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INVESTIGATION OF LASER RANGEFINDERS WITH SENSOR NETWORK INTERFACE

Об'єктом дослідження є лазерний віддалемір з безпровідним сенсорним мережевим інтерфейсом протоколу ZigBee, що в даному дослідженні пропонуються для виконання функції вимірювання відстані між об'єктами. Основні сфери застосування – це сфери, де потрібна достовірна інформація про розташування об'єктів відносно один одного. Для підвищення достовірності пропонується поєднання можливості вимірювання відстані між об'єктами сенсорних мереж та даних, отриманих від лазерного віддалеміра. Ці два методи поєднані в одному пристрої.

Одним з найбільш проблемних місць є похибка засобів вимірювальної техніки. Також, для описаних вище об'єктів характерні різного роду перешкоди, як механічні (дерева, пагорби, низини тощо), так і радіоперешкоди.

В ході дослідження використовувався метод підвищення точності вимірювання відстані безпровідних сенсорних мереж. Для цього вони поєднуються з лазерними віддалемірами, що перебувають у складі комп'ютеризованих систем вимірювання відстані, побудованих на основі поєднання методів вимірювання різної природи.

Дослідження локалізації вузлів проводилось для середнього значення відхилення при ранжируванні в 1 м (20 вимірювань), а також за прогресивною функцією необхідної кількості транзакцій. Для калібрування ранжируючих вимірювань був розрахований мінімальний період двостороннього проходу по середньому значенню, коли приймачі знаходяться в безпосередній близькості один до одного (0,01 м). Це середнє значення далі було обчислено з кожного ранжируючого вимірювання перед конвертацією в безпосереднє значення відстані.

Результати підтверджують поліпшення ефективності ранжування за допомогою усереднення множини вибірок до значення похибки в 6,0 м. Точність методу була постійна у всьому діапазоні тестування розповсюдження (в радіусі 250 м).

Ключові слова: *сенсорна мережа, лазерний віддалемір, механічні величини, комп'ютеризована система вимірювання, інформаційно-вимірювальна система.*

1. Introduction

Inaccurate positioning of the object included in the wireless sensor networks leads to the generation of false information in a computerized system for measuring the distance between objects. Such shortcoming, in turn, can lead, for example, to the untimely detection of a source of ignition. Particularly favorable environment for this kind of negative consequences is jamming situation [1]. Among the various classes of information and measurement systems, the problem of reducing the measurement error is common. Therefore, when creating the scientific basis for the construction of computerized systems for measuring mechanical quantities, the accuracy of information-measuring mechanical quantities occupies a place. It is better not to use this terminology One way to solve this problem is modification of existing measuring devices by adding a touch-sensitive network interface. Equally important is the theoretical analysis and search for optimal modeling methods and increasing the accuracy of computerized distance measuring systems. Thus, one of the weaknesses of computerized systems for measuring mechanical quantities is jamming situation, which leads to a high probability of errors in measuring distance.

Therefore, it is important to study new methods for measuring distance. In particular, those that combine measuring instruments that have different nature, and the comparison of the results of their measurement significantly reduces the probability of error.

2. The object of research and its technological audit

The object of research is a computerized laser rangefinder with a touch-sensitive network interface. Fig. 1 is a block diagram of the given rangefinder, which combines a classic laser rangefinder and network interface, which allows using the function of determining the distance between objects of sensor networks.

The technology of this device is as follows: the control unit 1 performs power management, determines the distance to the desired object based on the time alignment of the beam direction and its reflection time. And also sends the command to send the packet and the package containing the measurement results are transmitted by the sensor block 3 and the photodiode receiver 6. The high-frequency phase modulator 7 turns the packet into an ordered stream of electromagnetic signals coded in phase and sends to the Gaussian filter 8 where the signals are superimposed on the carrier frequency and through the antenna 9 is sent to the radio air. The battery cell 2 through the control unit 1 supplies a DC electric current to a computerized laser rangefinder with a sensor network interface. This ensures its autonomy and functionality over a long period of time.

In this paper, a method is proposed for increasing the accuracy of computerized systems for measuring mechanical quantities, consisting in the simultaneous use of laser rangefinder measurement data and indicators obtained through the localization function of wireless sensor network objects.

These two functions are combined in the device, shown in Fig. 1. Here blocks 2, 4–6 relate to the functional of the laser rangefinder, and 1, 3, 7–9 – to the functional of the computerized sensor network device containing the distance measuring function.

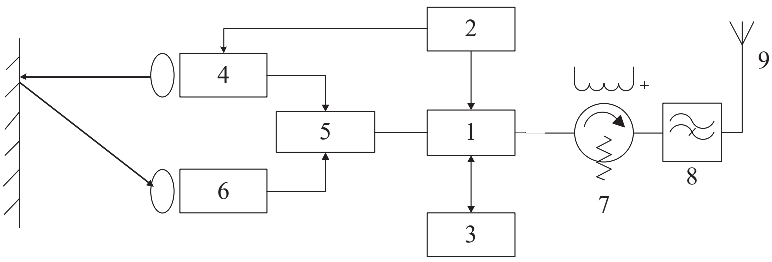

Fig. 1. Computerized laser rangefinder with sensor network interface:
1 – control computerized unit; 2 – battery cell; 3 – sensor block; 4 – semiconductor laser; 5 – unit for measuring time intervals; 6 – photodiode receiver; 7 – high-frequency phase modulator; 8 – Gaussian filter; 9 – antenna

3. The aim and objectives of research

The aim of research is development of new and improvement of existing technological solutions to reduce the measurement error of instruments included in computerized distance measuring systems.

To achieve this aim it is necessary to:

1. Develop a mathematical model of distance measurement by means of a signal power drop.
2. Propose a method for measuring distance using a laser rangefinder, including leveling.
3. Carry out experimental studies of a computerized laser rangefinder with a touch-sensitive network interface.

4. Research of existing solutions of the problem

Questions of the study of information and measurement systems, including the study of technologies for modeling, control and interactions of computerized systems for measuring mechanical quantities (in particular, the distances between objects) are devoted to the work of modern scientists, including:

– works [2, 3], devoted to measuring distance by means of measuring equipment;
– works [4–6], devoted to measuring distance by means of wireless sensor networks;
– works [7–9], which, in addition to measuring distance, are also devoted to analyzing the characteristics of the sensor networks themselves;
– works [6, 7, 10], devoted to the study of the use of GPS systems for determining the coordinates;
– works [11, 12], devoted to the development of an electronic compass, uses data obtained from the sensor network.

A device for measuring length [2] is known for measuring the distance between objects in geodesy and construction. This device can't carry out computerized control of distance measurement, nor does it contain a wireless network interface.

Another known distance measuring device [3] is used to locate objects in a computer sensory network. The device comprises a block for generating and digital signal processing, an integral-pulse entropy Galois converter containing a voltage/frequency converter is additionally introduced. While the device is operating, only a message about the distance between objects is provided, but it does not contain the function of confirming the results of the distance measurement with the help of a laser rangefinder.

Of the known distance measuring devices, the device closest in technical essence to the invention is the device [4], which contains the first and second fixed mirrors, the lens, the first and second laser emitters, the modeling voltage generator. It additionally introduced a calibrated light-fiber delay line, which is connected between the output of the second radiator and the input of the first photodetector, a modulation voltage generator, but does not contain a touch-sensitive network interface for transmitting measurement data.

In [5, 6], only the general concept of constructing sensory measurement networks is considered, but the model of the measurement process has not been proposed. In [7, 8], the systems of global positioning, determination of distance in sensor networks and data routing, are considered, but the use of measuring equipment is not suggested. In [6, 9] the fundamental principles of sensory distance measuring networks are considered, but examples of their use are not considered. The papers [7, 10] contain research in the field of global positioning, but they do not consider the use of other systems for checking the results. In works [11, 12] it is a question of constructing a compass on the basis of a sensor network using the «each with each» type of connection, but the infrastructural type of communication is not considered. In this paper, it is proposed to consider recommendations for improving the technical characteristics of wireless sensor networks by combining them with a laser rangefinder. This also affects the accuracy of the process of localization and measurement of the distance between objects in areas of uncertain reception and with insufficient noise immunity.

5. Methods of research

In this research, a method will be used to determine the distance based on the loss of signal power using the Friis equation. To start the derivation of the Friis equation, consider two antennas (Fig. 2) in free space (without interference near) located at a distance *R*.

Let's suppose that P_T – the total power of the transmitting antenna. Let the transmitting antenna be omnidirectional, lossless and the receiving antenna is at a distance from the transmitting antenna. Then the power density *p* (in watts per square meter) of the plane wave incident on the receiving antenna at a distance *R* from the transmitting antenna is determined by:

$$p=\frac{P_T}{4\pi R^2}.$$

If the transmit antenna has a gain in the direction of the receiving antenna G_T, then the equation for determining the power can be rewritten as follows:

$$p=\frac{P_T}{4\pi R^2}G_T.$$

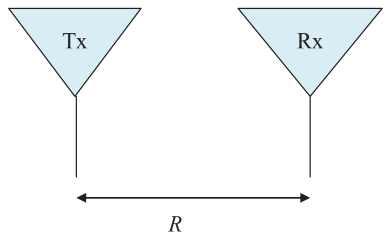

Fig. 2. Transmission (Tx) and reception (Rx) of antennas separated by R

Coefficient of gain and loss of real antenna. Let's suppose now that the receiving antenna has an active aperture given by A_{ER}. Then the power received by this antenna (P_R) is set:

$$p=\frac{P_T}{4\pi R^2}G_T A_{ER}.$$

Since the effective diaphragm for any antenna can be expressed as:

$$A_e=\frac{\lambda^2}{4\pi}G,$$

where A_e – the area of the active diaphragm; λ – the slope angle of the effective diaphragm; G – the gain of the antenna.

The received power can be written as:

$$P_R=\frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}, \quad (1)$$

where G_R – the gain in the direction of the transmit antenna.

This equation is known as the Friis transmission formula. This is due to signal loss, antenna gain and wavelength to the received and transmitted power. This is one of the fundamental equations in the theory of antennas, and it must be remembered (as well as it is derived above).

Another useful form of the Friis transfer equation is given in equation (2). Since the wavelength and the frequency f depend on the speed of light c, the obtained Friis formula is derived from the point of view of frequency:

$$P_R=\frac{P_T G_T G_R c^2}{(4\pi Rf)^2}. \quad (2)$$

Equation (2) shows that high power is lost at higher frequencies. This is the fundamental result of the transmission of the Friis equations. This means that for antennas with predetermined increments, the transmit power will be the highest at lower frequencies. The difference between the received power and the transmitted power is known as the loss of the signal level is inversely proportional to the distance between the transceivers. In other words, the Friis transmission equation indicates that the signal level loss at a distance is higher for higher frequencies.

The importance of this result from the Friis transmission formula can't be overstated. That's why mobile phones usually operate at a frequency of less than 2 GHz. There may be a larger frequency spectrum, but the associated power losses along the way do not allow you to get the signal quality. As another consequence of the Friis equation, one should keep in mind that this is an antenna of 60 GHz. Noting that this frequency is very high, it can be argued that the path loss will be too high for communication over a long range. At very high frequencies (60 GHz, sometimes called the mm (millimeter wave) zone), the loop loss is very high, so only point-to-point communication is possible. This happens when the receiver and transmitter are in the same room and in direct line of sight to each other.

The question arises: why are mobile operators satisfied with the new LTE (4G) band operating at 700 MHz? The answer is this: this is a lower frequency than the antennas that traditionally work, but from equation (2) let's note that the signal loss will also be lower. Thus, they can «cover more space» with this frequency spectrum.

On the other hand, mobile phone manufacturers must have a longer wavelength antenna on a compact device (lower frequency = longer wavelength), so the work of the antenna designer was somewhat more complicated.

Finally, if the antennas do not coincide with the polarization, then the power obtained above can be multiplied by the polarization loss coefficient (PLF) to correctly determine this discrepancy. The above equation (2) can be changed to obtain a generalized formula for the Friis transmission, including the polarization mismatch:

$$P_R=(PLF)\frac{P_T G_T G_R c^2}{(4\pi Rf)^2}.$$

Next, let's consider the mathematical model of the operation of the blocks of the laser rangefinder (Fig. 3).

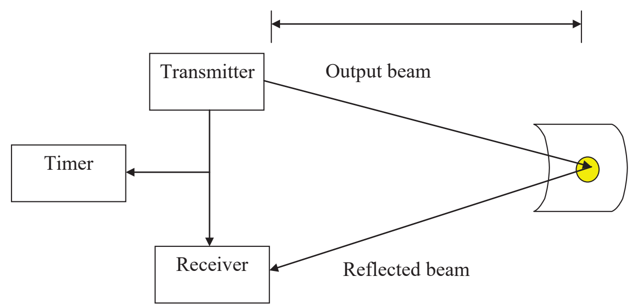

Fig. 3. Principle of laser rangefinder operation

The property of radiation to propagate at a constant speed makes it possible to determine the range to the object. Thus, for the pulse measurement method, the following relationship is used:

$$D=\frac{ct}{2n},$$

where D – the distance to the object; c – the speed of light in a vacuum; n – the refractive index of the medium in which the radiation is propagated; t – time of passage of a pulse to the target and back (Table 1).

Table 1

Time of passage of a pulse to the target and back

Distance to target	1 m	10 m	100 m	1 km	10 km	100 km
Response time	6.7 ns	67 ns	0.67 μs	6.7 μs	67 μs	0.67 ms

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Examination of this relationship shows that the potential accuracy of the range measurement is determined by the accuracy of determining the time of passage of the energy pulse to the object and back. The shorter the pulse, the better.

Trigonometric leveling is suggested as a measurement method. Trigonometric leveling is a method of determining the elevation from the measured angle of inclination and the distance between points. It is used in topographic surveys and when determining large excesses. Fig. 4 shows a simplified scheme of trigonometric leveling. Above point A set the theodolite and measure the height of the device i, and at point B set the rail. To determine the excess of h, measure the inclination angle ν, horizontal spacers d and fix the height of the sight a (the count on which the sighting beam is aimed), ΔK_{AB} – correction for the curvature of the Earth and refraction [13].

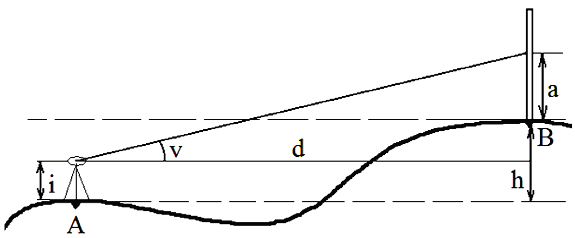

Fig. 4. Simplified scheme of trigonometric leveling

The general formula of trigonometric leveling:

$$h = d\,\mathrm{tg}\,v + i - a + \Delta K_{AB}.$$

This formula is relevant only for the unilateral leveling used in this paper.

6. Research results

The linear nature of the algorithm under direct line of sight conditions is the propagation shown in Fig. 5. The results confirm an improvement in the efficiency of the ranking by averaging a plurality of samples to an error value of 6.0 m. The accuracy of the method was constant throughout the test propagation range (within a radius of 250 m).

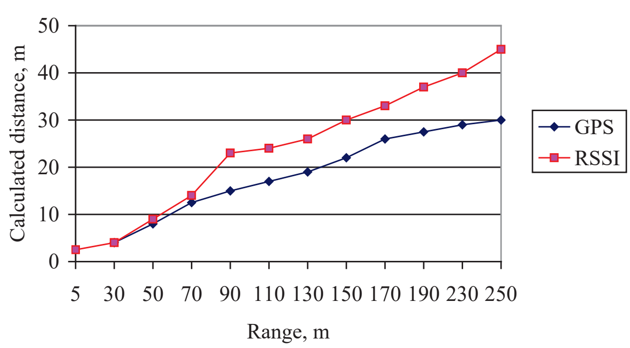

Fig. 5. Accuracy of localization in conditions of signal propagation in the line of sight, for RSSI and GPS

For simulation, a network with 200–1000 nodes is selected, this network generates a value at random positions on a square plane (250 by 250). The number of anchor nodes is 10 % of all nodes. For a fixed radius, the transmission range for all devices in each of the networks in question is shown in Table 2.

Table 2

The expected transmission range for different networks

No.	Number of nodes	Radius of the sensor
1	200	35
2	500	30
3	1000	20

The results of modeling according to the data of Table 2 for networks consisting of 200 nodes is shown in Fig. 6.

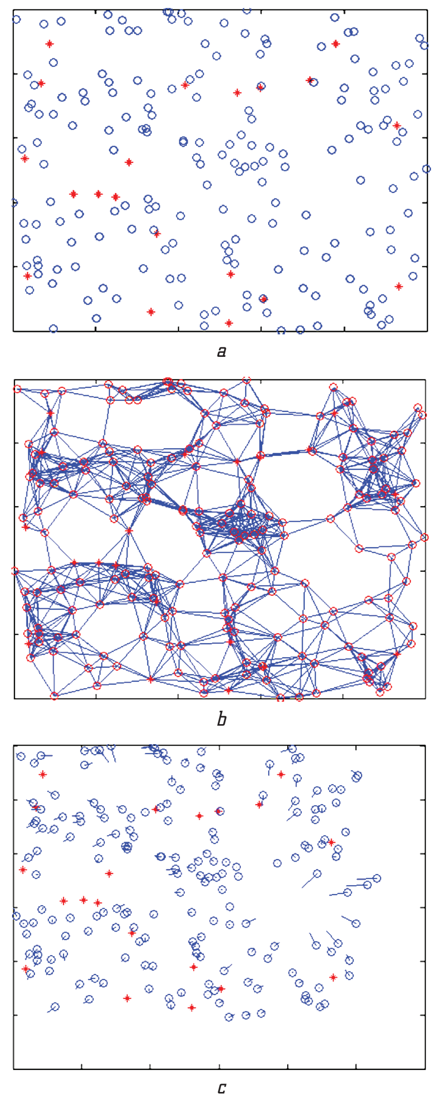

Fig. 6. Localization of the sensor network using 200 nodes: *a* – location of nodes; *b* – localization of the network; *c* – error estimation

Fig. 6, *a* shows the location of nodes, which is generated by random selection. Fig. 6, *b* shows that the network is localized and all nodes are found in the radius of their action. If pay attention to Fig. 6, *c*, it is possible to see the error in determining the coordinates of the nodes. The circles show the location of the node after localization, and the end of the line is the actual location of the node. This can be seen if we compare Fig. 6, *a*, *c*.

If pay attention to a network consisting of 200 nodes in terms of fault tolerance, then it can't be called fault tolerance. Therefore, the failure of the four nodes, which are in the upper right-hand part (Fig. 6, *b*), will disable a significant portion of the network. To prevent this, it is necessary to increase the range of nodes or increase the number of nodes, as shown in Fig. 7.

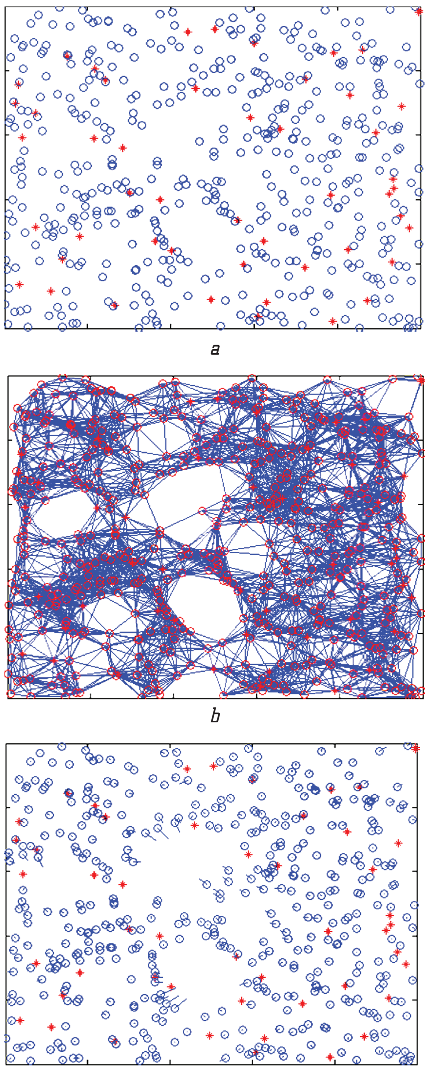

Fig. 7. Localization of the sensor network using 500 nodes: *a* – location of nodes; *b* – localization of the network; *c* – error estimation

In Fig. 7, it can be seen that an estimate of the error in the location of nodes of a network consisting of more nodes, namely 500 and a smaller radius of action 75 (compared to a network of 200 nodes), increased fault tolerance and increased network reliability.

Simulation of a network consisting of 1000 nodes with a range of 20 m (Fig. 8) is fault-tolerant, and the error in calculating the coordinates of unknown nodes is minimal in comparison with previous experiments. The error is $\delta \approx 2$ m, which is 2.5 times less than in similar devices.

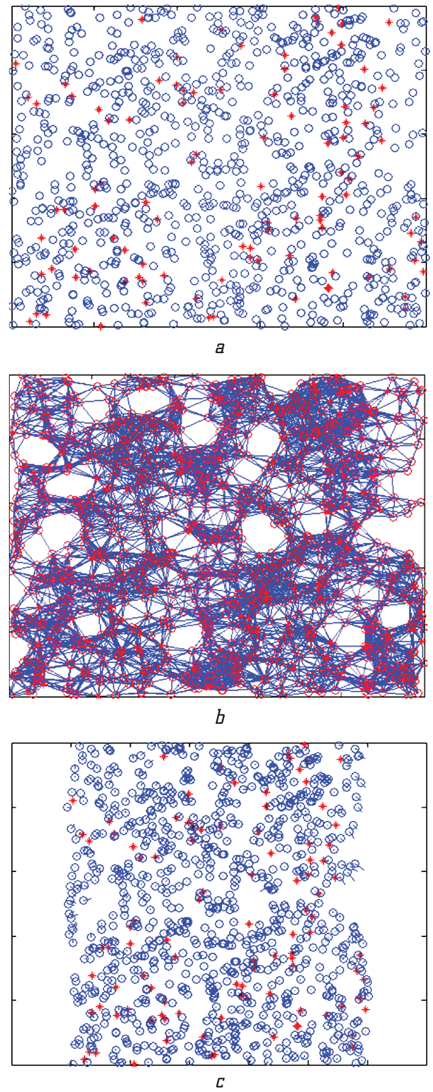

Fig. 8. Localization of the sensor network using 500 nodes: *a* – location of nodes; *b* – localization of the network; *c* – error estimation

In future studies, it is planned to expand the deployment area of the sensory network.

7. SWOT analysis of research results

Strengths. The strength of this research, in comparison with analogues, is the possibility of providing more accurate results of distance measurement in the presence of interference. This development will not incur additional costs for more powerful batteries for sensor devices, and does not require additional technical support after its introduction.

Weaknesses. The weak side of research is that there will be additional costs for the modernization of sensor devices related to the replacement of microcontrollers and/or their reprogramming for the method proposed in the work. Also, additional costs associated with the addition of laser rangefinder units to the sensor network device.

Opportunities. The introduction of the proposed development in the sensor network will enable it to perform more accurate measurements of the distance with a large number of interference, while maintaining the accuracy of 2.5 times greater than the analogs.

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Threats. At the first stage of the implementation of the system, it is necessary to allocate additional funds for the implementation of the software and hardware complex.

8. Conclusions

1. A mathematical model is developed to study the distance measurement process in wireless sensor networks in combination with laser rangefinder units. The input parameters from the sensor network side are the powers of the sent and received signal, and from the side of the laser rangefinder – the speed of light in vacuum, the refractive index of the medium and the time of passage of the beam to the target and back. The output parameters, in both cases, are the distance between objects, obtained by two different methods. This made it possible to obtain the results of the investigations with sufficient accuracy, by comparing the initial parameters, namely the error $\delta \approx 2$ m, which is permissible for a site 250×250 m.

2. It is revealed that the distance measuring method with the help of a laser rangefinder, including leveling, is able to measure the angle between the laser rangefinder and the target in addition to the distance. This makes it possible to assess the position of the target in space.

3. The structural scheme of the sensor network device is modernized by including laser rangefinder units in its structure. This makes it possible to obtain an alternative value for the distance between objects. This allowed, with constant interference, to reduce the measurement error by 2.5 times, using for comparison the data of the sensor network and the laser rangefinder.

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