

p-ISSN 1607-3274
e-ISSN 2313-688X



**Радіоелектроніка
Інформатика
Управління**

**Radio Electronics
Computer Science
Control**



2025/2

Науковий журнал «Радіоелектроніка, інформатика, управління» (скорочена назва – РІУ) видається Національним університетом «Запорізька політехніка» (НУ «Запорізька політехніка») з 1999 р. періодичністю чотири номери на рік.

Ресстрація суб'єкта у сфері друкованих медіа: Рішення Національної ради України з питань телебачення і радіомовлення № 3040 від 07.11.2024 року. Ідентифікатор медіа: R30-05582.

ISSN 1607-3274 (друкований), ISSN 2313-688X (електронний).

Наказом Міністерства освіти і науки України № 409 від 17.03.2020 р. «Про затвердження рішень Атестаційної колегії Міністерства щодо діяльності спеціалізованих вчених рад від 06 березня 2020 року» журнал включений до переліку наукових фахових видань України в категорії «А» (найвищий рівень), в яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора наук і доктора філософії (кандидата наук).

Журнал включений до польського Переліку наукових журналів та рецензованих матеріалів міжнародних конференцій з присвоєною кількістю балів (додаток до оголошення Міністра науки та вищої освіти Республіки Польща від 31 липня 2019 р.: № 16981).

В журналі безкоштовно публікуються наукові статті англійською, російською та українською мовами.

Правила оформлення статей подано на сайті: <http://ric.zntu.edu.ua/information/authors>.

Журнал забезпечує **безкоштовний відкритий он-лайн доступ** до повнотекстових публікацій.

Журнал дозволяє авторам мати авторські права і зберігати права на видання без обмежень. Журнал дозволяє користувачам читати, завантажувати, копіювати, поширювати, друкувати, шукати або посилається на повні тексти своїх статей. Журнал дозволяє повторне використання його вмісту у відповідності Creative Commons ліцензією CC BY-SA..

Опублікованим статтям присвоюється унікальний ідентифікатор цифрового об'єкта DOI.

Журнал входить до наукометричної бази Web of Science.

Журнал реферується та індексується у провідних міжнародних та національних реферативних журналах і наукометричних базах даних, а також розміщується у цифрових архівах та бібліотеках з безкоштовним доступом у режимі on-line, повний перелік яких подано на сайті: <http://ric.zntu.edu.ua/about/editorialPolicies#custom-0>.

Тематика журналу: телекомунікації та радіоелектроніка, програмна інженерія (включаючи теорію алгоритмів і програмування), комп'ютерні науки (математичне і комп'ютерне моделювання, оптимізація і дослідження операцій, управління в технічних системах, міжмашинна і людино-машинна взаємодія, штучний інтелект, включаючи системи, засновані на знаннях, і експертні системи, інтелектуальний аналіз даних, розпізнавання образів, штучні нейронні і нейро-нечіткі мережі, нечітку логіку, колективний інтелект і мультиагентні системи, гібридні системи), комп'ютерна інженерія (апаратне забезпечення обчислювальної техніки, комп'ютерні мережі), інформаційні системи та технології (структури та бази даних, системи, засновані на знаннях та експертні системи, обробка даних і сигналів).

Усі статті, пропонувані до публікації, одержують **об'єктивний розгляд**, що оцінюється за суттю без урахування раси, статі, віросповідання, етнічного походження, громадянства або політичної філософії автора(ів).

Усі статті проходять двоступінчасте закриті (анонімне для автора) **резензування** штатними редакторами і незалежними рецензентами – провідними вченими за профілем журналу.

РЕДАКЦІЙНА КОЛЕГІЯ

Головний редактор – Субботін Сергій Олександрович – доктор технічних наук, професор, завідувач кафедри програмних засобів, Національний університет «Запорізька політехніка», Україна.

Заступник головного редактора – Піза Дмитро Макарович – доктор технічних наук, професор, директор інституту інформатики та радіоелектроніки, професор кафедри радіотехніки та телекомунікацій, Національний університет «Запорізька політехніка», Україна.

Члени редколегії:

Андролідакіс Іосіф – доктор філософії, голова департаменту телефонії Центру обслуговування мереж, Університет Яніни, Греція;

Бодяньський Євгеній Володимирович – доктор технічних наук, професор, професор кафедри штучного інтелекту, Харківський національний університет радіоелектроніки, Україна;

Веннекенс Юст – доктор філософії, доцент, доцент факультету інженерних технологій (кампус Де Наір), Католицький університет Льовена, Бельгія;

Вольф Карстен – доктор філософії, професор, професор кафедри технічної інформатики, Дортмундський університет прикладних наук та мистецтв, Німеччина;

Вуттке Ганс-Дітріх – доктор філософії, доцент, провідний науковий співробітник інституту технічної інформатики, Технічний університет Льменау, Німеччина;

Горбань Олександр Миколайович – доктор фізико-математичних наук, професор, професор факультету математики, Університет Лестера, Велика Британія;

Городничий Дмитро Олегович – доктор філософії, кандидат технічних наук, доцент, провідний науковий співробітник Дирекції науки та інженерії, Канадська агенція прикордонної служби, Канада;

Дробахін Олег Олегович – доктор фізико-математичних наук, професор, перший проректор, Дніпровський національний університет імені Олеся Гончара, Україна;

Зайцева Олена Миколаївна – кандидат фізико-математичних наук, професор, професор кафедри інформатики, Жилінський університет в Жиліні, Словаччина;

Камеяма Мічітака – доктор наук, професор, професор факультету науки та інженерії, Університет Ішіномакі Сеншу, Японія;

Карташов Володимир Михайлович – доктор технічних наук, професор, завідувач кафедри медіаінженерії та інформаційних радіоелектронних систем, Харківський національний університет радіоелектроніки, Україна;

Леващенко Віталій Григорович – кандидат фізико-математичних наук, професор, завідувач кафедри інформатики, Жилінський університет в Жиліні, Словаччина;

Луенго Давид – доктор філософії, професор, завідувач кафедри теорії сигналів та комунікацій, Мадридський політехнічний університет, Іспанія;

Марковська-Качмар Урсула – доктор технічних наук, професор, професор кафедри обчислювального інтелекту, Вроцлавська політехніка, Польща;

Олійник Андрій Олександрович – доктор технічних наук, професор, професор кафедри програмних засобів, Національний університет «Запорізька політехніка», Україна;

Павліков Володимир Володимирович – доктор технічних наук, старший науковий співробітник, проректор з наукової роботи, Національний аерокосмічний університет ім. Н.Е. Жуковського «ХАІ», Україна;

Папшицький Марцін – доктор наук, професор, професор відділу інтелектуальних систем, Дослідний інститут систем Польської академії наук, м. Варшава, Польща;

Скруський Степан Юрійович – кандидат технічних наук, доцент, доцент кафедри комп'ютерних систем і мереж, Національний університет «Запорізька політехніка», Україна;

Табунчик Галина Володимирівна – кандидат технічних наук, професор, професор кафедри програмних засобів, Національний університет «Запорізька політехніка», Україна;

Тригано Томас – доктор філософії, старший викладач кафедри електричної та електронної інженерії, Інженерний коледж ім. С. Шамоу, м. Ашдод, Ізраїль;

Хенке Карстен – доктор технічних наук, професор, науковий співробітник факультету інформатики та автоматизації, Технічний університет Ільменау, Німеччина;

Шарпанських Олексій Альбертович – доктор філософії, доцент, доцент факультету аерокосмічної інженерії, Делфтський технічний університет, Нідерланди.

РЕДАКЦІЙНО-КОНСУЛЬТАТИВНА РАДА

Аррас Пітер – доктор філософії, доцент, доцент факультету інженерних технологій (кампус Де Наір), Католицький університет Льовена, Бельгія;

Ліснянський Анатолій – кандидат фізико-математичних наук, головний науковий експерт, Ізраїльська електрична корпорація, Хайфа, Ізраїль;

Мадрицх Христіан – доктор філософії, професор факультету інженерії та інформаційних технологій, Університет прикладних наук Каринфії, Австрія;

Маркосян Мгер Вардкесович – доктор технічних наук, професор, директор Єреванського науково-дослідного інституту засобів зв'язку, професор кафедри телекомунікацій, Російсько-вірменський університет, м. Єреван, Вірменія;

Рубель Олег Володимирович – кандидат технічних наук, доцент факультету інженерії, Університет МакМастера, Гамільтон, Канада;

Тавхелідзе Автанділ – кандидат фізико-математичних наук, професор, професор школи бізнесу, технології та освіти, Державний університет ім. Іллі Чавчавадзе, Тбілісі, Грузія;

Уреутью Дору – доктор фізико-математичних наук, професор, професор кафедри електроніки та обчислювальної техніки, Трансильванський університет в Брашові, Румунія;

Шульц Пітер – доктор технічних наук, професор, професор факультету інженерії та комп'ютерних наук, Гамбургський університет прикладних наук (HAW Hamburg), Гамбург, Німеччина.

Рекомендовано до видання Вченою радою НУ «Запорізька політехніка», протокол № 10 від 27.05.2025.

Журнал зверстаний редакційно-видавничим відділом НУ «Запорізька політехніка».

Веб-сайт журналу: <http://ric.zntu.edu.ua>.

Адреса редакції: Редакція журналу «РІУ», Національний університет «Запорізька політехніка», вул. Жуковського, 64, м. Запоріжжя, 69063, Україна.

Тел: (061) 769-82-96 – редакційно-видавничий відділ

Факс: +38-061-764-46-62

E-mail: rvv@zntu.edu.ua

© Національний університет «Запорізька політехніка, 2025

The scientific journal **Radio Electronics, Computer Science, Control** is published by the National University Zaporizhzhia Polytechnic NU Zaporizhzhia Polytechnic since 1999 with periodicity four numbers per year.

Registration of an entity in the field of print media: Decision of the National Council of Ukraine on Television and Radio Broadcasting No. 3040 of November 7, 2024. Media ID: R30-05582.

ISSN 1607-3274 (print), ISSN 2313-688X (on-line).

By the Order of the Ministry of Education and Science of Ukraine from 17.03.2020 № 409 "On approval of the decision of the Certifying Collegium of the Ministry on the activities of the specialized scientific councils dated 06 March 2020" journal is included in the list of scientific specialized periodicals of Ukraine in category "A" (highest level), where the results of dissertations for Doctor of Science and Doctor of Philosophy may be published.

The journal is included to the Polish List of scientific journals and peer-reviewed materials from international conferences with assigned number of points (Annex to the announcement of the Minister of Science and Higher Education of Poland from July 31, 2019: Lp. 16981).

The journal publishes scientific articles in English, Russian, and Ukrainian free of charge.

The article formatting rules are presented on the site: <http://ric.zntu.edu.ua/information/authors>.

The journal provides policy of **on-line open (free of charge) access** for full-text publications. The journal allow the authors to hold the copyright without restrictions and to retain publishing rights without restrictions. The journal allow readers to read, download, copy, distribute, print, search, or link to the full texts of its articles. The journal allow reuse and remixing of its content, in accordance with Creative Commons license CC BY-SA.

Published articles have a unique digital object identifier (DOI).

The journal is included into **Web of Science**.

The journal is abstracted and indexed in leading international and national abstracting journals and scientometric databases, and also placed to the digital archives and libraries with a free on-line access, full list of which is presented at the site: <http://ric.zntu.edu.ua/about/editorialPolicies#custom-0>.

The journal scope: telecommunications and radio electronics, software engineering (including algorithm and programming theory), computer science (mathematical modeling and computer simulation, optimization and operations research, control in technical systems, machine-machine and man-machine interfacing, artificial intelligence, including data mining, pattern recognition, artificial neural and neuro-fuzzy networks, fuzzy logic, swarm intelligence and multiagent systems, hybrid systems), computer engineering (computer hardware, computer networks), information systems and technologies (data structures and bases, knowledge-based and expert systems, data and signal processing methods).

All articles proposed for publication receive an **objective review** that evaluates substantially without regard to race, sex, religion, ethnic origin, nationality, or political philosophy of the author(s).

All articles undergo a two-stage **blind peer review** by the editorial staff and independent reviewers – the leading scientists on the profile of the journal.

EDITORIAL BOARD

Editor-in-Chief – **Sergey Subbotin** – Dr. Sc., Professor, Head of Software Tools Department, National University Zaporizhzhia Polytechnic, Ukraine.

Deputy Editor-in-Chief – **Dmytro Piza** – Dr. Sc., Professor, Director of the Institute of Informatics and Radio Electronics, Professor of the Department of Radio Engineering and Telecommunications, National University Zaporizhzhia Polytechnic, Ukraine.

Members of the Editorial Board:

Iosif Androulidakis – PhD, Head of Telephony Department, Network Operation Center, University of Ioannina, Greece;

Evgeniy Bodyanskiy – Dr. Sc., Professor, Professor of the Department of Artificial Intelligence, Kharkiv National University of Radio Electronics, Ukraine;

Oleg Drobakhin – Dr. Sc., Professor, First Vice-Rector, Oles Honchar Dnipro National University, Ukraine;

Alexander Gorban – PhD, Professor, Professor of the Faculty of Mathematics, University of Leicester, United Kingdom;

Dmitry Gorodnichy – PhD, Associate Professor, Leading Research Fellow at the Directorate of Science and Engineering, Canada Border Services Agency, Ottawa, Canada;

Karsten Henke – Dr. Sc., Professor, Research Fellow, Faculty of Informatics and Automation, Technical University of Ilmenay, Germany;

Michitaka Kameyama – Dr. Sc., Professor, Professor of the Faculty of Science and Engineering, Ishinomaki Senshu University, Japan;

Volodymyr Kartashov – Dr. Sc., Professor, Head of the Department of Media Engineering and Information Radio Electronic Systems, Kharkiv National University of Radio Electronics, Ukraine;

Vitaly Levashenko – PhD, Professor, Head of Department of Informatics, University of Žilina, Slovakia;

David Luengo – PhD, Professor, Head of the Department of Signal Theory and Communication, Madrid Polytechnic University, Spain;

Ursula Markowska-Kaczmar – Dr. Sc., Professor, Professor of the Department of Computational Intelligence, Wrocław University of Technology, Poland;

Andrii Oliinyk – Dr. Sc., Professor, Professor of the Department of Software Tools, National University Zaporizhzhia Polytechnic, Ukraine;

Marcin Paprzycki – Dr. Sc., Professor, Professor of the Department of Intelligent Systems, Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland;

Volodymyr Pavlikov – Dr. Sc., Senior Researcher, Vice-Rector for Research, N. E. Zhukovsky National Aerospace University "KhAI", Ukraine;

Alexei Sharpanskykh – PhD, Associate Professor, Associate Professor of Aerospace Engineering Faculty, Delft University of Technology, Netherlands;

Stepan Skrupsky – PhD, Associate Professor, Associate Professor of the Department of Computer Systems and Networks, National University Zaporizhzhia Polytechnic, Ukraine;

Galyna Tabunshchyyk – PhD, Professor, Professor of the Department of Software Tools, National University Zaporizhzhia Polytechnic, Ukraine;

Thomas (Tom) Trigano – PhD, Senior Lecturer of the Department of Electrical and Electronic Engineering, Sami Shamoon College of Engineering, Ashdod, Israel;

Joost Vennekens – PhD, Associate Professor, Associate Professor, Faculty of Engineering (Campus de Nair), Katholieke Universiteit Leuven, Belgium;

Carsten Wolff – PhD, Professor, Professor of the Department of Technical Informatics, Dortmund University of Applied Sciences and Arts, Germany;

Heinz-Dietrich Wuttke – PhD, Associate Professor, Leading Researcher at the Institute of Technical Informatics, Technical University of Ilmenay, Germany;

Elena Zaitseva – PhD, Professor, Professor, Department of Informatics, University of Žilina, Slovakia.

EDITORIAL-ADVISORY COUNCIL

Peter Arras – PhD, Associate Professor, Associate Professor, Faculty of Engineering (Campus De Nair), Katholieke Universiteit Leuven, Belgium;

Anatoly Lisnianski – PhD, Chief Scientific Expert, Israel Electric Corporation Ltd., Haifa, Israel;

Christian Madritsch – PhD, Professor of the Faculty of Engineering and Information Technology, Carinthia University of Applied Sciences, Austria;

Mher Markosyan – Dr. Sc., Professor, Director of the Yerevan Research Institute of Communications, Professor of the Department of Telecommunications, Russian-Armenian University, Yerevan, Armenia;

Oleg Rubel – PhD, Associate Professor, Faculty of Engineering, McMaster University, Hamilton, Canada;

Peter Schulz – Dr. Sc., Professor, Professor, Faculty of Engineering and Computer Science, Hamburg University of Applied Sciences (HAW Hamburg), Hamburg, Germany;

Avtandil Tavkheldze – PhD, Professor, Professor of the School of Business, Technology and Education, Iliia State University, Tbilisi, Georgia;

Doru Ursuțiu – Dr. Sc., Professor, Professor, Department of Electronics and Computer Engineering, University of Transylvania at Brasov, Romania.

Recommended for publication by the Academic Council of NU Zaporizhzhia Polytechnic, protocol № 10 dated 27.05.2025.

The journal is imposed by the editorial-publishing department of NU Zaporizhzhia Polytechnic.

The journal web-site is <http://ric.zntu.edu.ua>.

The address of the editorial office: Editorial office of the journal Radio Electronics, Computer Science, Control, National University Zaporizhzhia Polytechnic, Zhukovskiy street, 64, Zaporizhzhia, 69063, Ukraine.

Tel.: +38-061-769-82-96 – the editorial-publishing department.

E-mail: rvv@zntu.edu.ua

Fax: +38-061-764-46-62

© National University Zaporizhzhia Polytechnic, 2025

ЗМІСТ

РАДІОЕЛЕКТРОНІКА ТА ТЕЛЕКОМУНІКАЦІЇ.....	6
<i>Khandetskyi V. S., Karpenko N. V., Gerasimov V. V.</i> EVALUATING THE EFFICIENCY OF MECHANISMS FOR FRAME BLOCKS TRANSMISSION IN NOISY CHANNELS OF IEEE 802.11 NETWORKS.....	6
<i>Mammadov J. F., Ahmadova T. A., Huseynov A. H., Talibov N. H., Hashimova H. M., Ahmadov A. A.</i> THE SELECTION OF INFORMATION-MEASURING MEANS FOR THE ROBOTOTECHNICAL COMPLEX AND THE RESEARCH OF THEIR WORKER CHARACTERISTICS.....	20
<i>Sotnik S. V.</i> DEVELOPMENT OF A RANGE MEASUREMENT MODULE ON AN ULTRASONIC SENSOR WITH A GSM MODULE.....	32
МАТЕМАТИЧНЕ ТА КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ.....	45
<i>Fedorov E. E., Khramova-Baranova O. L., Utkina T. Y., Kozhushko Ya. M., Nesen I. O.</i> THE INTELLECTUAL ANALYSIS METHOD OF COLOR IMAGES.....	45
<i>Kolodochka D. O., Polyakova M. V., Rogachko V. V.</i> PREDICTION THE ACCURACY OF IMAGE INPAINTING USING TEXTURE DESCRIPTORS.....	56
<i>Koriashkina L. S., Lubenets D. E., Minieiev O. S., Sazonova M. S.</i> MATHEMATICAL FOUNDATIONS OF METHODS FOR SOLVING CONTINUOUS PROBLEMS OF OPTIMAL MULTIPLEX PARTITIONING OF SETS.....	68
НЕЙРОІНФОРМАТИКА ТА ІНТЕЛЕКТУАЛЬНІ СИСТЕМИ.....	84
<i>Batsamut V. M., Batsamut M. V., Bashkatov Y. H., Tolstonosov D. Yu.</i> TWO-LAYER GRAPH INVARIANT FOR PATTERN RECOGNITION.....	84
<i>Burov E. V., Zhovnir Y. I., Zakhariya O. V., Kunanets N. E.</i> SITUATION ANTICIPATION AND PLANNING FRAMEWORK FOR INTELLIGENT ENVIRONMENTS.....	94
<i>Kondruk N. E.</i> A STUDY ON THE USE OF NORMALIZED L2-METRIC IN CLASSIFICATION TASKS.....	110
<i>Kysarin M. K.</i> BEARING FAULT DETECTION BY USING AUTOENCODER CONVOLUTIONAL NEURAL NETWORK.....	116
<i>Leoshchenko S. D., Oliinyk A. O., Subbotin S. A., Morklyanyk B. V.</i> SYNTHESIS OF NEURAL NETWORK MODELS FOR TECHNICAL DIAGNOSTICS OF NONLINEAR SYSTEMS.....	126
<i>Nedashkovskaya N. I., Yeremichuk R. I.</i> EVALUATION OF QUANTIZED LARGE LANGUAGE MODELS IN THE TEXT SUMMARIZATION PROBLEM.....	133
<i>Shalimov O. Y., Moskalchuk O. O., Yevseienko O. M.</i> METHOD FOR ANALYZING INPUT DATA FROM GEAR VIBRATIONS.....	148
ПРОГРЕСИВНІ ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ.....	154
<i>Батюк Т. М., Досин Д. Г.</i> ОБРОБКА ТЕКСТОВИХ ДАНИХ СОЦІАЛЬНИХ МЕДІА НА ПРИРОДНІЙ МОВІ ЗА ДОПОМОГОЮ BERT ТА XGBOOST.....	154
<i>Berezsky O., M. Berezkyi M. O., Dombrovskiy M. O., Liashchynskiy P. B., Melnyk G.M.</i> COMBINED METRIC FOR EVALUATING THE QUALITY OF SYNTHESIZED BIOMEDICAL IMAGES.....	168
<i>Boyko N. I., Salanchii T. O.</i> DEVELOPMENT OF INNOVATIVE APPROACHES FOR NETWORK OPTIMIZATION USING GEOSPATIAL MULTI-COMPONENT SYSTEMS.....	182
<i>Czerniachowska K. S., Subbotin S. A.</i> OPTIMIZATION BASED ON FLOWER CUTTING HEURISTICS FOR SPACE ALLOCATION PROBLEM.....	196
<i>Косолап А. І.</i> ОПТИМАЛЬНИЙ РОЗПОДІЛ ОБМЕЖЕНИХ РЕСУРСІВ В МУЛЬТИПРОЦЕСОРНИХ СИСТЕМАХ.....	209
<i>Pukach A. I., Teslyuk V. M.</i> METHOD FOR DEVELOPMENT MODELS OF POLYSUBJECT MULTIFACTOR ENVIRONMENT OF SOFTWARE COMPLEX'S SUPPORT.....	217
УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ.....	232
<i>Yefymenko M. V., Kudermetov R. K.</i> TERMINAL CONTROL OF QUADCOPTER SPATIAL MOTION.....	232

DEVELOPMENT OF A RANGE MEASUREMENT MODULE ON AN ULTRASONIC SENSOR WITH A GSM MODULE

Sotnik S. V. – PhD, Associate Professor, Associate Professor of Department of Computer-Integrated Technologies, Automation and Robotics, Kharkiv, Ukraine.

ABSTRACT

Context. The development of a range measurement module based on an ultrasonic sensor with a Global System for Mobile Communications (GSM) module is extremely relevant in the field of telecommunications and radio electronics. In today's world, an increasing number of devices are integrated into Internet of Things (IoT) systems, where long-distance data transmission is provided by telecommunication technologies. The use of the GSM module allows real-time transmission of information from the measuring device to remote servers or end users, which is critical for remote monitoring and control solutions.

Ultrasonic sensors in combination with a GSM module can automate measurement processes in hard-to-reach or hazardous environments, which increases the efficiency and safety of systems. The use of radio electronic technologies for real-time transmission of measurement data can significantly expand the functionality of devices and facilitate their integration into existing telecommunication systems, particularly in the industrial, transportation, and infrastructure sectors.

Thus, the development of this module with precise measurements contributes to the development of innovations in the field of telecommunications and radio electronics, providing fast and reliable data transmission, which is an important component of modern information systems.

Objective. Development of a range measurement module based on an ultrasonic sensor with a GSM module and improving the accuracy of measurements by implementing the proposed mathematical model of ultrasonic sensor autocalibration.

Method. To achieve this goal, an integrated range measurement module was developed, which combines the HC-SR04 ultrasonic sensor with a GSM module. The method of improving accuracy is based on the proposed mathematical model of ultrasonic sensor autocalibration.

Results. The task was stated, and a range measurement module based on an ultrasonic sensor with an integrated GSM module was developed. In the course of the study, an electrical schematic diagram of the device was created using DipTrace software. An algorithm for the operation of the module has been developed, which optimizes the interaction between the ultrasonic sensor. A printed circuit board has been created. A mathematical model of autocalibration of an ultrasonic sensor to improve measurement accuracy has been proposed. A series of experimental studies were carried out to assess accuracy. The results of the experiments confirmed the effectiveness of the developed module for measuring distances.

Conclusions. The developed range measurement module based on an ultrasonic sensor with a GSM module is an innovative solution that meets the modern requirements of telecommunication and radio engineering systems. The integration of accurate distance measurement based on the proposed mathematical model of autocalibration of an ultrasonic sensor with the possibility of remote data transmission opens up new prospects for remote monitoring and automation of processes. Experimental studies have confirmed the accuracy and reliability of the device, and comparative analysis with analogs has demonstrated its competitive advantages. The cost-effectiveness and energy efficiency of the developed module make it attractive to a wide range of users, from individual developers to industrial enterprises. Further research can be aimed at improving data processing algorithms and expanding the functionality of the device, which will contribute to the development of innovative technologies in the field of radio electronics and telecommunications.

KEYWORDS: range, measurement, module, ultrasonic sensor, GSM module.

ABBREVIATIONS

AT – attention command;
FFBPN – feedforward backpropagation neural network;
GSM – global system for mobile communications;
ICSPCLK – in-circuit serial programming clock;
ICSPDAT – in-circuit serial programming data;
IoT – internet of things;
LVP – low voltage programming;
MCLR – master clear (reset);
PCB – printed circuit board;
PGC – programming clock;
PGD – programming data;
PGM – programming;
PIC – peripheral interface controller;
RA0/AN0 – analog input 0;
RA1/AN1 – analog input 1;
RAM – random access memory;

RB0/INT – transition / interruption;
RB1/RX/DT – receiver / data transmission;
SIM – subscriber identity module;
TTL – transistor-transistor logic;
UART – universal asynchronous receiver-transmitter;
UIPS – ultra-wideband indoor positioning system;
Vdd – positive supply voltage;
Vpp – programming voltage;
Vss – ground (grounding).

NOMENCLATURE

E – multitude of external influencing factors;
 E_b – bit energy;
 E_m – energy spent on measurement;
 E_{pr} – energy spent on data processing;
 E_{tot} – total energy consumption of the system;

E_{tr} – energy spent on data transmission;
 f_s – sampling frequency, which determines the number of signal samples per unit of time;
 H – relative humidity at the measurement site;
 K_{cor} – coefficient to compensate for systematic error;
 K_{rce} – correction coefficient of compensation for the random component of the error;
 L – distance, m;
 L_A – acoustic interference level;
 L_m – measured distance value;
 L_{tr} – true value of the distance;
 m – total number of measurements;
 N – total number of counts that have been made;
 N_0 – noise power spectral density;
 t – time of the reflected pulse per second;
 $s[n]$ – discrete signal samples;
 P – calibration options;
 P_e – probability of error;
 P_{noi} – noise power in the communication channel;
 P_{sig} – power of the useful signal;
 p_{SW} – Shapiro-Wilk criterion;
 R^2 – coefficient of determination;
 $RMSE$ – root mean square error;
 $Q(\)$ – function;
 SNR – signal-to-noise ratio;
 T – air temperature or directly temperature in the measurement environment of the HC-SR04 ultrasonic sensor, °C;
 T_s – sampling period, which determines the time interval at which samples are taken;
 $Y_{cal,i}$ – calibrated value for the i -th measurement;
 $Y_{mes,i}$ – measured value for the i -th measurement;
 Y_{pr} – primary measurement;
 $Y_{ref,i}$ – reference value for the i -th measurement;
 α – coefficient that determines the effect of temperature in a systematic error;
 β – coefficient that determines the effect of humidity in a systematic error;
 γ – coefficient that determines the influence of the level of acoustic interference in the systematic error;
 δ – relative error;
 θ – coefficient that determines the influence of the primary measurement into a systematic error;
 ε – measurement error, m;
 ε_{sys} – systematic error;
 μ – average error value, m;
 σ – variance, which characterizes the spread of errors around the mean value;
 v – ultrasonic speed, m/s.

INTRODUCTION

As the coverage of mobile networks increases, GSM modules are becoming increasingly popular. They allow efficient transmission of data or other information. This approach provides convenience and speed of information transfer in real time. This trend is especially relevant in an environment where automation and remote monitoring are becoming an integral part of modern technological systems [1–4].

Automated control allows precise control of process parameters such as temperature and metal casting speed, ensuring stable production conditions and preventing defects. In addition, the automated system records data in real time, which simplifies the maintenance of technical documentation and allows you to quickly respond to changes in process parameters.

Ultrasonic sensors are one of the most effective tools for precise distance measurement in various media. The combination of ultrasonic sensors with GSM modules opens up new possibilities for creating autonomous measurement systems that can transmit measurement results over long distances. This is especially important for applications where traditional methods of data collection and transmission are not efficient or possible.

The development of a range measurement module based on an ultrasonic sensor with the integration of a GSM module is aimed at creating a universal device that will provide accurate distance measurements and the ability to transmit them to remote servers or end users. This will significantly increase the efficiency in the field of radio engineering and telecommunications by improving the collection and processing of data in real time. The integration of the GSM module ensures stable communication over long distances, which reduces delays in data transmission. This allows you to improve monitoring systems, controlling remote devices and networks, especially in environments where the use of advanced technologies is difficult or impossible.

The research objectives include the development of an integrated module that combines the HC-SR04 ultrasonic sensor with a GSM module for remote monitoring and real-time data transmission. In addition, it is necessary to identify and analyze modern distance measurement devices, their characteristics, advantages and disadvantages, and develop an algorithm for the module to ensure measurement accuracy and reduce power consumption. These tasks are aimed at creating and implementing an innovative, energy-efficient and cost-effective solution for remote distance measurement with real-time data transmission to expand the capabilities of telecommunication systems, improve remote monitoring technologies in various industries and science, and develop applied aspects of radio engineering in the field of measurement systems and wireless data transmission. Practical tasks include the implementation of an algorithm and the creation of a remote distance measurement module that integrates an inexpensive HC-SR04 ultrasonic sensor with a GSM module, which allows for remote measurements at an affordable price.

Since one of the main problems that exist in the development and use of remote distance measurement systems is to ensure high accuracy of measurements in various operating conditions, improving the accuracy of distance measurement becomes a key task for improving such systems. This is especially important for applications where even small errors can have a significant impact on the results of the entire system, which is why this is the topic of our research.

The initial data include the results of previous studies, technical requirements for creating a distance measurement module [5–7].

The object of research is the distance measurement process and the GSM module for data transmission.

The subject of research is a distance measurement module.

The purpose of the research is to development of a range measurement module based on an ultrasonic sensor with a GSM module and increasing the accuracy of measurements by implementing the proposed mathematical model of ultrasonic sensor autocalibration.

1 PROBLEM STATEMENT

In the context of the rapid development of telecommunication technologies and the expansion of the application areas of radio systems, the issue of effective integration of measuring devices with data transmission systems is becoming particularly relevant. Modern radio engineering and telecommunications require reliable, accurate and cost-effective solutions for remote measurement and monitoring of various parameters, including distance.

Existing distance measurement systems in radio engineering applications often face accuracy and reliability issues, especially in variable electromagnetic environments or when working with different types of surfaces. These limitations have a significant impact on the efficiency and reliability of telecommunications' systems that use distance data to optimize signal transmission or antenna system setup.

Integration of measuring devices with modern telecommunications networks, in particular with mobile communication systems, remains a challenge. Many existing solutions do not have effective means for long-distance data transmission, which limits their use in distributed radio systems and networks. This problem is particularly acute in the context of the development of IoT technologies and the expansion of mobile network coverage, where efficient data transmission from remote sensors is critical.

In light of these challenges, there is an urgent need to develop an integrated range measurement module that would combine high measurement accuracy with the ability to efficiently transmit data over mobile networks. Such a module should be energy-efficient with the ability to operate autonomously, affordable, and able to operate in a variety of operating conditions typical of telecommunications systems.

The development of a module based on the HC-SR04 ultrasonic sensor with the integration of a GSM module

seems to be a promising solution that can meet the above requirements.

The mathematical formulation includes in the model the measurement of distance by an ultrasonic sensor: $L = (\nu \cdot t) / 2$. Taking into account the effect of temperature on the speed of sound: $L = 331,3 + 0,606 \cdot T$. Model of measurement error: $L_m = L_{tr} + \varepsilon$. While the measurement error can be modeled as a random variable with a normal distribution $N(\mu, \sigma^2)$, the average error value is zero, i.e., $\mu = 0$ on average, the error will not bias the result in a certain direction (no systematic error). Dispersion, which characterizes the spread of errors around the mean value. The larger the value σ , the more errors can deviate from zero.

Sampling of a signal for digital processing: $s[n] = s(T_s), n = 1, 2, \dots, N - 1$. The sampling period that determines at what interval samples are taken $f_s = 1/T_s$. It can be thought of as the inverse of the sampling rate Data transmission model via a GSM module: $SNR = P_{sig} / P_{noi}$. The probability of error when transmitting a bit of information: $P_e = Q(\sqrt{2E_b / N_0})$. Energy efficiency of the system: $E_{tot} = E_m + E_{pr} + E_{tr}$.

This mathematical formulation covers the main aspects of the developed module, including distance measurement, signal processing, data transmission, and energy efficiency of the system. It allows for a theoretical analysis and optimization of system parameters to achieve the best measurement accuracy and data transmission reliability.

2 REVIEW OF THE LITERATURE

Today, many authors have studied in detail the areas of application and various aspects of distance measurement technologies. In particular, numerous scientific publications and technical reports focus on analyzing the effectiveness of various distance measurement methods, their accuracy, speed, and adaptation to different conditions.

Thus, the ultrasonic method of measurement, namely sensors, is one of the most effective tools for accurate distance measurement. A striking example of the synergy of radio engineering and telecommunications is the development and implementation of an UIPS, presented in [8]. This system demonstrates how technologies traditionally associated with radio engineering (ultrasonic signals, specialized signal processing methods) are integrated with modern telecommunications solutions (Wi-Fi, wireless sensor networks) to create an effective positioning system.

Another important study [9] presents an innovative assistive device for navigation for blind and visually impaired people, which, although it has wide practical application, is based on the principles of radio engineering and telecommunications. This device combines radio engineering components (ultrasonic sensors for detecting obstacles, signal processing and analysis) with telecommu-

nications and information technologies (integration of a smartphone and its camera, visual information processing). These studies clearly demonstrate that modern developments in distance measurement and positioning lie at the intersection of radio engineering and telecommunications, combining signal processing principles with advanced data transmission methods.

In modern radio engineering and telecommunications, there is a wide range of technologies for measuring distance. Each of these technologies has its own advantages and limitations that determine their areas of application.

Ultrasonic and infrared technologies for detecting various objects on flat surfaces and from different materials are described in [10]. The focus is on measurements at short distances within useful ranges.

A study of the operation of an ultrasonic sensor that measures distance by the threshold method is presented in [11]. To improve the accuracy of distance measurement, the authors used the least-squares method, the piecewise method, and the Vandermonde method. The principle of operation of these sensors is based on measuring the time required for the reflection of an ultrasonic pulse from an object. Research shows that ultrasonic sensors are particularly effective for measurements up to 4 meters away, making them ideal for many industrial and domestic applications.

Paper [12] describes research in the field of laser sensors for movement, distance, and position. Laser distance measurement technologies are used in robotics, surveillance, autonomous driving, and biomedicine. Laser sensors are based on various optical methods, such as triangulation, time-of-flight, confocal and interferometric sensors.

Optical sensors use infrared radiation to measure distance [13, 14]. These sensors have the advantage of being fast and able to work with transparent objects.

In [14], a device was developed to measure the exact distance from 5 to 400 cm using three sensors using the proposed online FFBN. The field of application of the device is in robotics and radar for accurate object detection in robotics and radar, as this device successfully detects close and distant objects.

The use of GSM modules to transmit measurement data is becoming increasingly popular due to the wide coverage of mobile networks [15]. This makes it possible to create autonomous monitoring systems that can operate over long distances without the need for additional communications. The authors in [15] describe the experimental setup and discuss the measurement principle. To calculate the distance using this device, the target, the distance to which is to be measured, should always be perpendicular to the plane of propagation of ultrasonic waves. Thus, the target orientation is a limitation of this system. The paper describes the device in some detail but does not pay much attention to studies on accuracy and energy efficiency.

Paper [16] is devoted to the use of ultrasonic sensors to measure the distance to objects without physical contact. The device includes a built-in temperature compen-

sation sensor to improve measurement accuracy because temperature changes affect the propagation speed of ultrasonic waves. The work uses an ATmega32 and an ultrasonic transmitter and receiver operating at 40 kHz, generating and receiving ultrasonic pulses and calculating the time of their reflection from the obstacle. The authors also used the HC-SR04 sensor. Although the distance to the object can be measured up to 60 meters and the measurement results are displayed on an LCD screen, it is worth noting that our choice of the PIC16F628A may be more efficient because it has a power consumption advantage for battery-powered devices.

In [17], distance measurement methods are considered, in particular, the non-contact method that uses an ultrasonic sensor. An ultrasonic transducer uses the time-of-flight technique to determine distance. This method calculates the time interval between the transmitted and reflected signal, which allows for distance determination. Although the tests have shown successful results in measuring the distance to an object up to 5 meters, as well as calculating the corresponding area and volume, the described methods and results could be compared with analogs, as we have done in our work, to prove the effectiveness of the work. In addition, the article does not provide a detailed analysis of the impact of different environmental conditions on the accuracy of measurements, which is an important aspect to improve the overall performance of the system.

Measurements using ultrasonic sensor probes are among the cheapest of the various options. Such sensors are considered to be one of the most efficient and cost-effective methods of distance measurement, although there is potential for further development of this technology for longer distances. This paper describes measuring the distance to an obstacle using such a sensor.

The general trend of these scientific works is a great interest in the development and improvement of non-contact distance measurement methods using ultrasonic and other types of sensors. Researchers focus on improving the accuracy and range of measurements, as well as on integrating these technologies with various electronic systems to achieve better results in practical applications.

Therefore, in this work, emphasis is placed on the development of a range measurement module on an ultrasonic sensor with a GSM module and to increase the accuracy of distance measurement, and in addition, it will be possible to transmit the obtained values to remote servers or end users.

3 MATERIALS AND METHODS

To begin with, let's justify the choice of technical means for the distance measurement module.

For this study, we chose the HC-SR04 ultrasonic sensor developed by RoboBox because it is (Fig. 1) [18]:

- is widespread and easily available on the market of electronic components;
- is one of the most cost-effective solutions for distance measurement;

- has a simple interface that facilitates its integration with various microcontrollers;
- HC-SR04 measurement accuracy (usually ± 3 mm) is quite acceptable;
- no blind spots;
- the sensor is capable of measuring distances from 2 cm to 400 cm, which is suitable for many projects;
- consumes little power, which is important for mobile or autonomous devices;
- small dimensions of the sensor make it easy to integrate into various projects;
- less sensitive to light and color of objects compared to optical sensors.



Figure 1 – HC-SR04 sensor

To generate ultrasonic waves on the transducer, a TTL pulse of 10 μ s duration must be applied to the Trig pin.

When the pulse arrives, the circuit generates 8 pulses with a frequency of 40 kHz, which activate the piezoresistive transducer. This creates ultrasonic waves that propagate in the direction of the obstacle. The reflected waves are captured by a second piezoelectric transducer. By comparing the time between sending and receiving pulses, the circuit generates a TTL-level Echo pulse whose duration is proportional to the distance to the object.

After determining the width of the Echo pulse, you can calculate the distance to the reflected surface using the following formula: pulse width equals distance.

The PIC16F628A microcontroller is used to convert the duration of the signal generated by the ultrasonic sensor into a distance value and then transmit it to the SIM module. This microcontroller is part of the widely used PIC series. The choice of this microcontroller is due to the presence of a built-in timer and a UART interface, which allows you to transfer data and commands such as AT, which are recognized by the SIM module.

PIC16F628A is the best choice for developing a range measurement module with an ultrasonic sensor and GSM module because:

- PIC16F628A offers a good feature set at an affordable price;
- the small size of the microcontroller (18-pin DIP or SOIC package) allows you to create compact devices;
- PIC16F628A has power-saving modes, which is important for standalone devices;
- clock frequency up to 20 MHz provides sufficient performance for processing data from the ultrasonic sensor and GSM module;
- 2048 words of program Flash memory and 224 bytes of RAM are enough to implement the required functionality;

- the presence of UART, timers, and comparators simplifies the work with external devices;
- PIC series microcontrollers are known for their stability and resistance to interference.

The location of the pins of the microcontroller PIC16F628A in Fig. 2.

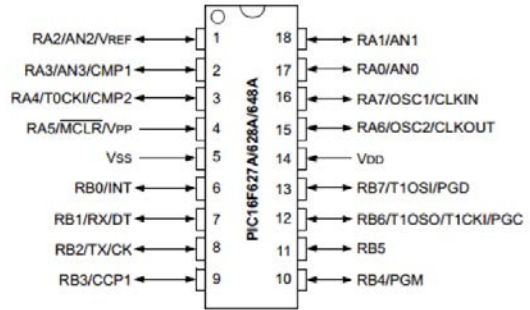


Figure 2 – Diagram of the location of the pins of the microcontroller PIC16F628A

In Fig. 2 the diagram shows the purpose of each of the 18 pins of the microcontroller, such as RA0/AN0, RA1/AN1, RB0/INT, RB1/RX/DT, etc. This information is important for the correct connection of the microcontroller to other components of the circuit, for example, to connect an ultrasonic sensor, GSM module, and other devices within the developed range measurement module.

Next, let's move on to the development of a diagram of an electrical circuit device for measuring distance.

In this study, a distance measurement module was developed using the DipTrace software.

DipTrace was chosen for designing component packages and creating PCB layouts due to its ease of use, intuitive interface, and powerful set of design tools. This program provides high accuracy when working with various components, which allows you to create complex electronic circuits and layouts with minimal errors. In addition, DipTrace supports a wide range of file formats, which facilitates integration with other tools and systems, making it a universal solution for PCB designers. The electrical schematic diagram of the device was created using the DipTrace Schematic module (Fig. 3).

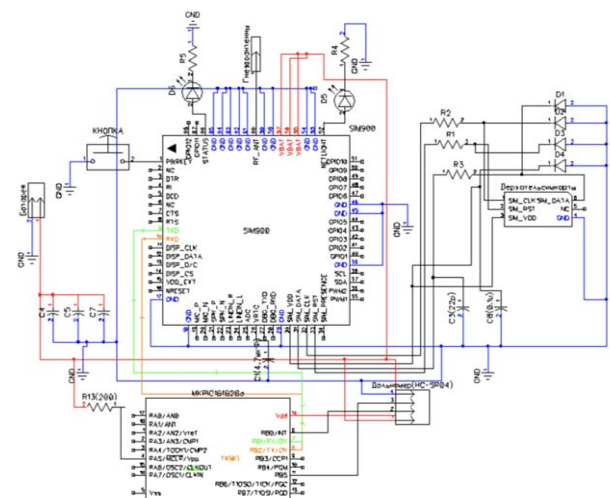


Figure 3 – Schematic diagram of the distance measurement module of the microcontroller PIC16F628A

First, the matching elements were removed from the antenna circuit. It is allowed to use a short connection between RF_ANT(60) and the antenna at short distances. The PWRKEY(1) pin has a button, which, when pressed for 0,5 seconds, turns on the module.

The LED indicators are connected via resistors. When the module is turned on, the LED connected to the STATUS(66) pin should light up.

The NETLIGHT(52), which shows the network status, operates in glow and non-beam modes.

The TX(9) and RX(10) pins of the module are connected to the PIC16F628A microcontroller, providing data exchange via a serial UART interface using AT commands.

Resistors R4 and R5 limit the current supplied to LED indicators set to 300 ohms.

Any antenna in the GSM band with an SMA-F connector is used.

Capacitors: C1–4,7 μ F, C3–22 pF, C4–100 μ F, C5–104 nF, C7–10 pF, C8–0.47 μ F.

The SIM cardholder is installed with protective diodes.

It is recommended to use a powerful power supply since, when searching for a network, the peak current can reach 1.5 A.

Now, let's move on to the development of the module's algorithm. Consider the principle of operation of the distance measurement module.

When idle, the module goes into sleep mode.

The microcontroller is configured in such a way that it automatically activates when it is in idle mode. The wake-up of the microcontroller is due to a signal from the SIM900, specifically from the RI pin (4), which is connected to the RB4 pin of the microcontroller.

When an incoming call or SMS is received at the RI(4) input of the SIM900, the logical level on this pin is lowered to 0, which causes an interrupt in the microcontroller and activates it.

After waking up, the device is configured so that when receiving an incoming call, the microcontroller sends a pulse of 10 μ s to the HC-SR04 ultrasonic sensor.

After receiving a signal from the sensor, the microcontroller calculates the distance (in centimeters) and transmits this data via AT commands to the communication module.

The general algorithm of the program is shown in Figure 4.

Declaring variables is the first step in executing a program.

Next, the microcontroller timers are configured.

After that, it is necessary to implement the output of the AT command to configure the operation of SMS transmission, so the program outputs the AT command for the configuration of SMS transmission. AT commands allow: to configure communication parameters, initiate a connection, send and receive data (in this case, SMS), control the functions of a modem or GSM module.

At the stage "Output of AT commands to configure the operation of SMS transmission", the program proba-

bly sends one or more AT commands to the GSM module for its configuration before sending SMS.

Next, the program waits for an incoming call, which is marked as "Ring" on the diagram – this is a special signal. This call serves as a trigger or signal to activate the measuring process. It is not designed for voice communication.

Advantages of this approach:

- the system does not carry out constant measurements but is activated only when necessary;
- access control, because only authorized numbers can initiate measurements;
- remote control: the ability to start measuring remotely.

If the "Ring" call is received, the following steps are performed:

- measuring the time around the input signal, that is, the program measures the duration of the input signal, so the trigger for the HC-SR04 is triggered, the sensor generates 8 pulses for transmission, and the displayed signal will be sent to the microcontroller;
- converting them into centimeters, that is, the measured time is converted into distance (centimeters);
- sending SMS, here the program generates and sends SMS messages.

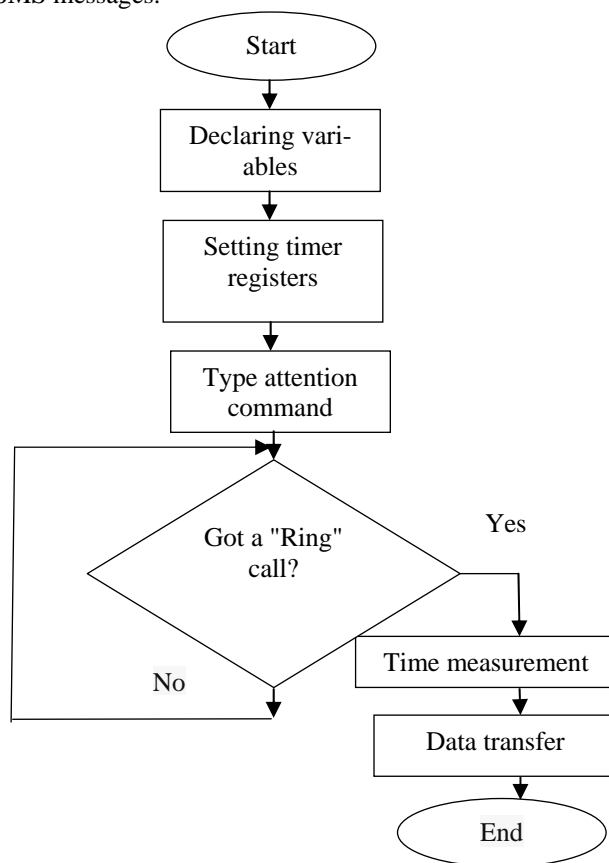


Figure 4 – Algorithm of the distance measurement module program

The "Ring" call does not require an answer or connection. The very fact of its receipt is a signal to start work.

The sensor data is sent to the user’s landline number.

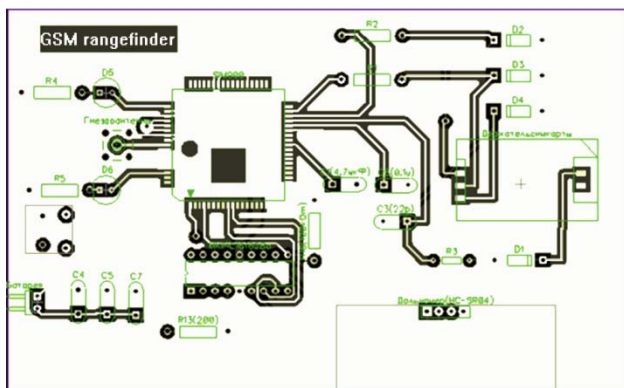
Thus, the microcontroller is in sleep mode while waiting for the “Ring” call and will “wake up” when interruptions occur from the contact of the module UART_RI(4), which reduces the power consumption of the device.

The application for the PIC16F628A microcontroller was downloaded using the PICkit 2v2.61 utility and the PICkit 2 programmer. Next, we describe which microcontroller pins should be connected to the outputs of the programmer for flashing the program:

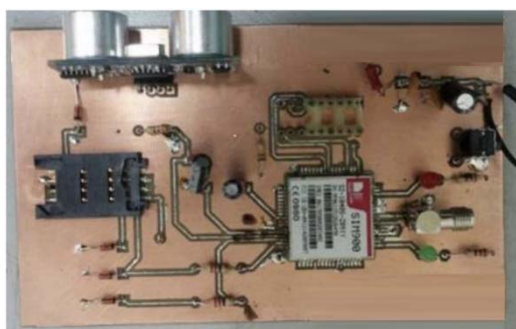
- 1 – MCLR/Vpp;
- 2 – Vdd Target;
- 3 – Vss (ground);
- 4 – PGD (ICSPDAT);
- 5 – PGC (ICSPCLK);
- 6 – PGM (LVP).

3.4 Creating a PCB for the distance measurement module

For this device, according to the above scheme (Fig. 3), a printed circuit board was created using laser-iron technology. The board drawing was made using the DipTrace PCB program, which has auto-positioning and auto-trace functions. The circuit board diagram is depicted in DipTrace (Fig. 5 a).



a



b

Figure 5 – Range measurement module PCB

Fiberglass board of the range measurement module measuring 13 cm × 8 cm in size (Fig. 5 b).

Images of the tracks, pins, and board elements were generated as a template using PCB design programs such

as DipTrace and then printed on A4 glossy paper for transfer to fiberglass during board manufacturing.

After that, the workpiece was prepared, namely, the surface of the fiberglass was cleaned with fine sandpaper and degreased with lotexolite, carefully placing it on the workpiece and smoothing it with an iron for 3–5 minutes. Then the paper is moistened with water and carefully removed. The workpiece was etched in a solution of ferric chloride prepared in a ratio of 1:1 with water.

Therefore, to increase accuracy, it is proposed to formalize the process of correcting measurements.

A mathematical model of autocalibration is proposed, which will be based on a statistical analysis of the discrepancies between the measured and reference values. The key idea is to determine the systematic error of the sensor and its subsequent compensation.

Therefore, the mathematical model of autocalibration of an ultrasonic sensor is a multicomponent approach to improving the accuracy of measurements by statistically correcting systematic errors.

The concept of the model is:

- analysis of discrepancies between measured and reference values;
- formalization of the process of determining errors;
- development of a mechanism for adaptive correction of measurements;
- taking into account the influence of external factors on the accuracy of measurements.

The experiments section presents the results of the measurements made with HC-SR04 and the reference values that were compared. These comparisons are the basis for the development of the autocalibration method.

The general mathematical model can be represented as a functional mapping:

$$Y_{cal} = F(Y_{pr}, E, T, H, L_A). \quad (1)$$

External conditions E include: atmospheric parameters (air pressure, density of the medium, presence of air currents); geometric characteristics of the environment (presence of physical obstacles, distance to objects, configuration of space); external physical influences (electromagnetic fields, acoustic background, vibrations).

Let’s formalize the process of determining errors. The component of systematic error can be represented as:

$$\begin{aligned} \varepsilon_{sys} &= f(Y_{pr}, T, H, L_A) = \\ &= \alpha \cdot T + \beta \cdot H + \gamma \cdot L_A + \theta \cdot Y_{pr}. \end{aligned} \quad (2)$$

The accuracy of the HC-SR04 ultrasonic sensor is key to its effective use in real-world applications. Minor errors in the operation of the sensor can accumulate, affecting the overall quality of the system. To ensure reliable operation of the system, it is important to take into account the errors (systematic or random) that occur during measurements. Therefore, systematic errors can be presented in the form of:

$$\sigma(\varepsilon) = \sqrt{\sum_{i=1}^m (Y_{mes,i} - Y_{ref,i})^2 \cdot w(T, H, L_A) / m}. \quad (3)$$

We will take into account the weight function of external factors $w(T, H, L_A)$, which allows us to estimate their influence on the variance of errors

The algorithm for the process of correcting ultrasonic sensor measurements is shown in Fig. 6.

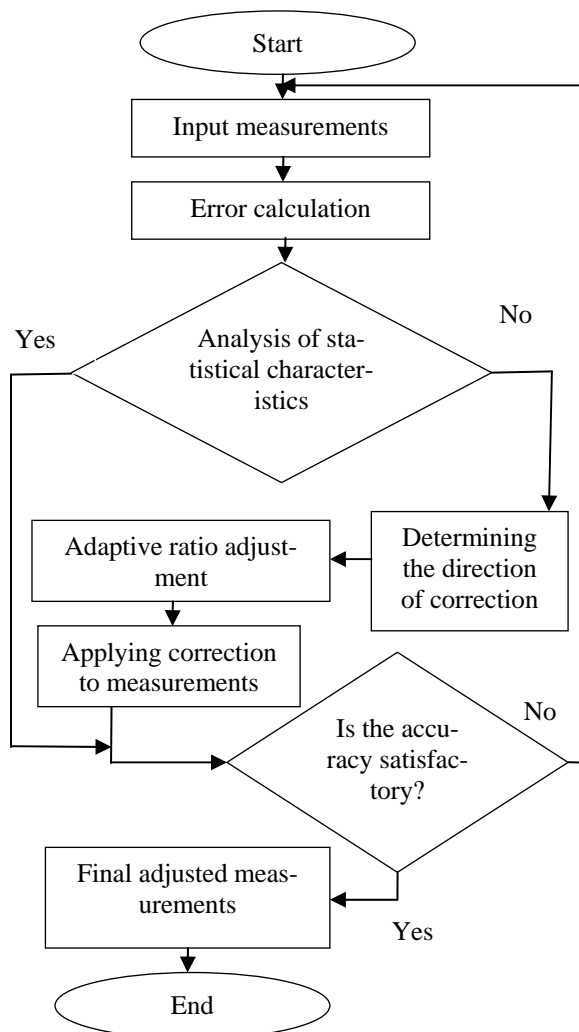


Figure 6 – Algorithm of the ultrasonic sensor measurement correction process

Step 1. Input measurements.

Step 2. Calculation of errors.

Розрахунок абсолютної похибки:

$$\varepsilon = |Y_{mes} - Y_{ref}|. \quad (4)$$

The relative error can be determined:

$$\delta = (|Y_{mes} - Y_{ref}|) / Y_{ref} \cdot 100\%. \quad (5)$$

Step 3. Analysis of statistical characteristics includes verification:

- the average value of the error > 0.1 , then the systematic error. If the average error value is ≤ 0.1 , then the error is within the normal range;

- variance of errors $>$ critical value, then this is a significant random error. If the variance \leq of a critical value, then the stability of the measurements;

- distribution asymmetry $\neq 0$, then, nonlinearity of errors. If the distribution asymmetry $= 0$, then the symmetric error distribution;

- the Shapiro-Wilk criterion $p_{SW} < 0.05$, then there is a deviation from the normal distribution. If the Shapiro-Wilk criterion $p_{SW} \geq 0.05$, then the normal error distribution.

Step 4. If the analysis of statistical characteristics showed that the obtained values of the monitored parameters (average error value, etc.) are not within the normal range, then the direction of correction is determined. This stage involves an analysis of the nature of the detected errors in order to choose the optimal approach to their compensation:

- if the average value of the error exceeds the norm, this indicates the presence of a systematic error. The direction of correction will be aimed at reducing this systematic component;

- if the error variance is too high, this indicates a significant random error. In this case, the direction of correction will be aimed at reducing the influence of random factors;

- analysis of the asymmetry of the error distribution helps to identify the presence of nonlinearities, which is also taken into account when determining the direction of correction;

- if the Shapiro-Wilk criterion < 0.05 , then there is a deviation from the normal distribution. In this case, it is necessary to apply other approaches to modeling and compensation for errors that are not based on the assumption of a normal distribution. For example, robust statistical methods can be used, which are less sensitive to deviations from normality. This will allow you to correctly take into account the peculiarities of the real distribution of errors when developing an automatic calibration algorithm.

If the statistical characteristics of the errors are within the normal range, that is, they show the stability of the measurements, then the next step should be to check the accuracy. The application of additional correction will not be necessary. After checking the accuracy, if it meets the requirements, it will be possible to complete the autocalibration process.

Step 5. Adaptive adjustment of correction coefficients based on the analysis of errors. This stage is key, as it allows you to dynamically adjust the compensation parameters depending on the current state of the measuring system.

The concept of adaptive coefficient adjustment will take into account the following factors:

- current statistical characteristics of errors (mean, variance, asymmetry);

- changes in external conditions that affect the sensor.

For example, if the analysis revealed the presence of a systematic component of error, the compensation coefficient will be increased to reduce this component.

Thus, the adaptive approach allows you to flexibly respond to changes in the operation of the sensor and optimally adjust the correction parameters to ensure high accuracy of measurements in real operating conditions.

Step 6. Step 6 consists of applying the calculated correction to the sensor's output measurements. At this stage, the adaptive correction coefficients determined in the previous step are used to compensate for systematic and random errors.

Thus, the initial uncorrected sensor readings are processed using the calculated correction coefficients, which allows you to obtain corrected, more accurate measurement values. This step completes the autocalibration process, providing an increase in the overall accuracy of the ultrasonic sensor.

Let the systematic error of the sensor be represented by the formula (2). Then the adjustment factor to compensate for the systematic error is calculated as:

$$K_{cor} = 1 / (1 + \varepsilon_{sys}) . \quad (6)$$

To compensate for the random component of the error, the correction factor is determined based on the variance of the errors:

$$K_{rec} = 1 / \sqrt{\sigma} . \quad (7)$$

If the analysis shows the presence of nonlinearities in the error distribution, i.e. asymmetry, or deviations from the normal distribution according to the Shapiro-Wilk criterion, this means that the errors cannot be compensated by linear correction coefficients alone. In general, deviation from normality requires the use of robust statistical analysis methods and appropriate nonlinear error-side compensation algorithms. This will allow you to more effectively take into account the real features of the distribution of sensor errors.

Step 7. Accuracy check. Accuracy verification is the final stage of the autocalibration process and is aimed at evaluating the effectiveness of the developed error correction methods. The main goal of this stage is to confirm that the applied correction algorithms have improved the accuracy of the ultrasonic sensor measurements. The procedure for checking accuracy usually consists of the following sub-stages:

1. Collection of new test data. At this stage, new measurements are made using the sensor after making adjustments. These measurements are compared with reference values. Reference values are usually obtained from high-precision systems or using special calibration equipment.

2. The residual errors are calculated after applying the correction factors:

$$\varepsilon_{res} = Y_{cal} - Y_{ref} . \quad (8)$$

3. Analysis of statistical characteristics of residual errors.

First, key parameters are evaluated, namely:

- average value of residual errors ($\bar{\varepsilon}$). If $\bar{\varepsilon} \approx 0$, this indicates the minimization of the systematic error;

- dispersion of residual errors (σ^2). If σ^2 has decreased significantly compared to the initial data, this means effective compensation for random errors;

- asymmetry (Skewness) and excess (Kurtosis). If the asymmetry (Skewness) is close to 0, and the excess (Kurtosis) is 3 (or close to 3), this confirms the normal distribution of residual errors;

- Shapiro-Wilk criterion p_{SW} . If $p_{SW} \geq 0.05$, the residual errors are normally distributed, which is a good indicator.

4. Comparison before and after correction. The key accuracy metrics before and after the application of correction algorithms are compared:

- standard error (RMSE):

$$RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^m (Y_{cal,i} - Y_{ref,i})^2} . \quad (9)$$

A decrease in $RMSE$ confirms the success of the correction.

The coefficient of determination (R^2) analyzes how much the adjusted values correspond to the reference values.

5. Assessment of the admissibility of residual errors. It is checked whether the residual errors are within the permissible range. If they go beyond these limits, it is necessary to reconfigure the correction algorithm.

Thus, the accuracy check covers the calculation of residual errors, their statistical analysis, visualization and comparison of results before and after correction. This allows you to evaluate the effectiveness of autocalibration and confirm the achievement of the required level of accuracy.

Step 8. Obtaining final corrected measurements.

A more in-depth analysis of the mathematical model of autocalibration will be presented in this paper.

4 EXPERIMENTS

A series of experimental studies were carried out to evaluate the accuracy and reliability of the developed distance measurement module. The main purpose of the experiments was to compare the indicators of the HC-SR04 ultrasonic sensor with reference measurements made using a ruler.

The methodology of the experiment included the following stages:

- preparation of an experimental bench consisting of a developed distance measurement module and a reference ruler;
- installation of the measuring object at different distances in the range of up to 15 cm;
- distance measurements using the HC-SR04 ultrasonic sensor;
- parallel distance measurement using a ruler to obtain reference values;
- distance measurements using the Sharp GP2Y0A21YK0F optical sensor;
- recording and comparing the results obtained;
- analysis of the obtained data: plotting the presence of the measured distance from the real one for both sensors and determining the ranges of greatest accuracy for each type of sensor.

It is necessary to take into account the influence of various environmental conditions on the accuracy of distance measurement:

- in environments with a high noise level, false alarms are possible;
- the sensor can be sensitive to changes in temperature and humidity, which can affect the speed of propagation of ultrasonic waves;
- measurement efficiency may decrease when working with soft or porous surfaces that reflect ultrasonic waves worse;
- the accuracy of measurements can be affected by the angle of inclination of the surface relative to the sensor;
- the presence of other ultrasonic sources nearby can create interference and lead to inaccurate measurements;
- the sensor has a “blind spot” at very close distances (usually less than 2 cm), where it cannot accurately measure the distance.

5 RESULTS

The measured distance of the HC-SR04 was compared with the ruler and the Sharp GP2Y0A21YK0F, the results were entered in Table 1.

Table 1 – Measurement results

Measured distance on HC-SR04, cm	Distance on the ruler, cm	Measured percentage on Sharp GP2Y0A21YK0F, cm
2	2	2
3	3	3
4	4	4
6	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	11
12	11	12,1
12	12	13
13	13	14,3
15	14	15,4
15	15	16

Graphs of the dependence of the measured distance on the real one for both sensors are plotted in Fig. 6.

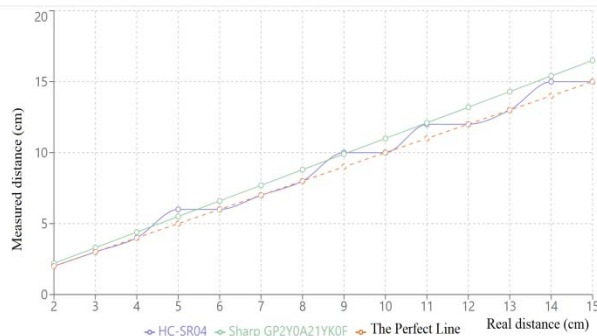


Figure 6 – Graph of the dependence of the measured distance on the real distance for HC-SR04 and Sharp GP2Y0A21YK0F

The analysis of the results of experiments showed that the accuracy of measurements depends on several factors:

1. The characteristics of the reflective surface because different materials can reflect ultrasonic waves differently, which affects the accuracy of measurements.
2. Measurement mediums because the speed of sound can vary depending on temperature, humidity and other environmental parameters.
3. Measurement errors. The measurement error of this range meter device on an ultrasonic sensor is ± 1 cm.

The results obtained confirm the high accuracy and reliability of the developed module based on the HC-SR04 for measuring distances in the range of up to 15 cm.

Comparison with the Sharp GP2Y0A21YK0F optical sensor demonstrates the advantages of the ultrasonic method in the context of measurement stability and less sensitivity to external factors.

6 DISCUSSION

The results of experiments carried out with the developed distance measurement module based on the HC-SR04 ultrasonic sensor demonstrate the high accuracy and reliability of the device. However, the data obtained require detailed analysis and interpretation in the context of potential applications and limitations of the technology.

Comparison of the readings of the ultrasonic sensor with the reference measurements with the ruler showed that the measurement accuracy is within ± 1 cm. This is an acceptable result for many practical applications, especially given the low cost and ease of implementation of the device.

However, it is worth noting that at distances of 9–11 cm, some deviations were observed. This may be due to the peculiarities of the propagation of ultrasonic waves or the specifics of a particular sensor sample. To increase accuracy at these distances, you can consider calibrating the sensor or using additional data processing algorithms.

Let's compare with other analogs. For example, compared to optical sensors such as infrared distance sensors, the HC-SR04 ultrasonic sensor has the advantage that it is less sensitive to the illumination and color of objects. This makes it more versatile for a variety of applications.

However, laser rangefinders usually provide higher measurement accuracy. However, they are significantly

more expensive and may have limitations when working with transparent or mirrored surfaces.

For a more detailed analysis, consider comparing the HC-SR04 with the common Sharp GP2Y0A21YK0F optical sensor.

Table 2 – Comparison of HC-SR04 and Sharp GP2Y0A21YK0F

Characteristic	HC-SR04 (Ultrasonic) [12, 13]	Sharp GP2Y0A21YK0F (Optical) [12, 13]
Measurement range	2 cm – 400 cm	10 cm – 80 cm
Accuracy	±3 mm	±10 % of the measured distance
Response time	~60 ms	~39 ms
Supply voltage	5V	4.5 V – 5.5 V
Current consumption	~15 mA (active mode)	~30 mA
Object color sensitivity	Low	High
Sensitivity to transparent objects	High	Low
Exposure to outdoor lighting	Low	High
Sizes	45 x 20 x 15 mm	29.5 x 13 x 13.5 mm
Price (approx.)	\$2–\$5	\$10–\$15

Analyzing the data from the table, the following conclusions can be drawn:

- the measurement range of the HC-SR04 is a much wider measurement range, which makes it more versatile for different applications;
- the accuracy of the HC-SR04 is higher, especially at longer distances.
- the speed of the optical sensor has a slightly better response time, which can be critical for some applications;
- the HC-SR04 has low power consumption, making it an ideal choice for energy-efficient and stand-alone devices. This allows the sensor to be used in battery-powered systems, ensuring long-term operation without the need for frequent maintenance or recharging. Thanks to this, the device can function effectively in remote places or in conditions where there is no constant power source;
- sensitivity to external factors in HC-SR04 it is less to the color of the object and ambient light, but it may have problems detecting transparent objects;
- dimensions and cost. The HC-SR04 is somewhat larger in size, but significantly cheaper.

The choice between these two types of sensors depends on the specific application. The HC-SR04 is the preferred choice for general use, especially in variable lighting environments or when working with objects of different colors. However, for applications that require high performance or working with transparent objects, an optical sensor may be the preferred choice.

Despite the overall effectiveness of the developed module, there are certain limitations that should be taken into account:

1. The maximum measurement distance is limited to 4 meters, which may not be sufficient for some applications.

2. Ultrasonic waves may not bounce off soft or porous surfaces as efficiently, which may affect the accuracy of measurements.

3. Influence of various environmental conditions on the accuracy of measurements In environments with a high noise level, false positives are possible.

Overall, the developed distance measurement module demonstrates high potential for practical applications, providing a balance between accuracy, ease of implementation and cost-effectiveness.

CONCLUSIONS

An urgent problem has been solved: the development of a range measurement module on an ultrasonic sensor with a GSM module, which allows for accurate distance measurement and transmission of results to remote servers or directly to end users.

The scientific novelty of the results obtained lies in the fact that a mathematical model of autocalibration of an ultrasonic sensor has been proposed. The key benefits of this approach are:

1. Comprehensive statistical error analysis, since the model allows you to detect and compensate for both systematic and random errors of the sensor based on the analysis of discrepancies between measured and reference values.
2. Adaptive correction because the proposed mechanism for adaptive adjustment of correction coefficients provides a flexible response to changes in external conditions that affect the accuracy of measurements.
3. Taking into account the influence of factors, because the model takes into account the influence of temperature, humidity, interference, etc., on sensor errors, which increases the efficiency of compensation.
4. Formalization of the process, since the presentation of a mathematical model in the form of clear equations and algo-rhythmic steps provides structure and the possibility of further improvement of the method.

In general, this approach allows you to significantly increase the accuracy of the ultrasonic sensor in real operating conditions due to comprehensive statistical error correction. The formalization of the model in mathematical form is an innovative step that contributes to the effective practical application of the method.

The practical value of the results obtained lies in the creation of a cost-effective solution for remote distance measurement, because the developed module combines an inexpensive HC-SR04 ultrasonic sensor with a GSM module, which allows remote measurements at an affordable price. This is especially useful for small businesses and individual developers in the field of radio electronics. The development can expand the capabilities of telecommunication systems because the integration of the GSM module allows you to transmit measurement data over a cellular network, expanding the scope of application of the device in telecommunication systems. This makes it

possible to monitor over long distances without the need for additional communications. Optimization of power consumption lies in the fact that the developed algorithm of the module, which provides for sleep mode and activation on an incoming call, can significantly reduce the power consumption of the device. This is crucial for autonomous systems in radio electronics and telecommunications.

Thus, an integrated range measurement module has been developed, which combines the HC-SR04 ultrasonic sensor with a GSM module, which allows for accurate remote measurement and data transmission in real time.

The experiments carried out using real data demonstrate the effectiveness of the developed module. A comparative analysis with an optical sensor showed that the developed module based on HC-SR04 is less sensitive to external factors (lighting, object color), which increases the reliability of measurements in various operating conditions.

A wide range of measurements (up to 4 m) and the ability to work with different types of surfaces makes the module versatile for many tasks in radio electronics, from industrial automation to security systems. Therefore, the results obtained make a significant contribution to the development of radio electronics.

Prospects for further research are as follows:

1. Integration of additional sensors (e.g. infrared) to increase the reliability of measurements.
2. Develop machine learning algorithms to improve accuracy and noise filtering.
3. Optimization of power consumption to increase the autonomy of the device

REFERENCES

1. Sotnik S. V., Redkin K. S. Design features of control panels and consoles in automation systems, *The 9th International scientific and practical conference "Science and innovation of modern world" (May 18–20, 2023) Cognum Publishing House*. London, United Kingdom. – 2023. – P. 201–205
2. Sotnik S. V. Development of automated control system for continuous casting, *Radio Electronics, Computer Science, Control*, 2024, № 2(69), pp. 181–189. DOI: 10.15588/1607-3274-2024-2-18
3. Polikanov K. et al. Smart home with house module: overview of automation technologies / K. Polikanov // *International Conference "DIGITAL INNOVATION & SUSTAINABLE DEVELOPMENT 2024"*, 2024, pp. 20–21
4. Sukhno P. et al. Critical review of GSM network structure, *Manufacturing & Mechatronic Systems 2024: Proceedings of VIII st International Conference*. Kharkiv, October 25–26, 2024, 2024, pp. 37–41
5. Abdulkhaleq N. I., Hasan I. J., Salih N. A. J. Investigating the resolution ability of the HC-SR04 ultrasonic sensor, *IOP Conference Series: Materials Science and Engineering*, 2020, T. 745, №. 1, pp. 1–8. DOI: 10.1088/1757-899X/745/1/012043
6. Al Tahtawi A. R. Kalman filter algorithm design for hc-sr04 ultrasonic sensor data acquisition system, *IJITEE (International Journal of Information Technology and Electrical Engineering)*, 2018, T. 2, №. 1, pp. 15–19
7. Rihmi M. K. et al Accuracy Analysis of Distance Measurement Using Sonar Ultrasonic Sensor HC-SR04 on Several Types of Materials, *Journal of Environmental Engineering and Sustainable Technology*, 2024, T. 11, № 01, pp. 10–13
8. Qi J., Liu G. P. A robust high-accuracy ultrasound indoor positioning system based on a wireless sensor network, *Sensors*, 2017, No. 17(11), pp. 1–17. DOI: 10.3390/s17112554
9. Mocanu B., Tapu R., Zaharia T. When ultrasonic sensors and computer vision join forces for efficient obstacle detection and recognition, *Sensors*, 2016, No. 16 (11), pp. 1–23. DOI: 10.3390/s16111807
10. Mohammad T. Using ultrasonic and infrared sensors for distance measurement, *World academy of science, engineering and technology*, 2009, T. 51, pp. 293–299
11. Aliew F. An approach for precise distance measuring using ultrasonic sensors, *Engineering Proceedings*, 2022, T. 24, № 1, pp. 1–9. DOI: 10.3390/IECMA2022-12901
12. Suh Y. S. Laser sensors for displacement, distance and position, *Sensors*, 2019, T. 19, №. 8, pp. 1–4. DOI: 10.3390/s19081924
13. de Bakker B. How to use a SHARP GP2Y0A21YK0F IR Distance Sensor with Arduino, *Makerguides. com.*, 2019, pp. 1–20
14. Khaleel H. Z., Raheem F. A. Design and Implementation Accurate Three Distance Sensors Device Using Neural Network, *Tikrit Journal of Engineering Sciences*, 2024, T. 31, №. 2, pp. 138–147. DOI: 10.25130/tjes.31.2.13
15. Soni A., Aman A. Distance Measurement of an Object by using Ultrasonic Sensors with Arduino and GSM Module, *International Journal of Science Technology & Engineering*, 2018, T. 4, №. 11, pp. 23–28
16. Gbotoso G. A. Development of distance measurement using ultrasonic based sensors, *International Journal of Engineering Research Updates*, 2024, No. 06(02), pp. 35–40. DOI: 10.53430/ijeru.2024.6.2.0028
17. Sharma J., Abrol P. Design and Implementation of digital distance measurement system using ultrasonic sensor, *International journal of research in electronics and computer engineering*, 2014, No. 2(3), pp. 27–30
18. Morgan E. J. HC-SR04 ultrasonic sensor. Nov., 2014, pp. 1–6

Received 03.02.2025.
Accepted 19.04.2025.

РОЗРОБКА МОДУЛЯ ВИМІРЮВАННЯ ДАЛЬНОСТІ НА УЛЬТРАЗВУКОВОМУ ДАТЧИКУ З GSM МОДУЛЕМ

Сотник С. В. – канд. техн. наук, доцент, доцент кафедри комп'ютерно-інтегрованих технологій, автоматизації та робототехніки Харківського національного університету радіоелектроніки, Харків, Україна.

АНОТАЦІЯ

Актуальність. Розробка модуля вимірювання дальності на основі ультразвукового датчика з GSM модулем є надзвичайно актуальною у сфері телекомунікацій та радіоелектроніки. У сучасному світі все більша кількість пристроїв інтегрується в системи Інтернету речей (IoT), де передача даних на великі відстані забезпечують телекомунікаційні технології. Використання GSM модуля дозволяє в режимі реального часу передавати інформацію з вимірювального пристрою на віддалені сервери або кінцевим користувачам, що є критичним для рішень у сфері дистанційного моніторингу та контролю.

Ультразвукові датчики у поєднанні з GSM модулем можуть дозволяти автоматизувати процеси вимірювання у важкодоступних або небезпечних для людини умовах, що підвищує ефективність та безпеку систем. Застосування радіоелектронних технологій для передачі вимірювальних даних у реальному часі дозволяє значно розширити функціональність пристроїв, полегшити їхню інтеграцію у вже існуючі системи телекомунікацій, зокрема у промислових, транспортних, та інфраструктурних секторах.

Таким чином, розробка даного модуля з точними вимірами сприяє розвитку інновацій у галузі телекомунікацій та радіоелектроніки, забезпечуючи швидку та надійну передачу даних, що є важливою складовою сучасних інформаційних систем.

Мета. Розробка модуля вимірювання дальності на основі ультразвукового датчика з GSM-модулем та підвищення точності вимірювань шляхом впровадження запропонованої математичної моделі автокалібрування ультразвукового датчика.

Метод. Для досягнення поставленої мети був розроблений інтегрований модуль вимірювання дальності, який поєднує ультразвуковий датчик HC-SR04 з GSM-модулем. Метод підвищення точності базується на запропонованій математичній моделі автокалібрування ультразвукового датчика.

Результати. Здійснена постановка задачі та розроблено модуль вимірювання дальності на основі ультразвукового датчика з інтегрованим GSM-модулем. У ході дослідження було створено електричну принципову схему пристрою за допомогою програмного забезпечення DipTrace. Розроблено алгоритм роботи модуля, який оптимізує взаємодію між ультразвуковим датчиком. Створено друковану плату. Запропоновано математичну модель автокалібрування ультразвукового датчика для підвищення точності вимірювання. Проведено серію експериментальних досліджень для оцінки точності. Результати експериментів підтвердили ефективність розробленого модуля для вимірювання відстаней.

Висновки. Розроблений модуль вимірювання дальності на основі ультразвукового датчика з GSM-модулем представляє собою інноваційне рішення, що відповідає сучасним вимогам телекомунікаційних та радіотехнічних систем. Інтеграція точного вимірювання відстані на базі запропонованої математичної моделі автокалібрування ультразвукового датчика з можливістю дистанційної передачі даних відкриває нові перспективи для дистанційного моніторингу та автоматизації процесів. Експериментальні дослідження підтвердили точність та надійність пристрою, а порівняльний аналіз з аналогами продемонстрував його конкурентні переваги. Економічна ефективність та енергоощадність розробленого модуля роблять його привабливим для широкого кола користувачів, від індивідуальних розробників до промислових підприємств. Подальші дослідження можуть бути спрямовані на вдосконалення алгоритмів обробки даних та розширення функціональних можливостей пристрою, що сприятиме розвитку інноваційних технологій у сфері радіоелектроніки та телекомунікацій.

КЛЮЧОВІ СЛОВА: дальність, вимірювання, модуль, ультразвуковий датчик, GSM модуль.

ЛІТЕРАТУРА

1. Sotnik S. V. Design features of control panels and consoles in automation systems / S. V. Sotnik, K. S. Redkin // The 9th International scientific and practical conference "Science and innovation of modern world" (May 18–20, 2023) Cognum Publishing House, London, United Kingdom. – 2023. – P. 201–205
2. Sotnik S. V. Development of automated control system for continuous casting / S. V. Sotnik // Radio Electronics, Computer Science, Control. – 2024. – № 2(69). – P. 181–189. DOI: 10.15588/1607-3274-2024-2-18
3. Polikanov K. Smart home with house module: overview of automation technologies / [K. Polikanov et al.] // International Conference "DIGITAL INNOVATION & SUSTAINABLE DEVELOPMENT 2024". – 2024. – P. 20–21
4. Sukhno P. Critical review of GSM network structure / [P. Sukhno et al.] // Manufacturing & Mechatronic Systems 2024: Proceedings of VIII st International Conference, Kharkiv, October 25–26, 2024. – 2024. – P. 37–41
5. Abdulkhaleq N. I. Investigating the resolution ability of the HC-SR04 ultrasonic sensor / N. I. Abdulkhaleq, I. J. Hasan, N. A. J. Salih // IOP Conference Series: Materials Science and Engineering. – 2020. – T. 745, №. 1. – P. 1–8. DOI: 10.1088/1757-899X/745/1/012043
6. Al Tahtawi A. R. Kalman filter algorithm design for hc-sr04 ultrasonic sensor data acquisition system / A. R. Al Tahtawi // IJITEE (International Journal of Information Technology and Electrical Engineering). – 2018. – T. 2, №. 1. – P. 15–19
7. Rihmi M. K. Accuracy Analysis of Distance Measurement Using Sonar Ultrasonic Sensor HC-SR04 on Several Types of Materials / [M. K. Rihmi et al.] // Journal of Environmental Engineering and Sustainable Technology. – 2024. – T. 11, №. 01. – P. 10–13
8. Qi J. A robust high-accuracy ultrasound indoor positioning system based on a wireless sensor network / J. Qi, G. P. Liu // Sensors. – 2017. – No. 17(11). – P. 1–17. DOI: 10.3390/s17112554
9. Mocanu B. When ultrasonic sensors and computer vision join forces for efficient obstacle detection and recognition / B. Mocanu, R. Tapu, T. Zaharia // Sensors. – 2016. – No. 16 (11). – P. 1–23. DOI: 10.3390/s16111807
10. Mohammad T. Using ultrasonic and infrared sensors for distance measurement / T. Mohammad // World academy of science, engineering and technology. – 2009. – T. 51. – P. 293–299
11. Aliew F. An approach for precise distance measuring using ultrasonic sensors / F. Aliew // Engineering Proceedings. – 2022. – T. 24, №. 1. – P. 1–9. DOI: 10.3390/IECMA2022-12901
12. Suh Y. S. Laser sensors for displacement, distance and position / Y. S. Suh // Sensors. – 2019. – T. 19, №. 8. – P. 1–4. DOI: 10.3390/s19081924
13. de Bakker B. How to use a SHARP GP2Y0A21YK0F IR Distance Sensor with Arduino / B. de Bakker // Makerguides. com. – 2019. – P. 1–20.
14. Khaleel H. Z. Design and Implementation Accurate Three Distance Sensors Device Using Neural Network / H. Z. Khaleel, F. A. Raheem // Tikrit Journal of Engineering Sciences. – 2024. – T. 31, №. 2. – P. 138–147. DOI: 10.25130/tjes.31.2.13
15. Soni A. Distance Measurement of an Object by using Ultrasonic Sensors with Arduino and GSM Module / A. Soni, A. Aman // International Journal of Science Technology & Engineering. – 2018. – T. 4, №. 11. – P. 23–28.
16. Gbotoso G. A. Development of distance measurement using ultrasonic based sensors / G. A. Gbotoso // International Journal of Engineering Research Updates. – 2024. – No. 06(02). – P. 35–40. DOI: 10.53430/ijeru.2024.6.2.0028
17. Sharma J. Design and Implementation of digital distance measurement system using ultrasonic sensor / J. Sharma, P. Abrol // International journal of research in electronics and computer engineering. – 2014. – No. 2(3). – P. 27–30.
18. Morgan E. J. HC-SR04 ultrasonic sensor / E. J. Morgan. – Nov. – 2014. – P. 1–6.