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Bohdan BORIAK, Alina YANKO, Oleksandr LAKTIONOV

National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine

MODEL OF AN AUTOMATED CONTROL SYSTEM FOR THE POSITIONING OF RADIO SIGNAL TRANSMISSION/RECEPTION DEVICES

The concept of automated control systems for positioning radio-signal transmission and reception devices is discussed in this article. The ***subjects*** *of this article are methods and means for ensuring precise and stable antenna positioning using web-based controllers with integrated sensors and actuators. This research* ***aimed*** *to develop a model of an automated control system for the positioning of radio signal transmission/reception antennas, including directional antennas with a radiation pattern angle of 60-90 degrees, ensuring the minimization of azimuth positioning error. The* ***objective*** *of this research is to develop automated antenna positioning systems using embedded systems. This article provides an example of the system's operation, where the controller performs antenna positioning tasks with high accuracy for directional antennas, such as Yagi–Uda antennas, ensuring that the azimuth position control error does not exceed 15 degrees. Positioning accuracy is achieved by a calibration procedure and dynamic servomotor adjustment based on the magnetometer data. This system is designed to ensure communication for operating a mobile robotic platform (unmanned vehicles), particularly in the presence of electromagnetic interference. Reliable communication with an unmanned vehicle depends on the positioning of the communication elements. It is a necessary condition for the operation of a mobile robotic platform, which, according to the classification by size groups, belongs to Micro, Mini, and Midi categories of wheeled vehicles and is used in search, rescue, and military operations. The* ***result*** *of the research is the development of the system, as well as its implementation and testing under laboratory conditions, which confirms the operability of the proposed control system model.* ***Conclusions****. This article discusses the concept of an automated control system for antenna positioning based on the use of embedded web technologies and their integration with hardware components that ensure precise positioning of radio-signal transmission/reception devices.*

Keywords: *control system; antenna positioning; electromagnetic interference; real-time control; web-based control; unmanned vehicles; mobile robotic platform.*

1. Introduction

The control of unmanned vehicles (UVs), unmanned ground vehicles (UGVs), and unmanned aerial vehicles (UAVs) is carried out in two main modes: manual control by an operator and automatic operation. Regardless of the chosen mode, the controllability and safety of unmanned vehicles are the main tasks.

There are different directions of UVs and UAVs operation automation, such as optimal pathfinding [1, 2] or the implementation of machine vision systems [3-5]. One of these areas is the dynamically developing direction of intelligent transport, where UV control is based on the Internet of Things (IoT) and artificial intelligence. IoT provides interchange data between UVs and traffic control centers, providing all the necessary information about the movement trajectory and existing obstacles on the path in real time. At the same time, accurate data control is realized for intelligent decision-making and UV path planning [6].

However, the execution of tasks by unmanned vehicles in open terrain significantly complicates the implementation of an automatic control system, and in these conditions, a manual control mode is usually used [7]. A critical aspect of the manual control mode is the assurance of constant and reliable radio communication between the operator's station and the UV. This is necessary for transmitting the video signal, which provides the operator with spatial orientation, and for transmitting the control signal.

The use of UVs for various tasks requires the development of operator station infrastructures, specific elements of which are discussed in this paper.

This article discusses aspects of ensuring communication between an operator and wheeled unmanned ground vehicles (UGV) [8], which, according to the classification by size groups [9], belong to the Micro, Mini, and Midi classes that can be used in search, rescue, and military operations.

1.1. Motivation

The analysis of unmanned vehicle usage indicates several issues related to the positioning of signal transmission/reception devices, which can lead to temporary loss of communication with the unmanned vehicle or even the loss of the vehicle itself [10]. The use of unmanned vehicles can be complicated in conditions in which the electromagnetic spectrum is actively used, creating interference for electronic devices [11].

Ground operator stations equipped with antennas and video signal reception devices are used to transmit control signals and receive video signals from unmanned platforms. The use of fixed antennas may be ineffective when performing a wide range of tasks, as well as when the operator needs to adapt to the terrain and environmental features of the robot platform being used [12]. When an unmanned vehicle is used under conditions of interference, this may result in partial or complete loss of communication with the vehicle. To restore communication, the operator may direct the vehicle beyond the range of the radio signals. When using directional antennas in ground stations, which can be employed to extend the range of unmanned vehicles, the chances of losing communication increase because of the limited width of the antenna's radiation pattern [13].

The antenna positioning problem can be addressed by implementing a rotational mechanism. The necessity of implementing the operation of a rotational positioning mechanism also indicates the need to develop a control system for antenna rotation mechanisms.

1.2. State of the Art

In the context of the rapid development of both ground and unmanned aerial vehicles for various tasks, various antenna tracking systems have been developed. Most of these systems are used specifically for unmanned aerial vehicles, but they can also be applied to ground-based unmanned vehicles.

A previous study [14] proposed an antenna tracking system for use during an unmanned aerial vehicle (UAV) monitoring mission in disaster areas. Because the mission covers a large area, standard omnidirectional antennas are limited in range. Therefore, a high-efficiency directional antenna was used. However, directional antennas require constant UAV orientation. To address this issue, a two-axis antenna tracking system was developed, which automatically adjusts its position using a microcontroller and GPS. This ensures stable communication between the UAV and the ground station with minimal signal loss.

Another study addressing the task of tracking UAVs was described in the article [15]. The system provides real-time autonomous antenna orientation based on Global Positioning System (GPS) data from a UAV. A discrete proportional controller based on computed torque was proposed to control the system and manage two axes (pan and tilt). The simulation results showed that this system is suitable for mobile ground stations and can effectively track UAVs with high accuracy and stability, ensuring minimal antenna orientation errors.

The proposed systems for automating the positioning process rely on GPS data from UAVs. However, when the UAV operates in the presence of interference, the GPS signal may be lost.

Ensuring high-quality communication requires an appropriate signal-to-noise ratio at the receiving point, which is limited by the receiver's sensitivity. This condition can be achieved in various ways. A well-known approach to solving this problem under incomplete, under conditions of incomplete and inaccurate data about interference levels was discussed in the work [16] and was based on adaptive regulation of the power of transmitted radio signals. However, this approach requires precise tuning of the prediction systems, which is not always feasible. Therefore, this paper suggests focusing on the possibility of achieving high values for other characteristics that are part of the main radio transmission equation, specifically: the directional gain of the antennas of the respective devices.

In recent years, interest in using alternative mathematical models based on innovative counting systems has increased. One such system is the system of residual classes that enables parallel and highly reliable processing of integer data. It can significantly improve the speed and reliability of command processing, system survivability, and flexibility of control for both ground-based and unmanned aerial vehicles, which is particularly important for real-time systems [17]. A previous study [18] proposed a mathematical model of a fault-tolerant special-purpose real-time computer system that operates using non-positional arithmetic in residual classes. Such computer systems (CS) are non-recoverable, single-use computational systems used in various onboard digital computing systems (such as ballistic missiles) and unmanned aerial vehicles. As a result, a mathematical model was developed that is implemented through the passive fault tolerance of real-time CSs. Moreover, the proposed model is practically realized with minimal structural redundancy, which is especially important for aircraft CSs.

To conduct a thorough analytical review of the existing analogs, it is important to define the requirements and quality criteria for the antenna's positioning system. The requirements for an antenna positioning system include simplicity, ease of installation, cost-effectiveness, and the ability to operate in the presence of interference sources.

Considering the above requirements, we examined the MFD mini Crossbow system [19], which is used for the automatic antenna tracking of unmanned aerial vehicles (UAVs). The primary function of the UAV is to track and maintain communication with the UAV regardless of its movements in space. This positioning system operates based on data transmission through a video signal (VBI - Vertical Blanking Interval). The device can be used with analog video systems. A special module adds information about the drone's location to the video signal were transmitted to the ground station. This information is inserted into the intervals between video frames; thus, there is no need for a separate data transmission channel.

The operation of the MFD mini Crossbow automatic tracker during the activity of an electronic warfare (EW) source depends on several factors. Because the tracker uses an analog video signal to transmit data via VBI technology, jamming devices can interfere with or completely disrupt this process. The interference generated by the frequency used by the video link can block the signal or distort the transmitted information. If the tracker does not receive clear data from the drone via the video signal, it will be unable to accurately direct the antenna.

There are other technical solutions from MyFlyDream, such as the Crossbow AAT, whose price is more than five times higher than that of the MFD mini Crossbow. However, their performance in the presence of interference may still be unreliable.

Another solution available in the category of devices examined in this study is the ArkBird Mini AAT 5.8 GHz [20] automatic antenna tracking system, which is designed for long-range video transmission and ensures constant alignment of the high-gain ground antenna. This device realizes dual-axis positioning. According to the manufacturer's instructions, the antenna movement is adjusted automatically. The device uses GPS to determine the location of the drone and ground module. Interferences aimed at jamming or distorting GPS signals can lead to the loss of coordinates and, consequently, an inability to track accurately.

The market also offers mechanized and electromechanical manual positioning systems; the issue with which is that the operator must be near the ground station to control the system.

In summary, the market-proposed systems can provide an automatic antenna positioning system for stable communication with unmanned vehicles in the absence of signal jamming sources. Among the unresolved issues are the need for operator intervention in positioning systems when a jamming source is present in the UV's operational area or when tasks need to be performed beyond the radio signal's range. Additionally, it is crucial for operators to ensure remote control of the positioning system if the ground station is located remotely or in a hard-to-reach area. These factors highlight the relevance of this research and the necessity to develop antenna positioning systems for signal transmission and reception stations.

The methods proposed in previous studies [21] can also be applied to evaluate the quality of the interaction between the operator and the technical equipment.

1.3. Objective and Approach

This paper provides a detailed examination of the **approach** to developing a model of an antenna positioning control system for a ground station, which is used for data transmission and reception to control an unmanned vehicle. The article justifies the choice of equipment for the system prototype and highlights the technical aspects of the implementation, including the prototype itself and the system software.

The **objective** of this research is to control the positioning of antennas in ground signal transmission and reception stations using embedded systems.

The **aim** of this research is to develop a model of an antenna positioning control system for the positioning of radio signal transmission/reception antennas, including directional antennas with a radiation pattern angle of 60-90 degrees, ensuring the minimization of azimuth positioning error with an acceptable value not exceeding 15°. The system must provide monitoring position data and remote control.

In this study, the term "model of an automated control system for the positioning of radio signal transmission/reception devices" characterizes the description of the interaction between hardware and software components for the implementation of a specific system, which is presented in the form of diagrams, schemes, and algorithmic flowcharts that describe the data processing and system operation processes.

The novelty and relevance of the research conducted in this article are as follows. The **novelty** of this research is that for the first time, a model of an automated control system for the antenna positioning of a ground station with remote control and position tracking capabilities was developed. The **relevance** of this research is based on the following circumstances. First, there is a need to improve the infrastructure for the use of robotic ground systems to enhance their efficiency and range, particularly under hazardous conditions for humans. Second, existing technical solutions must be adapted to the conditions of potential interference sources. The implementation of this system will expand the capabilities of UVs and enhance their flexibility in application.

The **paper structure** is as follows.

In Section 1, "Introduction" the features of unmanned vehicle usage, their control systems, and the potential application of these control system elements in other fields are discussed, as well as radio communication systems and the infrastructure that supports the operation of robotic platforms. Studies and existing systems that address the challenges of precise antenna positioning and tracking methods are reviewed, along with key technical solutions for UV control systems.

In Section 2, “Materials and Methods of Research”, the formalized requirements for the antenna positioning system based on the analytical review are presented. This section describes the system architecture, provides justification for the hardware selection for the system prototype, and outlines the specifics of implementing the control system software.

In Section 3, "Results and Discussion," the key aspects of the infrastructure required to ensure stable communication between ground-based unmanned vehicles and control stations are presented. The structure of the control system is summarized, and the advantages and disadvantages of the proposed system are outlined.

In the final section, "Conclusions," the tasks accomplished in the study are highlighted, and future research directions are outlined in terms of ensuring stable communication between the operator and the mobile platform.

2. Materials and methods of research

2.1. Formalized Requirements for the System

Here, we define the main requirements and criteria that the system must meet:

1. Simplicity: The system should be easy to use and set up to minimize the complexity of operations and maintenance.
2. Ease of Installation: The system should be straightforward to install, with clear instructions and minimal setup time.
3. Cost-Effectiveness: The system should balance performance and cost, ensuring that it is economically viable.
4. Interference Resistance: The system must operate effectively in the presence of electromagnetic interference, including the ability to maintain communication and control.
5. Remote Operation: The system should support remote control capabilities, allowing operators to manage the positioning of antennas from a distance, especially if the ground station is located remotely or in a difficult-to-access area.
6. Data Monitoring: The system should provide real-time monitoring of positioning data and the operational status.
7. Adaptability: The system must be adaptable to different environments and conditions, including those with potential interference sources.
8. Reliability: The system should demonstrate high reliability and stability in various operational scenarios to ensure consistent performance.
9. Accuracy: An azimuth orientation error of up to 15 degrees can be considered acceptable when using Yagi antennas with a beamwidth of 60-90 degrees. This is because the relatively wide radiation pattern ensures that the antenna can maintain sufficient signal strength and quality even with slight misalignments. Such tolerance allows reliable data transmission and reception by ground robots while accommodating practical limitations in terms of control system accuracy.

2.2. Architecture of the control system model

Based on the analysis and existing technical solutions, a system was developed with the following configuration. The proposed antenna positioning control system (Fig. 1) consists of two main modules:

1. Control Device: This module connects to actuators and measurement devices.
2. Interaction Terminal: Implemented as software with a user interface for data monitoring and remote control.

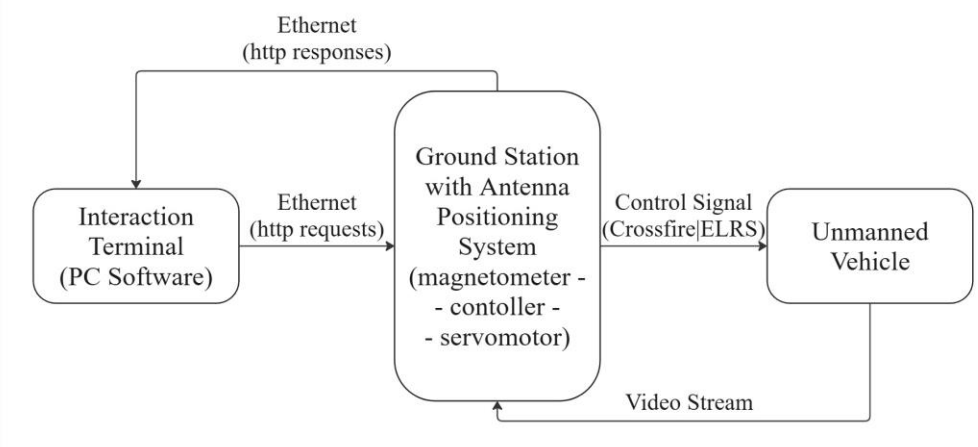

Fig. 1. Block diagram of the connection of the control system elements

The main task of the first module is to collect data on the current position of the antenna positioning mechanism and to send control signals to the actuators according to requests received from the operator.

This section discusses the configuration of the system, which was implemented as a prototype and tested under laboratory conditions. However, the technical modules can be modified according to usage requirements without significantly altering the overall configuration of the control system. Specifically, the control device consists of a control unit: Keyestudio W5500 Ethernet controller, a Tower Pro MG996R-180 servomotor, and an LSM303DLHC accelerometer and magnetometer module. The equipment selection is detailed in the following section.

During the development of the configuration, two types of rotational mechanisms were considered: a single-axis mechanism controlling the azimuth (yaw) and a dual-axis mechanism controlling both azimuth and elevation (pitch), as proposed in the study «Design, manufacture and performance analysis of an automatic antenna tracker for an unmanned aerial vehicle (UAV)» [14]. At this stage, to simplify the system and consider the assumption that, for ground unmanned vehicles, there is no significant reason to change the elevation position, a single-axis adjustment was implemented, allowing only changes in the azimuth.

The interaction terminal is software through which the operator receives information about the status of the control device, its connection, and potential signal loss. In addition to monitoring, a key function of the terminal is to set the desired azimuth for antenna positioning. The user interface of the terminal must ensure the correctness of action sequences, enabling the operator to perform the sequences while considering the system's operational features. Further details on the software implementation are provided in the following sections of the paper.

The interaction between the two modules allows the operation of the automated control system for antenna positioning and makes this process accessible in real-time.

2.3. Hardware selection justification

This section discusses the stages of prototype development for the control system and explains the criteria for selecting the equipment. The equipment chosen for the prototype may not be optimal for the implementation of a real system. It was selected based on the economic feasibility criterion, as well as considering the necessary functions that the hardware must provide.

We begin by considering the selection of control devices. Among the available and low-cost options that meet system requirements, Arduino hardware development platforms stand out. The Arduino framework significantly simplifies software development and reduces the time required to write the program, which is an advantage of this environment. The selection of the control board was also influenced by the communication method between the control device and the interaction terminal. In the first version of the prototype, communication via the UART data transmission protocol was considered. In this case, the Arduino UNO or NANO boards were selected, as the control device included one sensor (a magnetometer) and one actuator (a servomotor). The selected boards meet the resource and capability requirements for reading the sensor data and generating the PWM signal to control the servomotor.

Ensuring communication between the control device and the terminal using UART is not an issue under laboratory conditions. However, when attempting to establish a connection between the control device and the terminal under field conditions, where the ground station and operator may be located tens or hundreds of meters apart, the task becomes more challenging. Therefore, other communication protocols, such as Ethernet, were considered. Ethernet cables can support data transmission over long distances without significant loss of quality. For standard Ethernet cables (Cat5e or Cat6), the maximum length without repeaters is 100 m; however, specialized solutions such as Ethernet repeaters or media converters can be used for longer distances. Ethernet provides high data transfer speeds, which are important for transmitting large volumes of data, and is less susceptible to electromagnetic interference, especially over long distances, compared to UART, which can experience signal loss or noise with long cables.

Given the advantages of Ethernet technology, a second prototype was developed using Keyestudio W5500 Ethernet controller board. The Keyestudio W5500 Ethernet controller is based on the Arduino UNO microcontroller and Ethernet. It features a built-in USB bootloader and TF card slot, and it is fully compatible with UNO and Mega2560 pins. The controller can connect to the internet or a network to create a network application. The W5500 network module allows the control board to function as a web server or to read the states of digital and analog Arduino interfaces via network access. Additionally, it supports a simple web server using Ethernet libraries in the IDE environment and can handle large volumes of data with its MicroSD (TF card) reading/writing capability.

The measuring device is a key component of the system. In the proposed system, the ability to adjust the antenna's position is based on data received from an electronic compass (magnetometer). Several modules are compatible with the selected control board. During the study, a comparative analysis of the performance of five different modules was conducted: QMC5883L I2C

GY-273 digital compasses with the L883 and 5883 chips, the HSCDTD008A 3-axis magnetometer module, the GY-271M HMC5983 I2C/SPI digital magnetometer, and the LSM303DLHC accelerometer and magnetometer module. These modules are readily available on the market, are low-cost, and are compatible with control devices. To select the best module, an analysis of the performance and accuracy of the measurement data was conducted, considering the following criteria: ease of calibration and stability of the module's operation.

For the comparative analysis, measurements from the electronic measuring devices were taken and compared with data from the Konustar-10 analog compass. The results of the analysis showed the following: the digital compass QMC5883L I2C GY-273 with the L883 chip had a root mean square error of 5°, whereas with the module equipped with the 5883 chip, the error increased to 21°. The issue with using these modules lies in the complexity of the calibration mechanism, as described in the article [22]. When testing the HSCDTD008A 3-axis magnetometer module and the GY-271M HMC5983 I2C/SPI digital magnetometer using the existing libraries and software developed for these modules, it was noted that the data obtained from the magnetometers did not reflect reality and fluctuated within a limited range, for example, between 150-240 degrees. This may be due to defective modules or poor quality of the software used to calibrate these modules. The LSM303DLHC accelerometer and magnetometer module is characterized by a simple calibration process facilitated by the LSM303 library. This library includes a calibration program that determines two arrays of relative values (minimum and maximum sensor values for the x, y, and z axes) necessary for proper functioning of the sensor. The calibration process involves simply moving the sensor in various spatial orientations for a few seconds without the need for a precise reference point fix, as is required for calibrating the GY-273 module. The error magnitude of the LSM303DLHC module is comparable to that of the GY-273, but due to its easier calibration process and stable performance, the LSM303DLHC module was selected for use in the prototype.

The MG996R-180 servo motor with a 180° rotation angle and a maximum torque of 11 kg/cm was selected as the actuator. This device can be replaced with another servo motor of the required power and a different rotation angle depending on the system requirements. For the prototype, these parameters were not critical in the selection process. It is worth noting that the magnetometer module in the prototype was mounted on the servo motor shaft, allowing the module to rotate along with the shaft. The 3D model of the control device element arrangement is shown in Figure 2. The elements in Figure 2 are numbered as follows:

1. Antenna holder.
2. Magnetometer.
3. Platform for mounting components.
4. Servomotor.
5. Control board.

The electrical connection diagram of the components is shown in Figure 3.

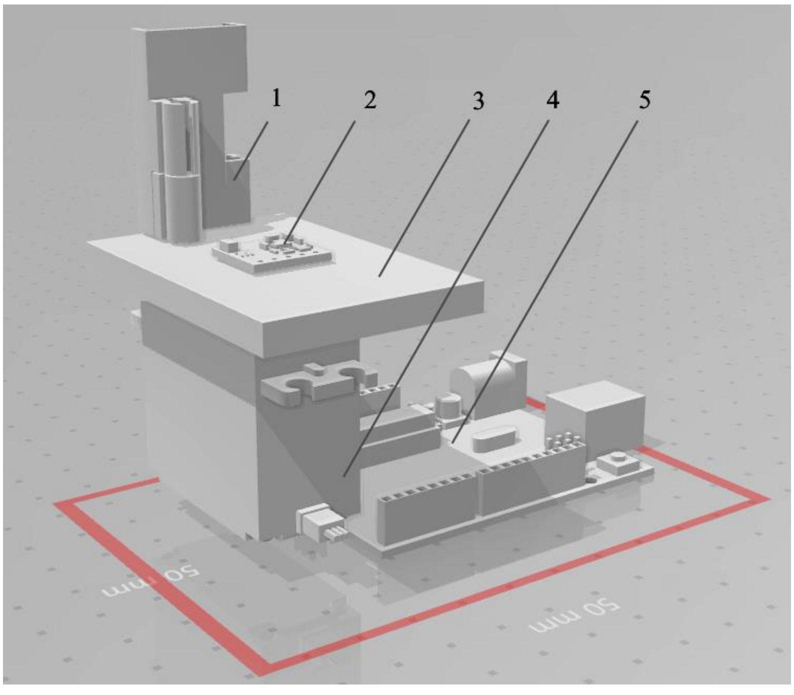

Fig. 2. 3D model of control device elements arrangement and connection of the control device elements

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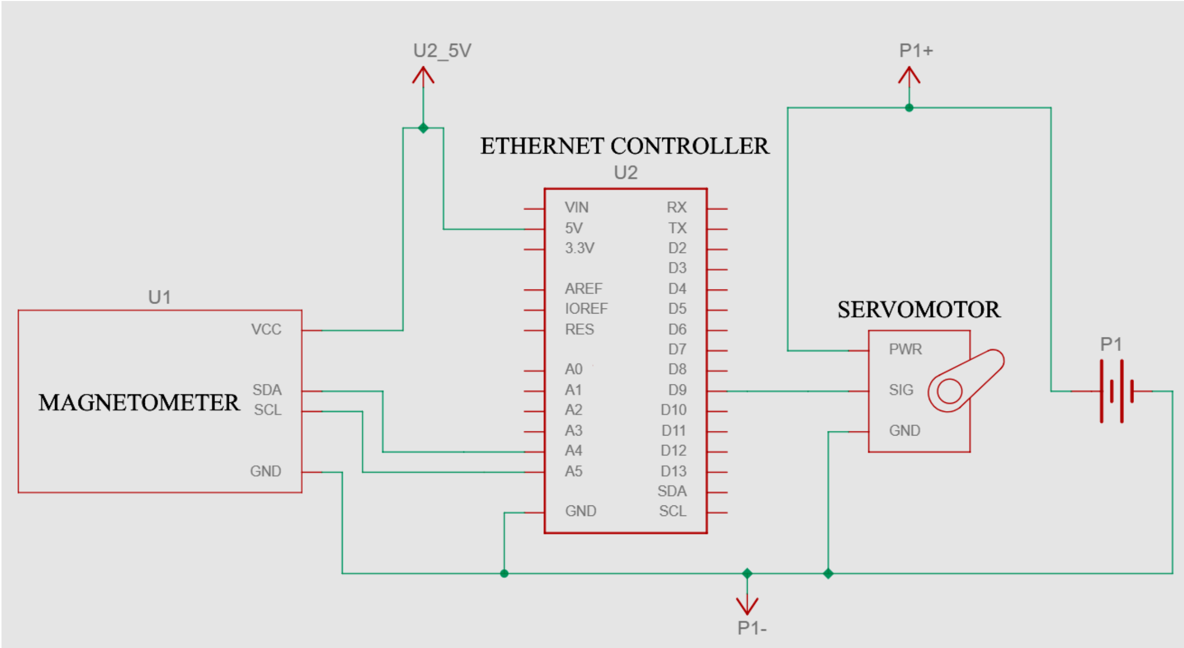

Fig. 3. Electrical connection diagram of the control device components

In addition to the main components described above, a laboratory power supply was used as the power source. However, when deploying the system in the field, it is necessary to select batteries to power both the control board and servo motor based on the nominal operating voltage of these devices.

2.4. System software implementation features

The system includes two software modules: the program that controls the device and a software application that implements the interaction terminal for a personal computer.

Let's consider the implementation of the control device program. As mentioned earlier, the control board chosen for the system prototype allows the use of the Arduino framework and its integrated development environment (IDE). After connecting all devices to the control board and ensuring the mechanical assembly of the components, the control device must undergo sensor calibration. This can be achieved using the LSM303 library. Among the examples provided with the library is the *Calibrate* program, which allows us to obtain the value arrays described in the previous section. This step is an intermediate but necessary step to ensure correct sensor operation. Once the data arrays are obtained using this program, they must be transferred to the main source code of the control program.

The main component of the control device program is the creation of a web server entity that operates in "listen and serve" mode. According to a study on server application architectures [23], a monolithic architecture was selected for our system. This requires the use of several libraries: Ethernet, SPI, and Wire. In addition, the Servo and LSM303 libraries were used to control the sensor and servo motor. To establish communication between the terminal and control device, the program specifies the MAC address and static IP address of the Ethernet controller. These configurations are necessary to configure the network between the control device and operator computer. Once this configuration is added, the program initializes the server entity on port 80.

To store data, several global variables were created, including an array for storing data from the magnetometer. This array is essential for mapping the data between the relative rotation angle of the servo motor (0-180 degrees) and the magnetometer readings.

According to the Arduino framework, the program code consists of two main functions: setup and loop. In the setup function (which runs once when the code is uploaded to the controller board), the servo motor is configured, serial communication is initialized for debugging, and the magnetometer is set up. The compass object is then configured with the data arrays obtained during the calibration process. In the setup function, the configuration of the web service (the MAC address and a static IP address) is also assigned to the server entity.

In the main loop function (which implements an infinite loop), the program checks for incoming HTTP requests to the controller. The loop function includes a program router with three endpoints. The first endpoint is responsible for reading the current sensor value and generating a response in JSON format. The second endpoint is used to set the servo motor's position to a specific angle corresponding to the desired azimuth value.

The third endpoint provides a mapping function between the servo motor's relative position (0-180 degrees) and the magnetometer data at the corresponding servo positions. Each request is handled by a separate function that ensures structured code.

The system operates as follows. The operator connects to the device via Ethernet. The interactive terminal displays the current connection status, and the operator needs to send a "calibration" request (in this case, to map data between the servo motor's position and the magnetometer readings at different motor positions). After calibration, the operator engages in continuous cyclic operation with the system. The operator can retrieve the magnetometer data at a specified interval and adjust the servo motor shaft position to set the desired azimuth. If the desired azimuth does not match the current magnetometer readings, the operator can repeat the "calibration" process and continue working.

A problem that arose during the research was the discrepancy between the calibration data and the real-time magnetometer readings. Sometimes the difference reached up to 7 degrees, necessitating an improvement in the calibration process. To address this issue, the servo motor rotation speed was slowed down from 0 to 180 degrees, and a low-pass filter [24] was applied to cyclically process the signal. This adjustment reduced the error to 3° but also slowed the calibration process. However, this approach had a drawback when operating the antenna rotation system within the azimuthal sector from 350° to 10° because the inertial filter smoothed the data, leading to distortion at this transition. Ultimately, we decided to abandon the use of the low-pass filter and slow down the calibration rotation to minimize the error to 5°. Consequently, this problem remains relevant and requires further resolution.

To improve operator feedback and the debugging process, after completing the calibration process, the controller responds to a request by sending three azimuth values corresponding to the servo motor angles of 0, 90, and 180 degrees. A flowchart of the developed Control Device program is shown in Figure 4.

The other component of the software is the interactive terminal. The implementation was decided to be performed using the Go programming language, as well as Fyne, a library for creating graphical user interfaces (GUI) in Go. Fyne allows developers to create cross-platform applications with a single codebase that can run on Windows, macOS, Linux, and mobile platforms, such as Android and iOS.

The choice of technologies is explained by the wide range of capabilities for implementing web service applications, for which the Go language is often used. Additionally, the advantages of this language are its support for asynchronous operations, high performance, ease of development, and ability to compile into an executable application file.

The user interface consists of an input field for the desired azimuth, a button to submit the desired azimuth, a calibration button, informational widgets that display the connection status, data received from the magnetometer, azimuth values after calibration at 0, 90, and 180 degrees, and an error display widget that provides the operator with complete information about the device's operation.

The implementation of an interactive terminal ensures that actions not intended by the user scenarios are prevented. For example, the calibration and azimuth submission buttons become inactive if the device is disconnected from the user's personal computer. In addition, the user cannot submit an azimuth until the initial calibration is complete. If the device is disconnected or reconnected to the computer during operation, the initial calibration must be redone before the positioning of the rotation mechanism is managed. The flowchart of the developed Control Device program is shown in Figure 5.

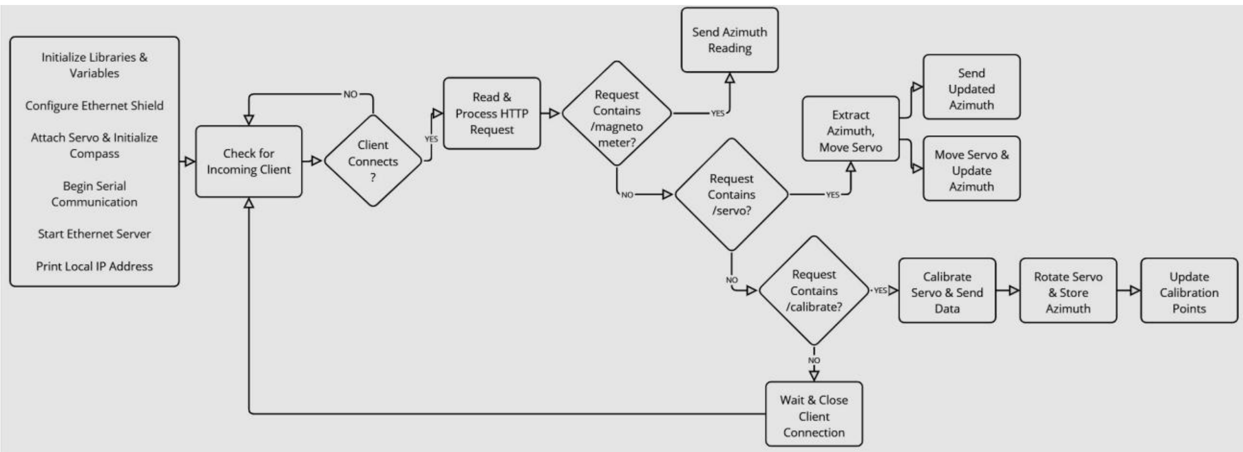

Fig. 4. Flowchart of the control device software

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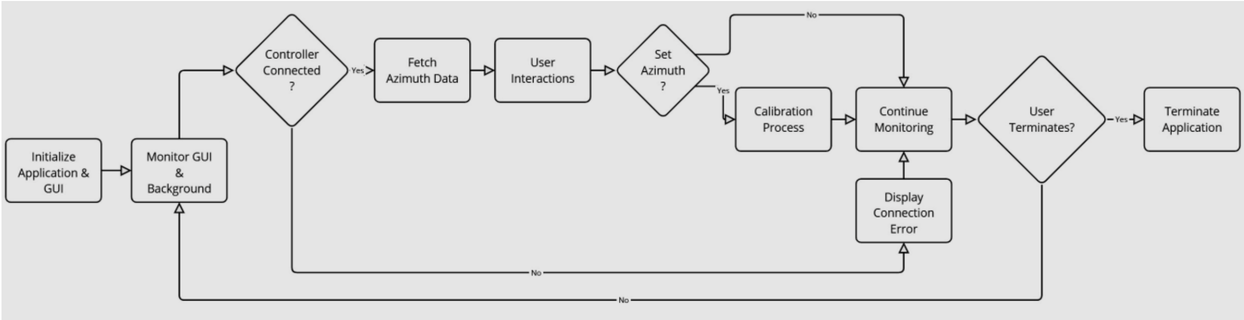

Fig. 5. Flowchart of interactive terminal software application

The proposed program implements multithreading to execute actions. Requests to obtain azimuths are sent in parallel with user interactions with the interactive terminal interface. This includes stopping and resuming their operation when sending the desired azimuth to the control device using Go's channel concept.

The interactive terminal program validates data sending to the control device and provides error handling for issues that may arise during system operation.

The graphical user interface is characterized by its simplicity and lack of unnecessary interactive elements, which also ensures adherence to user scenarios. The graphical user interface of the compiled application is illustrated in Figure 6.

3. Results and Discussion

Based on the research conducted in this article, it can be asserted that the infrastructure required to ensure stable communication between the ground-based unmanned vehicle and the ground station is as crucial as the technical and software components of the unmanned vehicle itself. Ensuring communication becomes significantly more challenging when using an unmanned vehicle in the presence of active electromagnetic spectrum sources or when the operator must adapt to the surrounding environment while controlling the UV.

An analysis of existing technical solutions reveals that most of them are not adapted to work in the presence of interference. This issue remains relevant, and effective solutions are needed.

The proposed system partially addresses the challenges by implementing a rotating mechanism for adjusting the positioning of signal reception/transmission devices within the control system. The spatial distribution of the control system allows the remote management of antenna positions when the operator is not in close proximity, particularly in environments that may be hazardous to humans.

The system allows for both remote monitoring and control of signal reception and transmission devices. It has several advantages and disadvantages. The advantages of the proposed system include the following:

1. Simplicity: The system has a straightforward design with a minimal number of components.

2. Modularity: Technical modules can be replaced with alternatives without significant changes to the system configuration.

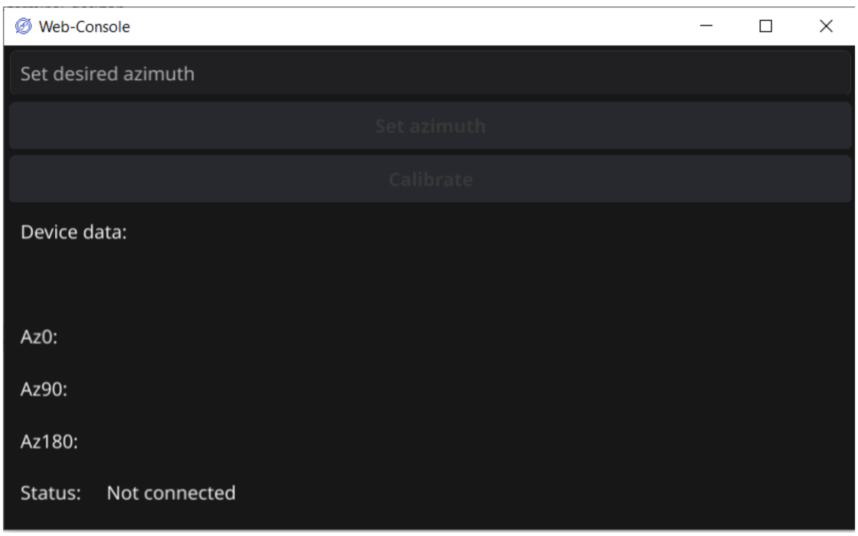

Fig. 6. Interactive terminal graphical user interface

3. Low Cost: The overall cost of the system prototype was more than seven times lower than that of commercially available prototypes.

4. Stability: The use of Ethernet communication protocol minimizes the risk of signal loss between system components.

5. Accuracy: In the developed system prototype, the azimuth orientation error should not exceed 10 degrees.

The disadvantages of the proposed system include the following:

1. Calibration Requirement: The sensors must be calibrated during system installation.

2. Measurement Device Errors: Errors in measurement devices may limit the control of directional antennas with narrow beamwidth.

3. Manual Operation: Despite automation, the system requires operators to manage the positioning of the antennas.

The use of the developed system can enhance the flexibility of unmanned vehicle operations, although it does not address the problem of automatic control of antenna positioning relative to the location of the ground robotic platform.

4. Conclusions

The architecture of using ground unmanned vehicles in the context of addressing modern tasks was analyzed. The current challenges associated with the application of mobile robotic platforms in open terrain were examined, deficiencies were identified, and solutions were proposed. This study reviews contemporary infrastructure elements available on the market for ensuring communication between unmanned vehicles and operators.

This paper proposes a model of an automated control system for positioning radio-signal transmission/reception devices. This section details the architecture of an automated control system that is spatially distributed to provide remote monitoring and control of antenna positions.

Because of the research, a prototype of the proposed system was developed, debugged, and tested under laboratory conditions. The performance quality of various technical modules, including measurement devices such as magnetometers, was analyzed during the creation of the prototype.

Software was developed for the technical module – control device interactive terminal software for remote management of the control device.

Future Research Development: Further steps in this research will involve exploring technical and software solutions to improve the accuracy of data obtained from measurement devices. Another research direction is the possibility of transforming the system from an automated to an automatic one. This requires the implementation of programmable radio communication technologies or pseudo-random frequency hopping for radio communication.

Contributions of authors: analytical review and analysis of information sources **– Alina Yanko;** statement of the problem and formulation of the research purpose **– Oleksandr Laktionov;** conceptualization, methodology – **Oleksandr Laktionov;** calculations and description of the result **– Bohdan Boriak;** analysis of results and formation of research conclusions **– Alina Yanko;** writing –original draft preparation, writing – review and editing **– Bohdan Boriak.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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Data Availability

Data will be made available upon reasonable request.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence technologies in their work.

All authors have read and agreed to the publication of the final version of this manuscript.

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МОДЕЛЬ АВТОМАТИЗОВАНОЇ СИСТЕМИ КЕРУВАННЯ ПОЗИЦІОНУВАННЯМ ПРИСТРОЇВ ПРИЙОМУ/ПЕРЕДАЧІ РАДІОСИГНАЛІВ

Б. Р. Боряк, А. С. Янко, О. І. Лактіонов

У цій статті обговорюється концепція розробки автоматизованої системи керування для позиціонування пристроїв передавання/приймання радіосигналів. Предметом статті є методи та засоби забезпечення точного та стабільного позиціонування антен за допомогою веб-контролера з вбудованими сенсорами та виконавчими механізмами. Метою цього дослідження є розробка моделі автоматизованої системи керування для позиціонування антен передавання/приймання радіосигналів, зокрема спрямованих антен з кутом діаграми спрямованості 60-90 градусів, що забезпечує мінімізацію похибки позиціонування азимуту. Об'єктом дослідження є процес автоматизованого позиціонування антени з використанням вбудованих систем. У статті наводиться приклад роботи системи, де контролер виконує завдання позиціонування антени з високою точністю для напрямних антен, таких як антени Ягі–Уда, забезпечуючи, щоб помилка керування за азимутом не перевищувала 15 градусів. Точність позиціонування досягається за допомогою процедури калібрування та динамічного налаштування серводвигуна на основі даних магнітометра. Ця система розроблена для забезпечення зв'язку для керування мобільною роботизованою платформою (безпілотними транспортними засобами), зокрема в умовах наявності електромагнітних завад. Надійний зв'язок з безпілотним транспортним засобом залежить від позиціонування елементів зв'язку. Це необхідна умова для функціонування мобільної роботизованої платформи, яка за класифікацією за розмірними групами належить до категорій Micro, Mini та Midi колісних транспортних засобів і використовується в пошуково-рятувальних та військових операціях. Результатом дослідження є розробка системи, а також її впровадження та тестування в лабораторних умовах, що підтверджує працездатність запропонованої моделі системи керування. Висновки. У статті обговорюється концепція розробки автоматизованої системи керування для позиціонування антен на основі використання вбудованих веб-технологій та їх інтеграції з апаратними компонентами, що забезпечують точне позиціонування пристроїв передавання/приймання радіосигналів.

Ключові слова: система керування; позиціонування антен; електромагнітні перешкоди; керування в реальному часі; веб-контроль; безпілотні апарати; мобільна роботизована платформа.

Боряк Богдан Радиславович – канд. техн. наук, доц. каф. автоматики, електроніки та телекомунікацій, Національний університет «Полтавська політехніка імені Юрія Кондратюка», Полтава, Україна.

Янко Аліна Сергіївна – канд. техн. наук, доц., доц. каф. комп'ютерних та інформаційних технологій і систем, Національний університет «Полтавська політехніка імені Юрія Кондратюка», Полтава, Україна.

Лактіонов Олександр Ігорович – канд. техн. наук, доц. каф. автоматики, електроніки та телекомунікацій, Національний університет «Полтавська політехніка імені Юрія Кондратюка», Полтава, Україна.

Bohdan Boriak – PhD (Technical Sciences), Associate Professor at the Department of Automation, Electronics and Telecommunications, National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine,
e-mail: boriakbr@nupp.edu.ua, ORCID: 0000-0002-8114-7930, Scopus Author ID: 58983614200.

Alina Yanko – PhD (Technical Sciences), Associate Professor, Associate Professor at the Department of Computer and Information Technologies and Systems, National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine,
e-mail: al9_yanko@ukr.net, ORCID: 0000-0003-2876-9316, Scopus Author ID: 57094953000.

Oleksandr Laktionov – PhD (Technical Sciences), Associate Professor at the Department of Automation, Electronics and Telecommunications, National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine,
e-mail: itm.olaktionov@nupp.edu.ua, ORCID: 0000-0002-5230-524X, Scopus Author ID: 57210360300.