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FEATURES OF THE DEVELOPMENT AND IMPLEMENTATION OF A GROUND ROBOTIC COMPLEX MOTION CONTROL SYSTEM

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The goal is to develop a motion control system for a ground robotic complex that ensures stability and movement accuracy under various operating conditions in real time. The paper presents the general structure of the control system, which includes hardware and software components, and provides the rationale for the selection of hardware elements and software implementation tools.

Method. To achieve the stated goal, both theoretical and practical research methods were used, including the analysis of existing technical solutions, systematization of operational requirements for ground robotic complexes, modeling of control processes, and testing of selected hardware and software solutions.

Results. The study proposes a motion control system structure for a ground robotic complex, which includes a main controller, brushless motor drivers, and a radio communication system, all interacting through standardized communication protocols. The selection of microcontroller platforms, actuators, and communication tools ensuring the required levels of system reliability and flexibility is substantiated. The paper also considers specific features of the software implementation of control algorithms, particularly the processing of radio communication system data and the generation of control signals for platform movement.

Practical significance. The proposed structure and implementation principles of the control system can be applied to the development of robotic mobile platforms for various purposes, requiring high autonomy and real-time control with minimized delay between the operator's control signal and the system's reaction. The obtained results are of practical significance for the creation of ground robotic complexes for both civil and defense applications.

Key words: ground robotic complex, motion control system, microcontroller platform, remote control.

Боряк Богдан, Янко Аліна, Лактіонов Олександр. Особливості розроблення та реалізації системи керування рухом наземного роботизованого комплексу

Мета роботи полягає в розробленні системи керування рухом наземного роботизованого комплексу, що забезпечує стабільність, точність руху в різних умовах експлуатації в режимі реального часу. У статті розглянуто загальну структуру системи керування, яка включає технічне та програмне забезпечення, а також обґрунтовано вибір апаратних компонентів і засобів програмної реалізації.

Методи. Для досягнення поставленої мети використано теоретичні та практичні методи дослідження, зокрема аналіз наявних технічних рішень, систематизацію вимог до роботи наземних роботизованих комплексів, моделювання процесів керування та апробацію вибраних технічних і програмних рішень.

Результати. У дослідженні запропоновано структуру системи керування рухом наземного роботизованого комплексу, що включає основний контролер, драйвери безколекторних двигунів, систему радіозв'язку, які забезпечують взаємодію через стандартизовані протоколи взаємодії. Обґрунтовано вибір мікроконтролерних платформ, виконавчих пристроїв, засобів комунікації, що забезпечують необхідний

рівень надійності та гнучкості системи. Розглянуто особливості програмної реалізації алгоритмів керування, зокрема оброблення даних системи радіозв'язку, генерації сигналів керування рухом платформи.

Практичне значення. *Запропонована структура та принципи реалізації системи керування можуть бути використані для розроблення роботизованих мобільних платформ різного призначення, що потребують високої автономності, керування в режимі реального часу з мінімізацією затримки від подачі сигналу керування оператора до реакції системи. Отримані результати мають практичне значення для створення наземних роботизованих комплексів цивільного та оборонного призначення.*

Ключові слова: наземний роботизований комплекс, система керування рухом, мікроконтролерна платформа, дистанційне керування.

Relevance. In recent years, there has been a rapid development in the creation and application of Unmanned Ground Vehicles (UGVs) worldwide. The main drivers of this process include the increasing demands for autonomy, mobility, and operational safety in complex or hazardous environments. In the military sector, UGVs are actively implemented for reconnaissance, casualty evacuation, ammunition transport, demining, and even direct combat operations. Global trends indicate growing interest in the development of lightweight, highly maneuverable platforms with advanced remote control capabilities and integration of artificial intelligence [1]. For example, American projects such as the Robotic Combat Vehicle (RCV) and European programs aimed at creating autonomous platforms for tactical operations emphasize operational flexibility and the ability to function in network-centric environments [2]. In Ukraine, the development of UGVs has significantly intensified since 2022 in response to challenges posed by the full-scale war. Ukrainian companies and volunteer groups are developing a variety of solutions – from compact platforms for casualty evacuation to assault robots equipped with machine guns and anti-tank systems [3]. More than 200 companies in Ukraine are currently engaged in the development and deployment of ground robotic systems, many of which are undergoing successful trials or already in operational use [4].

Beyond the military domain, unmanned ground vehicles are increasingly being adopted in civilian sectors. Ground robotic platforms are utilized to automate warehouse operations and agricultural tasks [5; 6] – such as autonomous harvesting or fertilizer application – as well as for missions in hard-to-reach or hazardous environments, including disaster response, inspections, and rescue operations. The global trend shows a growing demand for systems with a high level of autonomy that can adapt their behavior to changing external conditions and responding promptly to emergency situations.

Thus, the development of effective motion control systems for unmanned ground vehicles is one of the key challenges in modern robotics, holding significant importance for both the defense industry and a wide range of civilian applications.

Literature review. In [7], the author emphasizes that leading countries such as the United States, the United Kingdom, Japan, China, and others are actively developing unmanned ground vehicles as part of their «robotic warfare» strategies. These nations are integrating cutting-edge technologies, including artificial intelligence, to enhance the efficiency and autonomy of their armed forces. The author also proposes a functional classification of UGVs into three main groups: combat, special-purpose, and multipurpose platforms. This categorization allows for a clearer understanding of the specific roles each type of system plays in operational scenarios. Furthermore, the author analyzes key policy documents, such as the U.S. Army Robotic and Autonomous Systems Strategy to 2035 and the U.S. Army Operational Concept to 2040, which outline the future directions for UGV development in the American military. The paper also addresses challenges faced by UGV developers, including the integration of new technologies into military strategies and the need to solve complex technical and tactical issues.

In article [8], the issue of improving the mobility and stability of multipurpose robotic platforms (MRPs) is examined, which is particularly relevant in challenging terrain conditions, especially in the context of the Russian-Ukrainian war. The author proposes the use of multifunctional interaction tools between the MRPs and external objects and environments (referred to as MRP-EOI systems), which can be transformed and perform additional functions to enhance the operational capabilities of the platforms.

Particular attention is given to the Abenics technology, which enables the transformation of MRP-EOI systems with minimal mass and dimensional characteristics while providing the necessary degrees of freedom. Functional differences between propulsion systems and manipulators – used for movement and interaction with objects – are also established.

The monograph [9] is dedicated to a systematic study of ground robotic systems. The authors provide a detailed analysis of the design of modern robotic systems, including their structural layouts and engineering solutions, particularly

for special-purpose applications such as military robots. The work addresses the geometry, kinematics, and statics of these systems and develops methods for calculating kinematic parameters and determining positioning errors. Conditions for static stability and dynamic properties are examined using fuzzy set theory. The monograph also formulates the fundamental principles of ground robotic system design theory and proposes conceptual and structural solutions for their development.

Objective of the study. Considering the complexity of most existing systems, the objective of this research is to develop and test a motion control system for a ground robotic complex (GRC), distinguished by its simplicity, flexibility, and the ability to configure acceleration and deceleration modes of the motors.

Materials and methods. The general structure and the rationale for selecting individual components of the ground robotic complex are presented in studies [10; 11]. The main components of the control system include the primary controller, brushless motor controllers, and the radio communication system.

One of the key aspects of ensuring effective remote control of ground robotic complexes is the selection of a radio communication channel that meets the requirements for communication range, interference resistance, and minimal control latency. The radio communication system ensures the transmission of control signals from the operator to the GRC, including the possibility of control via ground control stations [12]. Among modern communication systems widely used for mobile platform control, particular attention is given to ExpressLRS (ELRS) [13] and TBS Crossfire [14]. Both technologies operate in the 868/915 MHz frequency band, which provides high signal penetration through obstacles and enables long-range communication under line-of-sight (LoS) conditions.

The TBS Crossfire system is designed for maximum reliability over long distances. According to practical tests, it can provide stable communication at distances of up to 40–100 km under favorable conditions. Its advantages include high resistance to electromagnetic interference, support for bi-directional telemetry, and the ability to operate in rugged terrain. On the other hand, ExpressLRS is an open-source project focused on minimizing latency and optimizing channel bandwidth. In the 900 MHz frequency range, ELRS ensures stable communication at distances up to 30 km with standard transmitters and antennas, which is sufficient for most tactical-level tasks. In real-world

conditions, the control range depends on several factors, including the terrain and the line of sight of the radio communication.

The choice between the mentioned technologies depends on the specific mission requirements of the unmanned ground robotic complex. For tasks that require ultra-long-range communication or maximum resilience in radio interference conditions, TBS Crossfire is the preferable option. On the other hand, for platforms designed for shorter or medium-range operations with an emphasis on low control latency and flexible configuration, ExpressLRS is the optimal choice. Both systems support the transmission of both control commands and real-time telemetry data, which is critical for establishing closed-loop control systems and ensuring the autonomy of GRCs.

In the prototype system, it is proposed to use the TBS Crossfire Diversity Nano RX as the signal receiver to ensure reliable and long-range communication in the unmanned ground robotic complex remote control system. One of the key features of this receiver is the implementation of signal diversification through the use of two independent antennas and separate radio-frequency paths. This ensures stable communication even in challenging conditions, reducing the likelihood of signal loss due to multipath propagation or shielding.

The main controller used in the system is the ESP32, which has the capability to read data from the radio receiver and generate and send control signals to the brushless motor controllers and modular actuators. The support for wireless data transmission technologies allows for real-time system debugging and logging of system state changes. The ESP32 is also characterized by low power consumption and features 3 hardware UART (Universal Asynchronous Receiver-Transmitter) interfaces, which can be used for connecting external devices for data exchange. Another argument for choosing this microcontroller is the availability of software libraries that simplify the implementation of control algorithms.

Data reading from the radio receiver is accomplished by connecting the TBS Crossfire Diversity Nano RX to the ESP32 via UART and utilizing external libraries. This setup allows for the retrieval of at least 8 control channels, including pitch, roll, arm, yaw, throttle, and others.

For direct control of brushless DC (BLDC) motors, which are the primary drive in unmanned ground robotic systems, it is proposed to use BLDC drivers. There is a wide range of devices that perform these functions, but in this system prototype, the VESC controller, specifically the VESC FlipSky v6.7pro, is chosen.

The FlipSky VESC 6.7 Pro controller is an electronic speed controller (ESC) that facilitates control of brushless motors in various mobile platforms, including robotic systems. A significant advantage of this controller is its ability to operate within a wide voltage range of 8 to 60 V, allowing the use of different types of batteries. Additionally, the controller features built-in protection against overloads, high and low voltage, and overheating. Its interfaces, such as USB, CAN, UART, PPM, and others, provide ease of integration into various systems, while the ability to configure through the VESC Tool (Vedder Electronic Speed Controller) allows users to tailor the controller to specific needs.

In this study, it is proposed to use two channels, namely roll and pitch, to generate control signals for the BLDC driver. This approach is intuitively understandable for operators.

The number of drive motors in the unmanned ground robotic complex can vary depending on the application requirements. In this study, it is proposed to use two motors, the direction and

speed of which depend on the position of the control stick on the remote control. For larger models, the number of motors may increase in pairs. If the drive motors are positioned on both sides of the platform, the control signals are simultaneously sent to the motors on each side. In this study, two motors are used, mounted on the sides of the platform, with each connected to a BLDC controller that is linked to the ESP32 controller, which is connected to the radio receiver. This configuration and its installations are shown in Figure 1.

The control signal generation model can be conventionally divided into two levels. The first level involves the generation of signals transmitted from the main controller to the brushless motor drivers. The second level refers to the generation of voltage control signals for the brushless motors by the BLDC drivers.

The study examined the generation of control signals depending on the inputs received from the remote-control unit. Several options for controlling signal generation were considered. Roll and pitch

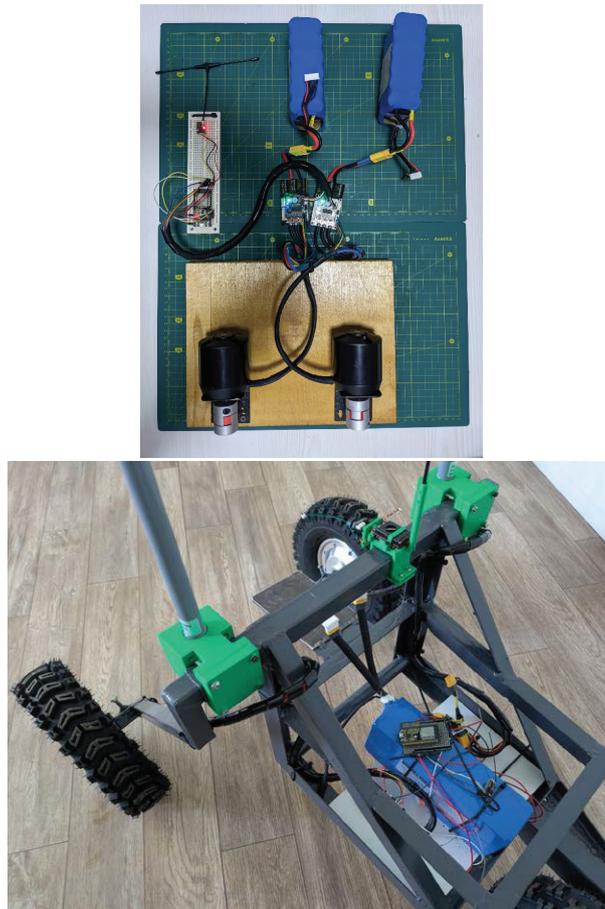


Fig. 1. Configuration of the Control System Components

signal mapping diagram, illustrating the signals received from the remote control is shown in Figure 2. The shaded area in the figure indicates the possible boundaries for the placement of trigger lines used to generate control signals.

The mapping involves dividing the signal sectors of the pitch and roll channels in relation to the control signal. The lines define the sector boundaries, the crossing of which triggers the generation of control signals for each motor. A distinctive feature is the placement of these lines on the map, conventionally marked as F (forward), B (backward), R (right), and L (left). Their position on the map determines the sensitivity of the control stick movement to the response of the robotic system. At the same time, reducing the blind zone may increase the likelihood of unintentional operator movements, leading to sudden changes in the robot's direction, which can cause motor reversal, current spikes, and, as a result, motor overheating.

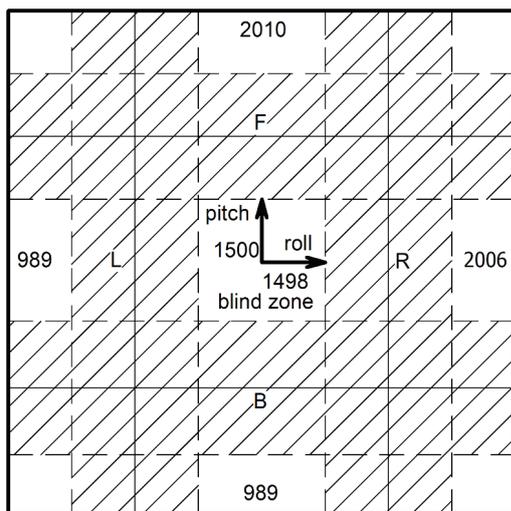


Fig. 2. Roll and pitch signal mapping diagram

One of the tasks addressed in this study was to determine the optimal positions of the sector boundary lines that minimize the number of false activations while simultaneously providing a wide range of pitch and roll channel values. This ensures broader control signal generation for the BLDC drivers. Experiments were conducted to determine the placement of trigger boundaries, the crossing of which results in the generation of control signals, and consequently to define the limits of the blind zone.

As a result of the field tests, the following control signal generation model was proposed. The presented model is intended for generating

control signals for a differential drive robotic platform based on input received from a remote control system. The logic processes signals from the pitch, roll, and arm channels and, depending on their values, adjusts the speed of the left and right brushless DC motors via corresponding PWM signals.

Initially, the algorithm verifies the system's connectivity. If the connection is established and the arm signal exceeds a predefined threshold (greater than 1500), the system enters an active state in which control commands are executed. Otherwise, it defaults to a disarmed state, and both motors receive a neutral control signal (1500 μ s), effectively stopping the robot.

When the system is armed, the behavior of the robot is determined primarily by the values of the roll and pitch channels. Within the central range of the roll signal (between 1195 and 1800), the algorithm interprets the operator's intent as a request for forward or backward motion, with the specific direction and speed defined by the pitch value. If the roll value is approximately centered (between 1400 and 1600), both motors receive the same PWM signal calculated by linearly mapping the pitch range [989, 2010] to the output PWM range [500, 2500] μ s, resulting in straight motion. However, if the roll value deviates from the center within this band, the algorithm introduces differential speed adjustments between the left and right motors, enabling curved trajectories. For instance, when roll value exceeds 1600, the left motor is prioritized and the right motor's speed is reduced proportionally to the magnitude of deviation, resulting in a right turn. Conversely, when roll falls below 1400, the right motor is prioritized with the left motor being adjusted accordingly, yielding a left turn.

Outside the neutral roll zone, i.e., when the value is either greater than or equal to 1800 or less than or equal to 1195, the algorithm interprets the command as a request for in-place rotation (yaw control). In this case, a differential mapping is applied to both motors to induce a turning motion: the motor on one side is sped up while the other is slowed down, creating a pivot around the robot's vertical axis. Specifically, a high roll value corresponds to right rotation, and a low value to left rotation.

If none of these conditions are met, or if the system is disarmed or disconnected, both motors are set to their neutral state, halting all motion. This approach ensures that the robot remains stationary under any undefined or unsafe condition.

At the level of BLDC control on the driver side, a 20% blind zone is implemented on the pitch

channel, which limits movement in the forward and backward directions.

The mapping of control signals is shown in Figure 3.

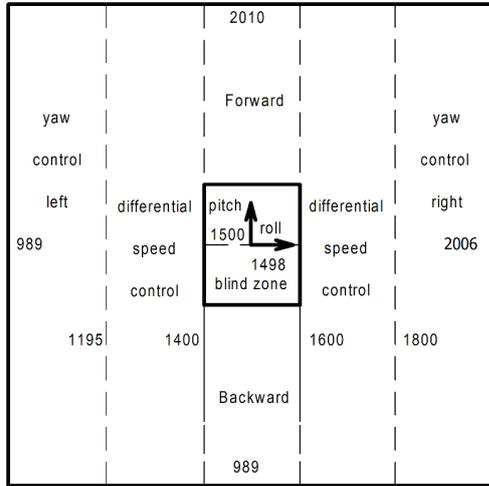


Fig. 3. Mapping of control signals generation

An experiment was conducted involving the adjustment of the positions of lines that define the formation of the control signal. The experiment included the traversal of a rectangular trajectory with a total length of 12 meters by a ground-based robotic system. The primary efficiency criterion was defined as the time required to complete the trajectory. To minimize the subjectivity associated with human influence on the control of the robotic system, the route was repeated five times by the operator using identical settings. The average traversal time of the robotic system, depending on the positions of the trigger lines, is presented in Table 1.

The positions of the lines that determine the formation of the control signal, indicated by dashed lines in Figure 3, are conventionally denoted as

L1 = 1400, L2 = 1195, R1 = 1600, and R2 = 1800 for the purpose of representation in the experimental results table. The table presents the values of L1, L2, R1, and R2 that yielded similar results. When testing other combinations of values, the trajectory traversal time increased by 36% or more.

Conclusions and future research directions.

The proposed configuration allows for the implementation of a simple and cost-effective GRC prototype for research and testing of different models and modifications. The main controller has sufficient resources to manage external modular devices and communicate with computer modules. The system's flexibility is achieved through the ability to control the acceleration and deceleration characteristics of the GRC in two ways. Changes in the characteristics can be made by modifying the ESP32 controller's software code, adjusting the signal mapping parameters based on the radio receiver signals. Another way to adjust the motor performance characteristics is by changing the parameters of the BLDC controllers themselves using software designed for configuring and monitoring electronic speed controllers based on VESC technology. The practical value of the study lies in the implementation of the control algorithm and its validation through field experiments.

The scientific novelty of the study lies in the identification of optimal or near-optimal values for the positioning of trigger lines that determine the movement of the robotic platform in response to changes in the control stick position. These values have been validated through an experiment conducted on the developed ground-based robotic system. The comparative analysis is supported by the data presented in Table 1.

In the future, there is a need to analyze and explore methods for selecting optimal parameters that define the motor performance characteristics based on load conditions, to avoid overheating both the motors and the BLDC controllers.

Table 1

Average Trajectory Traversal Time of the UGV Depending on Trigger Line Positions

Trigger Lines Values: L1, L2, R1, R2	L1 = 1450; L2 = 1245; R1 = 1550; R2 = 1750.	L1 = 1400; L2 = 1195; R1 = 1600; R2 = 1800.	L1 = 1350; L2 = 1145; R1 = 1650; R2 = 1850.	L1 = 1300; L2 = 1095; R1 = 1700; R2 = 1900.	L1 = 1250; L2 = 1045; R1 = 1750; R2 = 1950.
Average Trajectory Traversal Time, s	18.86	17.81	19.34	19.11	22.75

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