values into expression (9) we determine that the combined error of the ultrasonic device for measuring distance with consideration of environmental parameters shall be 0.889%.

Main results of the study

Fig. 1 shows structural diagram of the proposed device for measuring distance with consideration of environmental parameters, which comprises an ultrasonic distance sensor (USDS), a temperature and humidity sensor (THS), a microcontroller unit (MCU) and displaying and monitoring module (DMM) of LCD Keypad Shield. The scheme also indicates the object of measurement (OM). To ensure microcontroller operation, the circuit includes a clock pulse generator G and a source of base voltage (SBV).

Distribution of microcontroller ports is as follows:

- port 1 – indication of measurement results and management of display parameters;
- port 2 – communication with personal computer through USB interface;
- port 3 – channel of output ultrasonic signal of the beginning of distance measuring;
- port 4 – channel of input ultrasonic signal of the end of distance measuring;
- port 5 – channel of air temperature and relative humidity measuring.

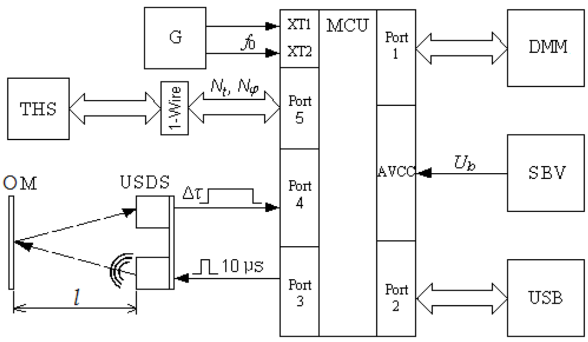

Fig.1. The structural diagram of the device for distance measuring with consideration of environmental parameters

An ultrasonic distance sensor may serve as a sensor for a robot or transportation vehicle, enabling it to determine distances to objects, assist in going round obstacles or form premises chart. It may also be used as a sensor for alarm, activated upon approach of objects, as well as in construction for measuring size of facilities and distance between them.

Unlike infrared rangefinders, sunrays or object colour may not affect readings of ultrasonic rangefinder. Even a transparent surface will be an obstacle to it. However, there may be difficulties in determining distance to fuzzy or very thin objects.

Arduino HC-SR04 ultrasonic distance sensor is a small acoustic low power locator. It contains an emitter, an acoustic receiver and quartz with amplifier that sets the frequency. Arduino ultrasound sensor has a digital signal output.

Ultrasound rangefinder determines distance to objects according to sonar principle, just the same as dolphins or bats do it. It offers a range of 2-400 cm of non-contact detection of objects with high accuracy and stability of readings and is characterized by simplicity of use. It generates 8 short ultrasonic pulses at a frequency of 40 kHz so that the sound could be well reflected from obstacles and received by the sensor. For this, the sensor contains a piezo ceramic projector, capable of generating the sound of such high frequency. This projector is designed in such a way that the sound does not travel to all sides, as it happens with ordinary speakers, but in a narrow direction. The frequency of the sound wave is within the ultrasound range, which provides a concentrated direction of the sound wave, because the sound with a high frequency is less dispersed in the environment. Ultrasound may even locate objects that the laser range finder may not spot. The distance is calculated on the basis of the time taken for the echo to be received and speed of sound in the air. By the time the sound wave travels forward and back it is possible to determine exactly distance to the object.

The sensor plug has 4 conventional pins, which allows to simply connect it to solderless board, solder it to a bread board, or use ordinary pins for connection.

The sensor pins have the following functions:

- + 5V (VCC) – positive power supply contact.
- Trig – digital input. To start measurement, it is necessary to supply to this input a logical unit of 10 μs. Subsequent measurement is recommended to be performed not earlier than after 50 ms, which is due to duration of first pulse processing.
- Echo – digital output. After measurement completion, this output will receive a logical unit for the time, proportional to distance to the object.
- GND – negative power supply contact (ground).

Left ultrasound projector (marked with the letter T – transmitter) is an ultrasonic transmitter, right ultrasound projector (labelled with the letter R – receiver) is a receiver of the ultrasound signal (echo), reflected from the object.

Thus, the sensor receives an echo signal, and produces distance, encoded by duration of the electric signal at the sensor output (Echo).

The next pulse can be irradiated only after the echo from the previous one has disappeared. This time is called the cycle period. The recommended period between pulses should be at least 50 μs.

If a pulse of 10 μs duration is applied to the signal pin (Trig), the ultrasonic module will emit eight pulses of 40 kHz ultrasonic signal, activating the timer and detecting their echo. These pulses reach the object and are reflected from it in the opposite direction (a reflected wave is formed). From the moment of sensor activation, the receiver is ready to receive pulses. As soon as the reflected pulses reach the receiver, measurement of distance to the object is made and at the Echo output a high-level pulse of up to 38 μs appears, which stops the timer. On the basis of time period of the timer and speed of sound, it will be possible to calculate the distance, travelled by the sound wave. The distance to the object will be approximately half the distance, travelled by the sound wave.

The sensor documentation shows that if no obstacles have been detected, then the output will have a pulse with duration of 38 μs.

HC-SR04 sensor may be connected by connecting + 5V and GND from Arduino controller and linking Trig and Echo sensor outputs to the digital controller pins.

Characteristics of HC-SR04 distance ultrasound sensor:

- Power supply: 5 V.
- Consumption in idle mode: 2 mA.
- Consumption at work: 15 mA.
- Range of distances: 2-400 cm.
- Resolution: 0.3 cm.
- Effective viewing angle: 15°.
- Working angle of viewing: 30°.
- Dimensions: 37 × 20 × 15 mm.

It is not recommended to connect HC-SR04 module directly to the energized microcontroller. It is necessary to turn off power supply during connection of the module and the first to connect should be GND module output. Otherwise, this may affect normal operation of the module. When testing the module as to range and accuracy of measurement, area of the object of scanning should be not less than 0.5 m^2 and its surface should be as hard and even as possible. Otherwise, it will affect results of measurements.

To consider correction of sound velocity in the air, depending on the ambient parameters, temperature-humidity measuring module is used, based on DHT11 sensor, for measuring ambient temperature and humidity.

DHT11 sensor is an inexpensive digital combined sensor for measuring temperature and relative humidity with calibrated digital output signal. It comprises two elements – 16-bit sensors of humidity and temperature. It is equipped with a dedicated microcircuit chip, designed for analog-to-digital conversion as well as transmission of a signal to be read off by the controller. Temperature measurement range is from 0 to + 50 °C, with accuracy ± 2 °C, humidity – from 20 to 90%, with accuracy – 5%. Callback frequency is 1 Hz. Power supply – 3-5 V. The sensor is characterized by low power consumption – up to 2.5 mA at callback time (at other times less). Overall dimensions: 28.0 × 16.6 × 8.5 mm, weight 3 g [18,19,20].

The DHT11 sensor consists of a resistive moisture sensitive component and temperature-sensitive component (NTC thermistor). The thermistor is a variable resistor that changes its resistance upon temperature change. Temperature measurement occurs when current is supplied to the thermistor and depending on the temperature, it will change its resistance, i.e. temperature increase will lead to fall of its resistance. Resistive sensor is covered with a layer of material with a relatively low resistance, which depends on the humidity, absorbs it well, and, consequently, changes its specific resistance. The sensor is made by putting together semiconductor materials such as ceramics or polymers. The sensor calibration is carried out in a high-precision calibration chamber. Calibration coefficients are stored in OTP memory and are called upon reading signal from the sensor, so there is no need to re-calibrate the sensor. Presence of single-line bidirectional serial interface through 1-Wire protocol ensures easy and quick sensor connection.

3-pin module of DHT-11 sensor has three outputs: + 5V (VCC), Data, GND. Ground pin of DHT11 (leftmost) is connected by the conductor to GND contact of Arduino board. VCC pin in DHT11 (rightmost) is connected by a conductor to the 5 V power supply of Arduino board. Finally, Data pin (central) is connected to D12 digital contact of Arduino board [21-23].

Design of a resistive moisture sensor is a meander of two nontangential electrodes, having the surface with applied thin layer of hygroscopic dielectric. The latter, absorbing moisture from the environment, changes resistance of gaps between the electrodes of the meander. Humidity is evaluated by change of resistance or conductivity of such an element.

Sensor control is effected from Arduino controller or from other controlling microprocessor device with use of special program [24-25].

Arduino UNO R3 board has been chosen as controller – most common version of Arduino controllers, described in detail in the work [11,26-27].

The controller is programmed from integrated Arduino IDE software environment. Block scheme of the program algorithm is provided in Fig. 2.

To display results of distance measurements, LCD Keypad Shield is used, one of the most popular expansion cards for Arduino, described in detail in the work [11].

Connection of display and control module, sensors for measuring distance with consideration of the environment parameters to Arduino Uno R3 board, is shown in Fig. 3.

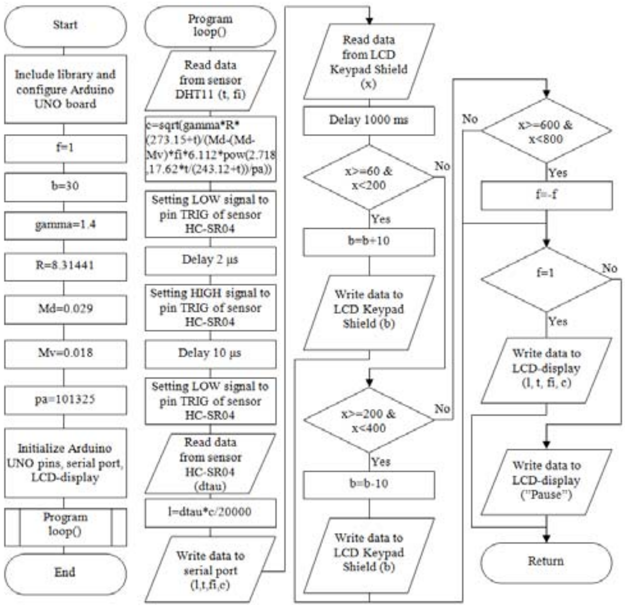

Fig.2. Block scheme of the main program algorithm and the loop program

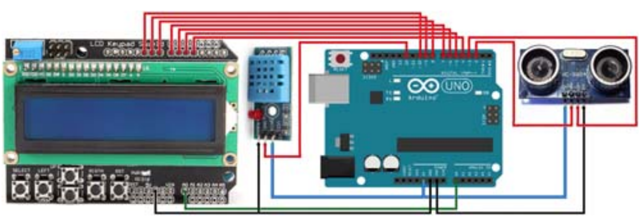

Fig.3. Connection of the indicating and controlling module, the sensor for distance measuring with consideration of environmental parameters to the Arduino Uno R3 board

The SELECT button is used to implement the pause/start function to fix the current value of the distance. The UP and DOWN buttons of the LCD Keypad module are used to increase and decrease the brightness of the screen, respectively, in order to improve the visibility of measurement results under different lighting conditions [28-30].

Results of experiments

With the help of the developed ultrasonic range finder, an experimental measuring of the distance *l* in the range of 25...500cm was carried out with consideration of environmental parameters (l_1) and without consideration of environmental parameters (l_2), the results of which are given in Table. 1. Table 1 also shows the absolute values of relative errors $|\delta_1|$ and $|\delta_2|$ for the cases of consideration and non-consideration of environment parameters, respectively [31-32].

Table 1. Experiment results on measuring the distance by ultrasonic range finder

l, cm	l1, cm	l2, cm	|δ1|, %	|δ2|, %
25	25.22	25.34	0.887	1.367
50	50.23	50.45	0.466	0.906
75	75.09	75.45	0.125	0.605
100	100.33	100.62	0.326	0.616
125	125.33	125.76	0.262	0.606
150	150.06	150.54	0.043	0.363
175	175.50	176.45	0.286	0.829
200	198.25	199.13	0.873	0.433
225	223.09	224.22	0.849	0.347
275	276.24	277.49	0.450	0.905
300	300.66	301.94	0.220	0.647
325	326.99	328.90	0.611	1.199
350	352.98	354.51	0.850	1.287
375	376.72	379.27	0.459	1.139
400	403.25	405.74	0.812	1.434
425	428.80	431.10	0.893	1.434
450	453.98	456.59	0.885	1.465
475	478.90	481.56	0.821	1.381
500	498.72	501.68	0.257	0.335

Fig. 4 shows graphical dependence of absolute values of relative errors $|\delta_1|$ and $|\delta_2|$ from the measured distance *l*.

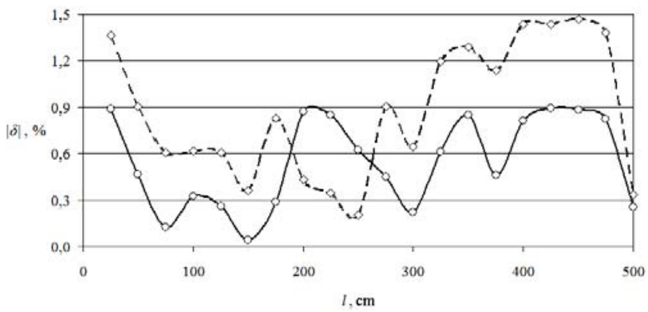

Fig.4. Dependence of absolute values of the relative error |δ| from the measured distance l: with consideration of environmental parameters —○ and without consideration of environmental parameters ---◊

Therefore, experimental research on distance measurements with the help of proposed ultrasound range finder has shown that consideration of environmental parameters such as temperature and relative humidity can significantly reduce the measurement error, and the developed device for distance measuring with consideration of environmental parameters corresponds to the international technical standards for the design of measurement control devices [33-36].

Conclusions

1. Based on the analysis of existing methods of signal processing and measurements of physical quantities, a device has been proposed that allows to measure the distances to obstacles for the development of highly efficient dustcarts as the main link in the structure of machines for the collection and primary processing of municipal solid wastes.

2. A structural scheme of the device is proposed and a block diagram of the program algorithm is also proposed that allows to control the operation of the microcontroller of the device for distance measuring with consideration of environmental parameters.

3. The proposed device for distance measuring with consideration of environmental parameters has the following main characteristics:

- range of measurements 2...500 cm;
- resolution 0.3 cm;
- the measurement error is not more than 0.9%;
- effective viewing angle: 15°;
- working angle of observation: 30°;
- 5 V power supply from USB or 6...20 V from external power supply;
- consumption current not more than 185 mA;
- interfaces: USB, LCD + Keypad.

4. Experimental studies on distance measurements with the help of the proposed ultrasonic range finder has showed that consideration of environmental parameters such as temperature and relative humidity can significantly reduce the measurement error, and the developed device for distance measuring with consideration of environmental parameters meets the international technical standards for the design of measurement control devices.

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