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Research Article

Development of a Model and Performance Analysis of the Characteristics of a Multifunctional Autonomous Unmanned Ground Vehicle

Dolya Alexandr,[1] **Kolumbetov Batyr**,[1] **and Kalkabek Aidos**[2]

[1] *Research Institute, National Defense University, Astana, Kazakhstan*
[2] *Center for Design and Technological Solutions, Kazakhstan Engineering R&D Center LLP, Astana, Kazakhstan*

Correspondence should be addressed to Dolya Alexandr; iskander_kst@mail.ru

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This article focuses on a multifunctional autonomous unmanned ground vehicle (MAUGV), aiming to enhance its maneuverability, stability, and obstacle-overcoming capabilities through the development and integration of control systems, sensor fusion, and modular design. The core problem addressed is the integration of autonomous capabilities with operational effectiveness across diverse and challenging environments. By implementing mathematical modeling and prototype testing, motor characteristics are analyzed, and various operational scenarios are simulated to predict the vehicle's behavior in real-world conditions. Results demonstrated the MAUGV's ability to tackle obstacles up to specific heights and inclines, highlighting the model's accuracy in replicating physical dynamics and the vehicle's potential in challenging environments. These outcomes stem from an examination of drive power, traction characteristics, and cross-country ability, underscoring the model's utility in enhancing vehicle design and functionality. Additionally, the integration of a bayonet connection for rapid module changes significantly enhances the MAUGV's adaptability across different missions. The practical implications of this work extend to the development and improvement of autonomous vehicles, offering insights into design considerations that improve adaptability and performance in varied operational contexts. By addressing specific challenges associated with autonomous mobility, the findings contribute to advancing the field, suggesting pathways for future research and application in areas requiring robust, versatile unmanned ground vehicles (UGVs).

Keywords: mathematical modeling; motor characteristics; multifunctional; obstacle overcoming; unmanned ground vehicle

1. Introduction

Given the growing demand for enhanced operational capabilities in both military and civilian sectors, the research on multifunctional autonomous unmanned ground vehicles (MAUGVs) has become increasingly relevant. MAUGVs can effectively perform various tasks ranging from search-and-rescue operations to complex military missions, significantly improving efficiency, safety, and mission success in hazardous conditions [1].

Modern conflict zones and disaster-stricken areas often present environments too dangerous for direct human intervention. This necessitates the development of robotic systems capable of navigating and operating autonomously in diverse and challenging terrains. Furthermore, the versatility required from these systems to adapt to various tasks such as surveillance, reconnaissance, or logistic support calls for innovative solutions in robotic mobility, control, and adaptability [2].

The development of ground-based robotic complexes for special purposes is aimed at creating remotely controlled models with the possibility of autonomous operation. The gradual improvement of these complexes includes the transition from simple remote control to interactive supervisory control, carried out without the constant presence of a person. This is facilitated by the improvement of vision and navigation systems, the integration of autonomous motion control functions, and specialized equipment, as well as remote-control capabilities using artificial intelligence.

A feature of the developed MAUGV is the creation of a specially designed universal robotic platform capable of adapting to various requirements and features, allowing you to install a variety of equipment depending on the operations performed: localization and extinguishing of fire, making passages in difficult terrain, rescue of the wounded and injured, neutralization of ammunition and improvised explosive devices using a manipulator, etc.

One of the main requirements for MAUGV is its cross-country ability and maneuverability on various types of surfaces, including asphalt, soil, sand, snow, and ice. An unmanned ground vehicle (UGV) must successfully navigate over rough terrain, overcome ascents and descents, staircases, ditches, pits, and debris structures. An important factor determining these properties is its motor characteristics and mass dimensions.

Despite substantial progress in robotic technologies, autonomy, and sensor integration, existing MAUGV systems still face limitations, particularly regarding reliable navigation in complex terrains, obstacle negotiation, and the seamless integration of autonomous control systems into realistic operational scenarios. For example, robotic systems designed for disaster environments often integrate advanced sensors effectively [3] yet lack full autonomy due to incomplete sensor fusion and limited decision-making capabilities. Other systems emphasize cost-effectiveness and ease of use through Arduino-based controllers [4] but fail to scale adequately for dynamic and unpredictable mission conditions. Vehicles employing advanced wheel systems, such as Mecanum wheels [5], enhance maneuverability in controlled tests, but their performance under real-world rough terrain conditions remains insufficiently studied.

Vibration reduction techniques using finite element modeling [6] demonstrate clear benefits but lack validation regarding their adaptability to diverse terrains and operational environments. Specialized firefighting robots [7, 8] showcase robust performance and improved safety in narrow application scenarios yet have substantial gaps in autonomous navigation and integration into broader operational systems. Modular robotic platforms [9] offer excellent operational flexibility but exhibit significant drawbacks related to rapid reconfiguration and reliability under field conditions. Military-oriented UGVs also indicate strong potential but continue to face integration challenges, particularly regarding soldier trust, responsiveness, and reliability in unpredictable battlefield environments [10, 11].

This research addresses these gaps by integrating solutions into a MAUGV platform. The main contribution lies in analyzing and verifying how existing technologies—control algorithms, sensor fusion techniques, modular payload systems, and a track-driven mobility system—can collectively enhance performance, adaptability, and reliability of MAUGVs across diverse operational environments. This integration approach aims to provide guidelines and insights for future design improvements and operational use of autonomous UGV.

The structure of this paper is organized as follows. Section 2 provides an overview of related research, highlighting previous developments, strengths, and existing limitations in the field of UGVs. Section 3 presents the aim and objectives of the study. Section 4 describes the research methods employed, including theoretical modeling, simulation approaches, and experimental validation procedures. Section 5 presents the experimental results obtained from simulations and prototype testing. In Section 6, a discussion and comparative analysis of theoretical predictions and practical outcomes are provided, emphasizing implications and practical insights. Finally, Section 7 summarizes the conclusions drawn from the research, outlines limitations encountered, and suggests directions for future development.

2. Literature Review and Problem Statement

The development of UGV has advanced over recent years, finding applications in military, search and rescue, and environmental monitoring operations.

The study [3] introduces designing a cost-effective unmanned vehicle system specialized for disaster detection, primarily focusing on detecting gas concentrations and manipulating objects with a robotic arm. The advantages include affordability and effective real-time communication with the operator. However, it is constrained to specific tasks, lacks multifunctionality, and is not adaptable for broader operational scenarios.

The article [4] presents an Arduino-based remotely operated UGV featuring a serial manipulator controlled via Wi-Fi. Important strengths include affordability, simplicity, and user-friendly design, beneficial for cost-constrained applications. However, Wi-Fi significantly restricts operational range, hindering long-distance missions. Additionally, reliance on Arduino controllers limits computational power, storage, and peripheral device integration, diminishing adaptability to complex tasks requiring advanced sensors or real-time processing.

The research [5] introduces a remotely operated multidirectional UGV based on Mecanum wheels, utilizing XBee modules (effective range up to 1500 m). Its maneuverability advantages and flexible movement configurations are evident. Nonetheless, the system lacks clearly defined procedures for payload interchangeability, reducing its adaptability for various operational scenarios. Moreover, compared to our design utilizing the SIYI MK32 communication module (range up to 10 km), their communication range remains considerably limited, restricting effectiveness in broader mission contexts.

The study [6] evaluated the design and construction of an Arduino-based UGV, focusing on vibration analysis via finite element modeling. While effectively optimizing chassis design and reducing sensor error due to vibrations, this study lacked simulation or experimental evaluation for obstacle negotiation and adaptability to diverse terrains.

Moreover, no comprehensive system control architecture or navigation capabilities were presented, resulting in a notable gap in practical operational validation and autonomy integration.

The article [7] introduces a small crawler firefighting robot incorporating an independent suspension system, explosion-proof shell, and thermal imaging. Its advantages include specialized safety features and structural reliability tailored for urban firefighting environments. However, the study did not provide details regarding remote-control implementation, theoretical performance calculations, or systematic obstacle negotiation analysis. The absence of prototype testing and geometric sizing data further limits its immediate practical applicability.

The research [8] introduces an Arduino-based firefighting robot designed for short-range fire suppression tasks, featuring Bluetooth remote control limited to 6 m. This robot demonstrated effective flame detection and basic obstacle avoidance. It also identifies room for enhancement in fire detection accuracy, autonomous navigation, and the incorporation of drones and eco-friendly materials, suggesting that future iterations could focus on achieving higher levels of autonomy and environmental sustainability in firefighting robotics. Nevertheless, it lacks multifunctionality and versatility, as it is strictly confined to firefighting roles. The robot is limited in power and water pressure capability (a powerful hydrant system) and lacks a tested real-world prototype.

The article [9] introduces "Rakshak," a modular UGV designed for adaptable use in surveillance, logistics, and potentially hazardous environments. Its modular design, enhanced by a suite of sensors (LiDAR, camera, GPS, and IMU) and Wi-Fi communication, demonstrates the feasibility of UGVs in providing real-time data and operational flexibility in various terrains and conditions. This showcases the evolving capabilities of UGVs in addressing the need for efficient and safe operations in challenging and inaccessible areas. Despite these strengths, the UGV's control range is restricted to 600 m, limiting operational scope. It lacks detailed calculations for obstacle negotiation and payload interchangeability (e.g., firefighting devices, combat modules, and manipulators) and is primarily suitable for laboratory environments, without autonomous decision-making or control system integration.

To summarize and evaluate the different UGV control methods, a comparison table summarizing and evaluating UGV control methods is presented in Table 1.

The U.S. Army's experimentation with battlefield robotics, as described in [10], not only illustrates the potential for enhancing safety and operational efficiency but also highlights the challenges of integrating and gaining trust in autonomous technologies among soldiers. This underscores the critical balance between technological innovation and user adaptability in military contexts.

The article [11] discusses the integration of robotics and autonomy into combat scenarios to enhance efficiency and safety, reflecting a significant shift towards advanced technological warfare. It highlights recent trends in military robotics and spatial control approaches, while also implying the need for further research on integration challenges, operational reliability, and policy implications of deploying autonomous technologies in complex and unpredictable environments.

A study of the literature shows that an important area of development is the creation of unmanned ground-based robotic complexes with a high degree of modularity and the ability to quickly change equipment to perform specific tasks. Modern platforms are developed using advanced technologies, including artificial intelligence algorithms and hybrid-electric power plants, which ensure high efficiency under diverse operating conditions. In addition, specialized UGV systems demonstrate a variety of approaches to improving mobility and adaptability to complex terrains, including the use of different chassis types and suspension architectures.

Within the Republic of Kazakhstan, research on MAUGVs for critical applications (firefighting, demining, and combat module deployment) remains significantly limited, highlighting a considerable developmental lag in areas such as autonomy, control system integration, and advanced computer vision applications. Localized studies addressing these areas are sparse, underscoring the necessity for practical, integrated research solutions.

Studies classify motion control systems for UGVs into several main types, differential steering, Ackermann steering, and omnidirectional (holonomic) drive systems [12]. Differential steering, based on independent control of wheel speeds on either side, is simple and well-suited for tight spaces, though it may struggle with traction on uneven terrain. Ackermann steering, often used in car-like robots, provides stable high-speed motion and efficient path tracking but is limited in turning radius. Omnidirectional drives allow motion in any direction and offer exceptional maneuverability, especially in confined environments, but require more complex mechanics and control algorithms.

Despite significant advancements, the gap in current UGV research lies in the integration of complex autonomous capabilities with robust operational effectiveness across diverse and challenging environments. Many studies show promising individual components and subsystems, yet the holistic integration that would allow UGVs to operate autonomously in a wide range of real-world applications remains elusive. The primary barriers include limitations in autonomous capabilities, sensor integration, real-time processing, and the physical robustness of systems designed for varied operational contexts. This research aims to address these challenges by developing a MAUGV that integrates advanced control systems, robust sensor fusion, and modular design to enhance its operational capabilities in complex environments.

In the context of our research, special attention is paid to the analysis of the differential type of steering on a tracked platform as the most versatile and adaptive solution for performing a wide range of tasks in difficult terrain. The choice of the tracked track is due to its high cross-country ability and stability on various types of surfaces, which makes it ideal for use in special operations where a high level of mobility and reliability is required.

Table 1: Comparison table summarizing and evaluating different UGV control methods

Control method	Flexibility and adaptability	Performance and reliability	Navigation ability	Level of automation
Mecanum wheel drive [5]	High flexibility in confined spaces; omnidirectional movements	Moderate performance; limited reliability on uneven terrain	Good indoor navigation; limited off-road capability	Low to moderate (remote operation)
Arduino-based control [4, 6, 8]	Moderate flexibility; easily programmable; limited peripheral integration	Limited computational capability and data handling	Basic obstacle avoidance and navigation; limited precision	Low (mostly remote/manual)
PID-based control system	Moderate flexibility; suitable for various applications after proper tuning	High reliability and accuracy under controlled conditions; requires extensive tuning for varying conditions	Effective in controlled scenarios; limited robustness in unpredictable terrains	Moderate (can be semiautonomous)
Finite element modeling [6]	Limited operational flexibility; mainly structural optimization-oriented	High performance in vibration reduction and structural optimization; indirectly increases reliability	Indirectly improves navigation by minimizing vibration impacts on sensors	Low (no direct automation)
Modular design concept [9]	High flexibility and adaptability; easy payload interchangeability	Reliable performance if properly designed for rapid reconfiguration	Good navigation ability when coupled with appropriate sensors	Moderate to high (depends on integrated sensors and control system)
AI-based sensor fusion and computer vision [8, 9]	Moderate to high flexibility; highly adaptable through software	High performance in environment perception; enhanced operational reliability through advanced sensing	Good navigation capability; obstacle detection and classification	High (semiautonomous to fully autonomous)
Remote control via radio and other transmissions [3–5, 8, 9]	Moderate flexibility; dependent on communication range	High reliability within operational range; degraded performance at range limits or signal loss	Navigation limited by communication strength; remote operator-dependent	Low (mostly remote/manual)

The article examines the structure and management system of the MAUGV, the important aspects of which are to ensure a high level of mobility and adaptability to diverse terrain conditions. The fifth section of the article provides an analysis of the drive power required to ensure effective movement in a straight line and perform maneuvers and also examines the patency of the MAUGV when overcoming various obstacles, which is critically important for performing support tasks in special operations. To assess the effectiveness of the developed solutions, the simulation results are compared with real tests of the MAUGV prototype developed during research and development work carried out within the framework of grant funding for young scientists for 2022–2024 (IRN AP130007/0222).

3. The Aim and Objectives of the Study

The aim of this research is to enhance the operational efficiency and autonomy of the MAUGV by developing and validating a control and performance model that integrates advanced control systems, robust sensor fusion, and modular design.

To achieve this aim, the following objectives are accomplished:

- Developing the MAUGV control model and examining its structure and fundamental principles of control to optimize the control process;
- Analyzing the motor characteristics of the MAUGV and determining the optimal drive parameters to ensure the required performance, which includes selecting power, torque, and efficiency;
- Investigating the MAUGV's capabilities to overcome various obstacles along its path and analyze its cross-country ability, which will help identify limitations and needs for additional control functions or adaptations;
- Integrating a rapid module change capability through a bayonet connection system to enhance the MAUGV's adaptability across different missions;
- Conducting a comparative analysis of the mathematical modeling results with data obtained during the prototype testing of the MAUGV to assess the effectiveness of the developed models and verify their applicability.

4. Materials and Methods of Research

The primary object of this study is the MAUGV, focusing on its structural, control, and operational characteristics. This vehicle is designed to be operated remotely or autonomously in various environments, adapting to different terrains and obstacles.

The hypothesis underlying this research is that the integration of a control model and optimized motor characteristics in the MAUGV can enhance its operational efficiency and autonomy, especially in complex environmental conditions.

Several assumptions have been made to streamline the study:

- The MAUGV operates under constant environmental conditions;
- The interactions between the vehicle's systems, such as, for example, between the navigation module and the drive system, are ideal;
- The dynamics of the MAUGV are simplified by treating it as a rigid body;
- The friction coefficients are assumed to be constant.

This research employs a combination of theoretical and experimental methods:

1. Theoretical methods include the development of a mathematical model using principles of kinematics and dynamics to describe the MAUGV's behavior. This model incorporates simulations in MATLAB and RecurDyn to predict the vehicle's performance under various operational conditions.
2. Experimental methods involve physical testing of the MAUGV prototype in a controlled environment designed to mimic realistic operational scenarios. These tests are aimed at validating the theoretical models and include measurements of energy consumption, maneuverability, and obstacle navigation capabilities.
3. Comparative analysis techniques are used to align experimental data with theoretical outcomes, ensuring that the models accurately reflect real-world capabilities.

4.1. Summary of Methods. In this study, a combination of theoretical modeling and experimental validation was applied to analyze and optimize the performance of the MAUGV.

4.1.1. Strengths of the Proposed Methodology

- Employing theoretical calculations and simulation software (MATLAB and RecurDyn) provided an understanding of the MAUGV's operational characteristics, including motor performance, maneuverability, and cross-country capabilities. Such integration facilitates predictions and optimization prior to physical testing;
- Conducting experimental tests with a physical MAUGV prototype enabled validation of theoretical models, ensuring reliability and relevance of simulation results for practical scenarios;
- Incorporating a modular payload system with rapid bayonet connections improved operational flexibility and adaptability to diverse mission requirements.

4.1.2. Limitations of the Methodology

- The modeling and simulations assumed constant friction coefficients and idealized environmental interactions, potentially limiting accuracy in real-world terrains;
- Experimental tests were conducted under a restricted set of conditions, and the prototype did not fully cover all possible operational scenarios (e.g., extreme weather and varied soil conditions);
- Discrepancies between theoretical calculations and prototype test outcomes indicate room for refinement in the mathematical models.

4.1.3. Future Research Directions

- Incorporation of dynamic terrain interactions and variable friction conditions through advanced machine-learning techniques could significantly improve predictive accuracy;
- Future studies should involve extensive field testing across broader terrain types and operational environments, capturing more comprehensive performance data;
- Exploration of interoperability with aerial and ground-based unmanned systems can enhance collaborative operational capabilities and mission effectiveness.

5. Results of Evaluation and Verification of the Developed MAUGV Model Through Mathematical Modeling and Prototype Testing

5.1. Development of the MAUGV Control Model

5.1.1. Technological Basis. The architecture of the MAUGV is envisioned as a modular platform, allowing for easy adaptation and scalability depending on mission requirements. The primary focus is laid on engineering a robust control mechanism that coordinates all onboard systems efficiently, a navigation suite that ensures precise location and trajectory control, and a communication setup that facilitates seamless data exchange between the MAUGV and the ground control station. This integration not only enhances the vehicle's autonomy but also optimizes its performance across diverse operational landscapes.

The general view of the MAUGV is shown in Figure 1. The UGV is a unified platform, inside which functionally complete modules are placed: an intermediate mixing controller, a navigation module, an engine module, a communication module, and a power module located in the rear parts of the platform. The modular platform is a tracked chassis on rubber-metal tracks with spring suspensions made of support rollers. At the same time, in accordance

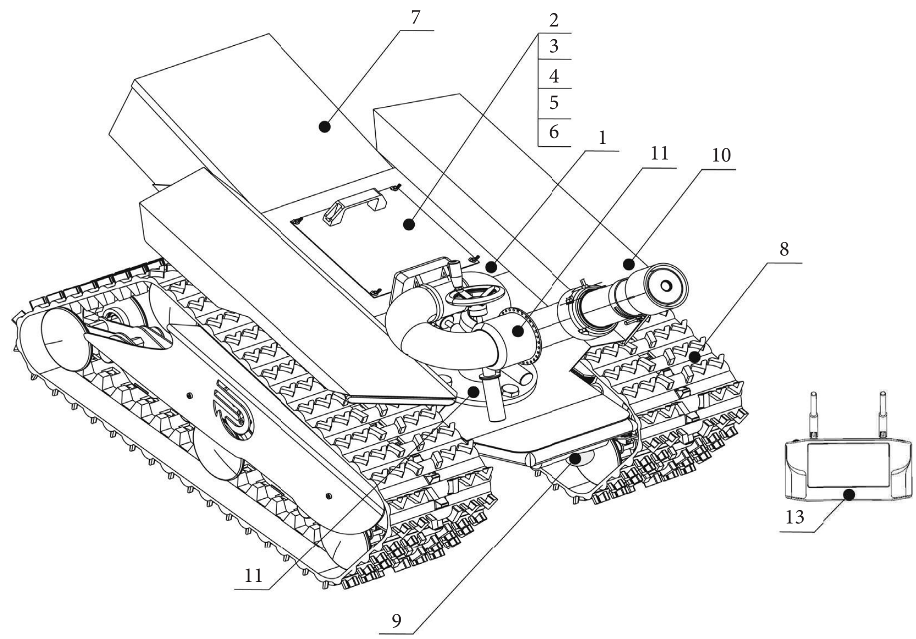

Figure 1: General view of the MAUGV highlighting important components: 1: platform; 2: cover; 3: intermediate mixing controller; 4: navigation module; 5: engine module; 6: communication module; 7: power module; 8: tracked chassis; 9: course camera; 10: lighting system; 11: universal connection; 12: interchangeable payload module; 13: ground control station.

with the peculiarities of the operation of the MAUGV, it is assumed that special methods of protection against destruction of rubber products and surfaces of individual groups of metals from corrosion will be used [13].

For real-time video surveillance during manual control, a course camera is installed on the body of the unified modular platform [14]. Halogen headlights are installed as a lighting system on the front of the body.

To enhance the multifunctionality of the MAUGV, a bayonet connection system is introduced within the universal connection of the platform. It allows for rapid and secure attachment and detachment of various payload modules, such as firefighting devices, manipulators, or weaponry, enabling the MAUGV to switch roles efficiently on the field. This connection not only significantly reduces the time required for module changes compared to traditional screw-based or manual locking systems but also ensures robustness and reliability in harsh operational environments.

A ground control station is used to control MAUGV, which exchanges data over a data transmission channel created for this purpose. The block diagram of the MAUGV control system is shown in Figure 2.

When the power is turned on, the power module provides electricity to the entire system. The battery charge controller continuously measures the charge/discharge level of the battery, its voltage, capacity, and temperature values. If these values exceed acceptable levels, the battery charging/discharging controller transmits a signal to the intermediate mixing controller. In addition, the functions of the battery charging/discharging controller include charging the battery, with voltage control of each cell. Then, using the power distribution system, the system receives differentiated power according to the set voltages for each module.

After activating the system startup, the intermediate mixing controller receives the initial data from the connected modules and goes into standby mode, ready for further processing.

In the next step, after the start of movement, the intermediate mixing controller receives data from the power module and the navigation module.

The intermediate mixing controller requests data from the navigation module about the current location of the MAUGV. Inside the navigation module, the automatic navigation system polls satellite navigation equipment to obtain current geographical coordinates, as well as inertial navigation equipment, to obtain azimuth values and deviation angles. The intermediate mixing controller uses the information received to follow the route.

The engine module controls the movement of the MAUGV. After determining the required direction of movement or receiving a command from the operator from the ground control station, the intermediate mixing controller transmits the corresponding control signal to the controllers of the left and right motors. These signals determine the speed and direction of rotation of each of the motors. The motors have their own controllers that receive commands from the intermediate mixing controller and control the corresponding motors.

The communication module exchanges information with the ground control station. This module includes a radio modem and remote-control equipment. By means of a radio modem, the signal/data are directly transmitted/received to/from the ground control station. The received signal includes a command to control a MAUGV with manual control, as well as commands to activate automatic movement. In the opposite direction, a confirmation signal

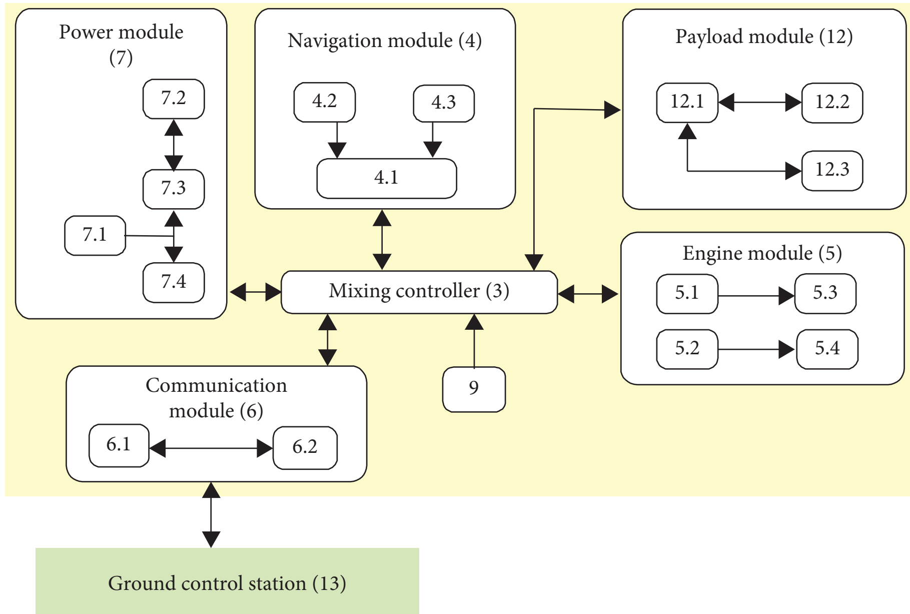

Figure 2: Block diagram of the MAUGV control system showing important components: 3: mixing controller; 4: navigation module; 4.1: automatic navigation system; 4.2: satellite navigation equipment; 4.3: inertial navigation equipment; 5: engine module; 5.1: left motor controller; 5.2: right motor controller; 5.3: left motor; 5.4: right motor; 6: communication module; 6.1: radio modem; 6.2: remote-control equipment; 7: power module; 7.1: power switch; 7.2: battery; 7.3: battery charge controller; 7.4: power distribution system; 9: camera; 12: payload module; 12.1: payload controller; 12.2: payload module controller; 12.3: position sensors; 13: ground control station.

of the received command, the current status of the system, and the readings of the remaining modules are sent to the ground control station.

The payload module receives signals from the intermediate mixing controller to control the payload and activate its functionality and sends current information about the status of the payload.

Thus, a MAUGV refers to robotic complexes designed for remote operation in open areas and indoors with the ability to install replaceable payload modules depending on the performance of various special tasks.

The technical parameters of the MAUGV are shown in Table 2.

Following Table 2, which outlines the technical parameters of the MAUGV, it is crucial to interpret the figures in the context of the vehicle's design and operational capabilities. The dimensions and weight of the MAUGV, including its length of 1000 mm, width of 770 mm, and height of 400 mm, with a weight of 100 kg without payload, are indicative of a compact yet robust platform capable of accommodating additional modules up to 150 kg. This balance of size and carrying capacity ensures that the vehicle can navigate through various terrains while carrying significant payloads, essential for diverse operational tasks.

The travel speed of 6 km/h, combined with a track support length of 770 mm and a track width of 220 mm, offers a stable and efficient movement across different surfaces, enhancing the MAUGV's ability to perform in challenging conditions. Furthermore, the ground clearance of 200 mm is particularly noteworthy as it enables the vehicle to overcome obstacles and navigate uneven terrain

Table 2: Technical parameters of MAUGV.

Name of the parameter	Meaning
Length (mm)	1000
Width (mm)	770
Height (mm)	400
Weight without payload (kg)	100
Maximum payload weight (kg)	150
Travel speed (km/h)	6
The length of the track support part (mm)	770
Track width (mm)	220
Ground clearance (mm)	200

effectively, which is critical for an autonomous vehicle operating in unpredictable environments.

5.1.2. Autopilot Implementation. Also, it is necessary to develop an integrated autopilot system for the MAUGV that ensures robust autonomous operation through precise control, navigation, and communication functionalities.

The autopilot system is implemented on the mixing controller. The autopilot's software, developed in C, runs on high-performance NVIDIA Jetson Xavier computer under the Ubuntu operating system, ensuring multitasking in real-time. The architecture is designed to be modular, which facilitates updates and scalability.

The MAUGV autopilot includes several important control loops. These loops enable autonomous mission execution, movement stabilization, and navigation in changing environments. The important control loops of the MAUGV autopilot include directional stability (heading or yaw control), speed control, and obstacle detection and avoidance.

In the MAUGV, equipped with a differential track speed control system, the process of stabilizing the direction of movement (heading) and speed is achieved through individual control of the rotational speed of the left and right tracks. PID controllers play a crucial role in this process, ensuring precise and stable control.

1. Heading stabilization in the MAUGV with a differential control system involves a process where the autopilot adjusts the vehicle's travel direction to maintain a set course. This process is described as follows:

   - Using sensors such as GNSS and the inertial measurement unit (IMU), the autopilot continuously determines the MAUGV's current direction of travel;
   - The heading error is defined as the difference between the MAUGV's current heading and the target heading it is supposed to maintain. The target heading can be set by the operator or the mission planning system;
   - Applying the PID controller;
   - Based on the output from the PID controller, the differential control system adjusts the rotational speeds of the left and right tracks independently, creating the necessary torque to change the direction of movement. Increasing the speed of one side and decreasing the speed of the other allows the MAUGV to turn and return to the target course.

2. In managing the movement speed of the MAUGV, the autopilot regulates the vehicle's speed to maintain it at a specified level. This is achieved using a PID controller, which analyzes the current speed of the vehicle, compares it with the desired speed, and generates the appropriate control commands for adjustment. The process of regulating the MAUGV's movement speed is described as follows:

   - Using speed sensors and other navigation systems (such as GNSS and IMU), the autopilot continuously determines the current speed of the MAUGV;
   - The speed error is defined as the difference between the current speed of the MAUGV and the target speed it aims to achieve. The target speed may be set in the mission parameters or by the operator;
   - Applying the PID controller;
   - Based on the output signal from the PID controller, the speed of the MAUGV is adjusted. This includes adjusting the power of the engine and changing the rotation speeds of the tracks.

3. Obstacle detection and avoidance are critical functions for the MAUGV, enabling it to safely navigate in diverse environments. The main aspects of the obstacle detection and avoidance process include the following:

   - Equipped with sensors (LIDARs, ultrasonic sensors, infrared sensors, and cameras), the MAUGV can perceive its surroundings and detect obstacles in its path;
   - Data collected by the sensors are processed using an intermediate mixing controller to recognize and classify objects around the vehicle and determine whether they are obstacles; upon detecting an obstacle, the MAUGV alerts the operator or employs an obstacle avoidance algorithm. In cases of autonomous obstacle avoidance, the MAUGV operates according to the «Bug 2» algorithm.
   Below is the Bug 2 algorithm:
   - Define the line from start to target (this line is an imaginary straight line connecting the starting point to the destination point);
   - Move towards the target along the line from start to target. If an obstacle is encountered remember the location where the obstacle was first encountered. This place is called the «collision point». Follow along the wall until you intersect again with the line from start to target. This place is called the «exit point». If the exit point is closer to the target than the collision point, leave the wall and move towards the target again. Otherwise, continue to follow along the wall.

Additionally, there is an automatic return mode. The MAUGV autonomously, or upon command from the operator, returns to a designated point or base for recharging or maintenance after completing a task or when the battery level is low.

The block diagram of the MAUGV autopilot system is illustrated in Figure 3.

5.2. Motor Characteristics Analysis and Drive Parameter Optimization of the MAUGV. The calculation of the drive power allows to determine the necessary power and energy required to effectively propel an UGV on a tracked track. At the same time, it is necessary to take into account such factors as the weight of the device, the required speed, the characteristics of the motors, and drive systems [12]. The results of calculating the drive power can help in selecting the appropriate components and optimizing the operation of the device [15].

To ensure the movement of the MAUGV, it is necessary to determine the required technical characteristics of the engine, namely, its traction characteristics. To do this, it is necessary to take into account the following counteracting forces acting on MAUGV: rolling resistance, slope resistance, aerodynamic forces, acceleration force, etc. [16].

In this section, the established drive power requirements calculation method is applied, previously used for tracked vehicles and tractors [17], to the specific needs of the MAUGV. This approach not only demonstrates an innovative application of existing methodologies to new domains but also enhances the design and selection of

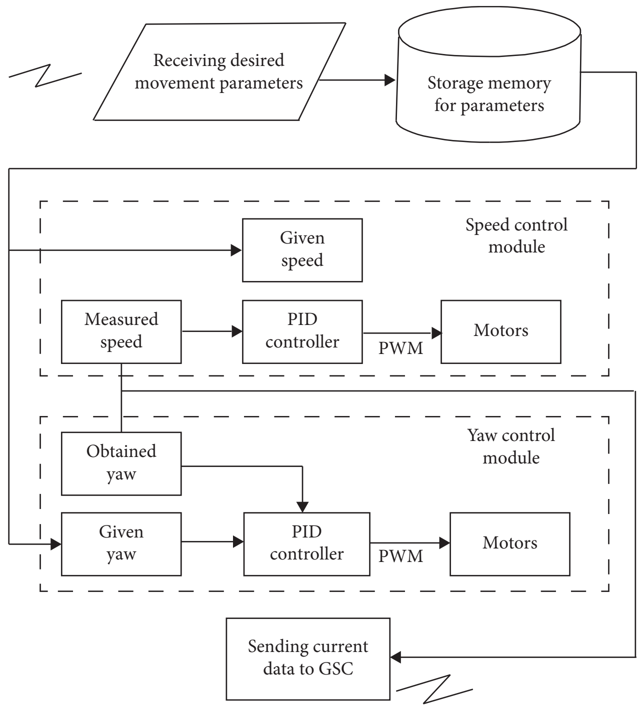

Figure 3: Block diagram of the MAUGV autopilot system.

components critical for the MAUGV's performance. By utilizing this method, the aim is to determine the precise power and traction necessary for the MAUGV to navigate effectively across different surface inclinations and to manage various operational demands.

5.2.1. Calculation of Engine Power When Moving Along a Straight Trajectory. First, the pressure of the MAUGV on the surface is determined:

$$p = \frac{m \cdot g}{2 \cdot a \cdot b}, \tag{1}$$

where a is the length of the track support part and b is the width of the track.

Then, the surface deflection resistance is determined as

$$P_1 = 2 \cdot \mu \cdot p \cdot a \cdot b. \tag{2}$$

The support rollers experience a resistance force calculated by the formula

$$P_2 = 2 \cdot \kappa \cdot p \cdot a \cdot b. \tag{3}$$

The component of gravity in motion of the MAUGV is

$$P_3 = m \cdot g \cdot \sin\phi, \tag{4}$$

where ϕ is the angle of the longitudinal roll.

At the beginning of movement or an increase in speed, inertia forces create resistance to movement

$$P_4 = c \cdot m \cdot \frac{(1-\varepsilon)\vartheta_0}{t}, \tag{5}$$

where c is the coefficient that takes into account the movement of masses with increasing speed and ε is the coefficient of slipping.

The total tractive effort required for movement is calculated using the formula

$$T = \sum_{i}^{N} P_i. \tag{6}$$

Then, the power for moving in a straight line is

$$N = \frac{T \cdot \vartheta_0}{1000\eta}. \tag{7}$$

The reserve of adhesion of the tracks to the surface is provided if the following conditions are met:

$$2f \cdot p \cdot a \cdot b > 2\mu \cdot \text{p} \cdot \text{a} \cdot b + m \cdot g \cdot \sin\phi + c \cdot m \cdot \frac{(1-\varepsilon)\vartheta_0}{t}. \tag{8}$$

Based on the above calculations and conditions, the engine is selected with a power of 350 W, with a maximum rotation speed of 4500 rpm. Then, the output torque for the selected engines will be 47.8 Nm.

The calculation of traction characteristics for several values of the surface inclination angles is shown in Table 3.

From the above data (Table 3), it can be concluded that with an increase in the angle of inclination, the value of the traction force and torque that must be applied to climb the inclined surface increases. At the same time, the 35° elevation angle turned out to be critical for MAUGV. In addition, traction forces are affected by the coefficient of adhesion of the tracks to the surface.

5.2.2. Calculation of Traction Characteristics When Turning. The calculation of traction characteristics during rotation makes it possible to evaluate the effectiveness and ability of an UGV on a tracked track to cope with the required level of thrust during maneuvers and turns. This calculation takes into account factors such as the geometry and design of the tracked system, the mass of the vehicle, friction, and resistance to movement. The results of the calculation of traction characteristics during rotation can help optimize the design and parameters of the device, as well as plan its behavior and maneuverability in various situations. The method given in [17] is used for the calculation.

The pressure exerted on the surface by the rear track is determined by the formula

$$p_1 = \frac{m \cdot g\left((d/c) - x_c\right)\cos\phi}{a \cdot b \cdot d}, \tag{9}$$

where d is the width of the MAUGV and x_c is the distance between the guiding axis of the MAUGV to its center of gravity along the transverse axis.

The pressure exerted on the surface by the front track is calculated as

$$p_2 = \frac{m \cdot g\left((d/c) + x_c\right)\cos\phi}{a \cdot b \cdot d}. \tag{10}$$

Table 3: Results of calculation of traction characteristics for various variants of the angle of inclination of the surface.

Required pulling force (N)	Required torque (Nm)	Surface adhesion margin
The angle is 2°; the surface type is asphalt		
166.7	9.7	Enough
The angle is 15°; the surface type is asphalt		
452.2	26.2	Enough
The angle is 30°; the surface type is asphalt		
759.8	44.1	Enough
The angle is 35°; the surface type is asphalt		
853.6	49.5 (not enough traction)	Enough
The angle of elevation is 2°; the type of surface is snow		
183.5	11.2	Enough
The angle of elevation is 15°; the type of surface is snow		
469.4	29.8	Not enough

Longitudinal components of the vector of external forces

$$P_y = -\mu \cdot a \cdot (p_1 + p_2) - m \cdot g \cdot \sin\phi. \tag{11}$$

The main moment of external forces is defined as

$$M = -\mu \cdot a \cdot (p_2 - p_1)\frac{d}{2} - m \cdot g \cdot \sin\phi \cdot x_c. \tag{12}$$

Displacement of the centers of rotation of the rear and front tracks

$$\begin{cases} e_{1x} = \dfrac{a^2}{8d} + \dfrac{\sqrt{\left(4d^2 + a^2\right)^3}}{32 f \cdot p \cdot d^3 \cdot b} \cdot \left(\dfrac{P_y}{2} - \dfrac{f \cdot a^2 b (p_1 - p_2)}{2\sqrt{4d^2 + a^2}} - \dfrac{4M \cdot d}{4d^2 + a^2}\right), \\ e_{2x} = \dfrac{a^2}{8d} + \dfrac{\sqrt{\left(4d^2 + a^2\right)^3}}{32 f \cdot p \cdot d^3 \cdot b} \cdot \left(-\dfrac{P_y}{2} + \dfrac{f \cdot a^2 b (p_1 - p_2)}{2\sqrt{4d^2 + a^2}} - \dfrac{4M \cdot d}{4d^2 + a^2}\right), \\ e_y = \dfrac{P_x\sqrt{4d^2 + a^2}}{16P \cdot b \cdot d}. \end{cases} \tag{13}$$

The friction forces are calculated as

$$\begin{cases} T_{1y} = -\dfrac{f \cdot p_1 a \cdot b \cdot e_{1x}}{\sqrt{e_{1x}^2 + \left(\left(a^2\right)/16\right)}}, \\ T_{2y} = -\dfrac{f \cdot p_2 a \cdot b \cdot e_{2x}}{\sqrt{e_{2x}^2 + \left(\left(a^2\right)/16\right)}}. \end{cases} \tag{14}$$

The lateral forces are calculated using the formulas

$$\begin{cases} T_{1a} = \dfrac{f \cdot p_1 \cdot a^2 \cdot b}{4 \cdot \sqrt{e_{1x}^2 + \left(\left(a^2\right)/16\right)}}, \\ T_{2a} = \dfrac{f \cdot p_2 \cdot a^2 \cdot b}{4 \cdot \sqrt{e_{2x}^2 + \left(\left(a^2\right)/16\right)}}. \end{cases} \tag{15}$$

Traction forces of the tracks

$$\begin{cases} T_{1T} = T_{1y} + \mu \cdot p_1 \cdot a \cdot b + k \cdot p_1 \cdot a \cdot b + k \cdot T_{1a}, \\ T_{2T} = T_{2y} + \mu \cdot p_2 \cdot a \cdot b + k \cdot p_2 \cdot a \cdot b + k \cdot T_{2a}. \end{cases} \tag{16}$$

Turning radius and angular velocity

$$\begin{cases} R = e_{1x} + \dfrac{d}{2}, \\ \omega = \dfrac{u_2}{e_{1x} + e_{2x} + d}, \end{cases} \tag{17}$$

where u_2 is the speed of the rear track.

Then, the power for driving on a turn is equal to

$$p = \frac{m \cdot g}{2 \cdot a \cdot b}, \qquad N_{\text{turn}} = \frac{T_{2T} \cdot u_2}{1000\eta}. \tag{18}$$

Let us determine the coupling coefficients of the first and second tracks:

$$\begin{cases} s_1 = \dfrac{\sqrt{e_{1x}^2 + e_y^2 + \left(\left(a^2\right)/16\right)}}{e_{1x}^2}, \\ s_2 = \dfrac{\sqrt{e_{2x}^2 + e_y^2 + \left(\left(a^2\right)/16\right)}}{e_{2x}^2}. \end{cases} \quad (19)$$

In order for MAUGV to make a turn, the following conditions must be met:

1. The thrust of the engines should be sufficient to make a turn:

$$N_{\text{turn}} > N_{\text{mot}}. \quad (20)$$

2. Providing traction:

$$s_1 > 1, s_2 > 1. \quad (21)$$

The results of calculating the traction characteristics during rotation for several values of the surface inclination angles are presented in Table 4.

The required traction force depends on the sum of the forces, including the traction force, the force of resistance to movement, and the force required to change the direction of movement when turning. Steeper surface angles require greater traction to overcome gravity resistance and maintain upward movement. The greater the angle of inclination, the more traction is needed to successfully complete turns. The turning radius determines the geometric constraints for the rotary movements of the device. At steeper surface angles, the device may need a wider turning radius to maintain the required level of thrust and avoid slipping or loss of stability.

5.2.3. Evaluation of MAUGV Performance on Soft Soil Conditions. To accurately assess the performance of the MAUGV on soft terrain, additional analyses are conducted using specialized heuristic formulas [18]. The interaction of the vehicle's tracks with soft soil surfaces significantly influences traction characteristics and motion resistance, which differ markedly from interactions with rigid terrain discussed in Sections 5.2.1 and 5.2.2.

The following formulas were applied:

Maximum tangential force transmitted by the track

$$X_{i\_\max} = \tau_{\max} A_{\text{track}}, \quad (22)$$

where $\tau_{\max}$ is the maximum tangential stress for the soil and A_{track} is the track contact area.

Maximum tangential stress (Mohr–Coulomb model) is

$$\tau_{\max} = c + p_{\text{track}} \tan \varphi, \quad (23)$$

where c is the soil cohesion, p_{track} is the track contact pressure, and φ is the soil internal friction angle (characterizing the soil shear strength).

Typical values were selected based on empirical data from similar applications, with soil parameters: cohesion $c = 20\,\text{kPa}$ and internal friction angle $\varphi = 30^\circ$. These parameters reflect common soft soil conditions, such as mud or wet clay, thus providing relevant insights into the vehicle's performance under realistic operational scenarios.

Table 4: Results of calculation of traction characteristics when turning

Traction force of the front track (N)	Turning radius (mm)	Conditions for making a turn
Angle = 2°; surface type: asphalt		
361.1	394	Provide
Angle = 10°; surface type: asphalt		
410.3	443	Provide
Angle = 15°; surface type: asphalt		
426.2	—	Provide

Results of calculations for the MAUGV's performance on soft soils are summarized in Table 5, demonstrating how variations in soil characteristics (soil cohesion and friction angle) impact resistance forces and traction capabilities.

As shown in Table 5, increasing soil cohesion and internal friction angle leads to significantly greater tangential stresses and corresponding traction forces. This emphasizes the importance of selecting appropriate design parameters to ensure optimal performance of the MAUGV in varied soft soil environments.

5.3. Cross-Country Analysis of a MAUGV. The cross-country analysis is aimed at assessing the ability of an UGV to overcome various types of obstacles. It takes into account parameters such as dimensions, weight, and track system, as well as surface properties and type of obstacle.

The patency analysis will allow identifying limitations and weaknesses in the design and characteristics of the device, when moving the MAUGV on a surface with a longitudinal roll and overcoming obstacles and depressions. The results of the analysis can be used to optimize parameters such as the shape and size of the tracks, suspension system, power, and drive control, which in turn can help improve the maneuverability of the vehicle. This subsection uses mathematical expressions proposed in [20].

5.3.1. The Possibility of Movement With a Longitudinal Roll of the Surface. When analyzing the lifting possibilities for MAUGV, the following factors must be taken into account (Figure 4):

- Its mechanical and geometric characteristics (mass, center of gravity, suspension and its parameters, type and characteristics of engines, and transmissions), affecting the ability of the MAUGV to overcome gravitational forces and stay on an inclined surface;
- The friction force determined by the coefficient of adhesion between the tracks and the road surface;
- The gravitational force depending on the angle of inclination β of the surface.

Table 5: Influence of soft soil characteristics on MAUGV traction and resistance forces [19].

Soil cohesion (kPa)	Friction angle (°)	Maximum tangential stress (kPa)	Maximum tangential force (N)
10	25	11.35	3845.4
20	30	21.67	7341.8
30	35	32.03	10,851.8
40	40	42.43	14,375.3

When climbing an inclined surface at a constant speed, the sum of the acting forces will be zero:

$$G \cdot u \cdot \cos\beta - G \cdot u \cdot \sin\beta - N \cdot w = 0, \tag{24}$$

where u is the distance from the center of gravity of the MAUGV to the vertical axis of the rear support wheel.

Then, the maximum lifting angle will be equal to

$$\beta_m = \arctan\left(\frac{u}{h}\right), \tag{25}$$

where h is the height of the center of gravity of the MAUGV.

Figure 5 shows a graph of the dependence of the maximum angle of inclination on the position of the MAUGV center of gravity. An increase in the height of the center of gravity leads to a decrease in the maximum angle of inclination of the surface at a constant value of the distance from the center of gravity to the vertical axis of the rear support wheel. In this case, the maximum tilt angle increases with increasing distance between the center of gravity and the vertical axis of the rear support wheels.

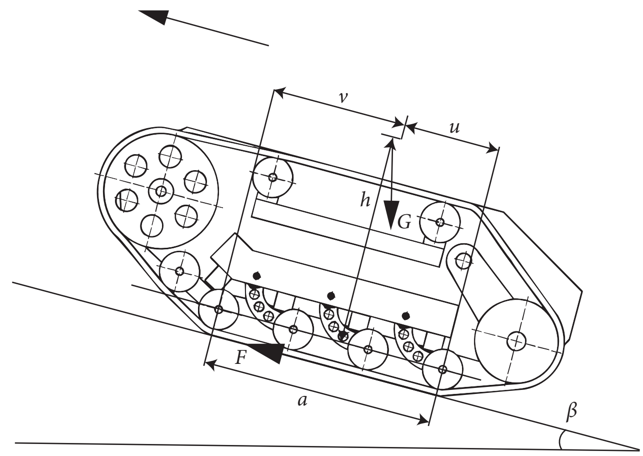

Figure 4: Forces acting on the MAUGV during ascent.

5.3.2. The Possibility of Overcoming Ledges. Figure 6 schematically shows a MAUGV overcoming an obstacle in the form of a step with a height of h_0.

To calculate the maximum possible height of the obstacle that the MAUGV can overcome, it is necessary to find the maximum possible angle of inclination of the MAUGV using the formula [20]

$$\theta_{\max} = \arctan\left(\frac{a}{2h_1}\right), \tag{26}$$

where a is the length of the track support part.

The maximum height of the ledge will be equal to

$$h_0(\theta) = \left(\frac{1}{2}a + R \cdot \tan\frac{\theta}{2} - h_2 \tan\theta\right)\sin\theta, \tag{27}$$

where R is the radius of the support wheel and h_2 is the height to the axis of the front driving wheel.

$$h_0 = \min\left(h_2, h_0\left(\theta_{\max}\right)\right). \tag{28}$$

Thus, with an increase in the possible angle of inclination of the device, its ability to overcome obstacles increases (Figure 7).

5.3.3. The Ability to Overcome Different Obstacles. Figure 8 schematically shows a MAUGV overcoming an obstacle in the form of a ditch with a width of H.

The maximum length of the depression H that the MAUGV can overcome is determined by the following formula [20]:

$$H = v + \left(h_1 + R\right)\tan\theta, \tag{29}$$

where v is the distance from the center of gravity of the MAUGV to the vertical axis of the front support wheel.

Figure 9 shows a graph of the dependence of the maximum length of the obstacle on the position of the MAUGV center of gravity. An increase in the height of the center of gravity, as well as the distance from it to the vertical axis of the front wheels, leads to an increase in the length of the recess to be overcome. At the same time, it is necessary to consider the design features of the MAUGV, which impose restrictions on the location of the center of gravity.

Using the above expressions, as well as considering the geometric dimensions of the MAUGV, the maximum lifting angle is 39°, the maximum height of the obstacle is 204 mm, and the maximum possible length of the ditch to be overcome (on a flat surface) will be 485 mm.

5.4. Comparative Analysis of Modeling and Prototype Testing Results

5.4.1. Simulation in RecurDyn. The RecurDyn software environment was used for additional analysis of MAUGV traction characteristics and assessment of MAUGV patency. A model of a path with obstacles [21] has been generated,

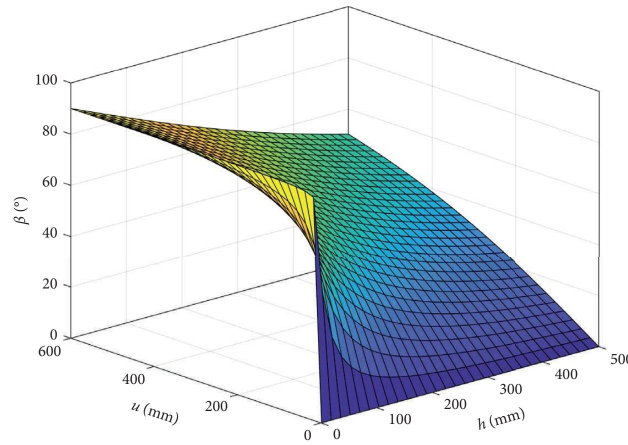

Figure 5: Graph of the dependence of the maximum angle of inclination on the position of the center of gravity of the MAUGV.

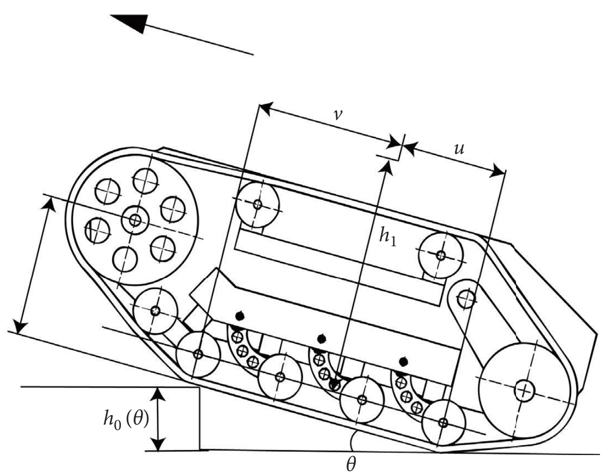

Figure 6: Overcoming an obstacle.

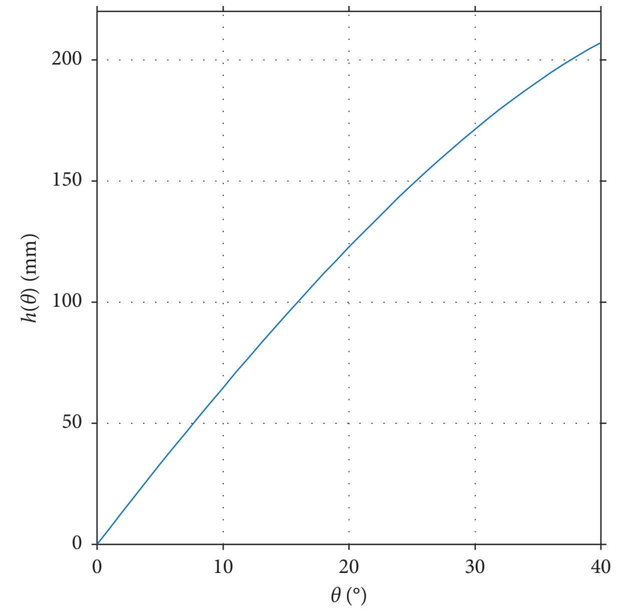

Figure 7: Graph of the dependence of the height of the obstacle on the angle and the slope of the MAUGV.

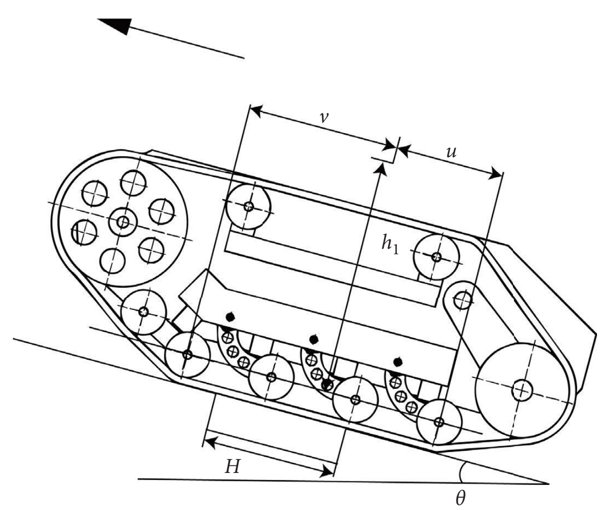

Figure 8: Overcoming the obstacles.

including ascents, steps, and ditches with dimensions close to real ones (Figure 10).

As a result of the simulation, a graph of the dependence of the traction force on the changing profile of the road was obtained (Figure 11). From this figure, it can be seen that the value of the traction force increases when the MAUGV ascends an inclined surface and overcomes obstacles. At the same time, the maximum tractive effort does not exceed 760 N (Table 2), which confirms the theoretical calculations for the selected engine type and the mass dimensions of the MAUGV.

As illustrated in Figure 11, the simulation conducted in the RecurDyn software environment highlights the MAUGV's robust traction capabilities across varied terrains, including inclined surfaces and obstacles. The increasing traction force corresponding to the vehicle's ascent and obstacle negotiation aligns with the anticipated physical behavior, validating the efficacy of the MAUGV's design for operational flexibility in challenging environments. The peak traction effort, capped at 760 N, underscores the engineered balance between power output and the vehicle's structural integrity, ensuring operational safety without compromising on performance. This alignment between simulation outcomes and theoretical predictions underscores the reliability of our model in forecasting the MAUGV's field performance, further corroborating the vehicle's engineered readiness for real-world applications. The subsequent analysis will delve into prototype testing results to compare and contrast with these simulated findings, aiming to provide a comprehensive evaluation of the MAUGV's operational capabilities.

5.4.2. Prototype Testing Results. To verify the theoretical calculations, as well as to assess the capabilities of the MAUGV, a series of practical tests of the prototype was carried out: climbing an inclined surface, climbing steps (Figure 12), and overcoming a moat.

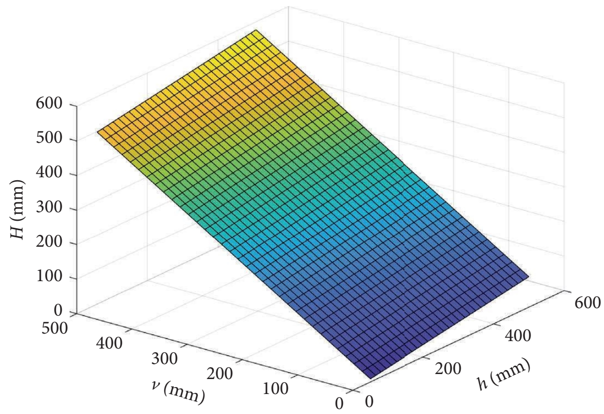

Figure 9: Graph of the dependence of the maximum length of the obstacle on the position of the center of gravity of the MAUGV.

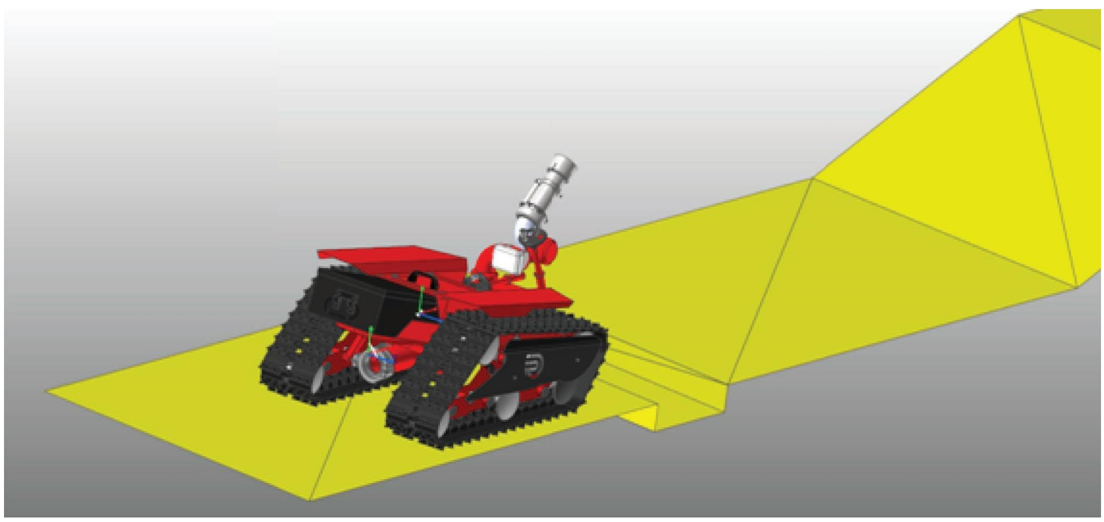

Figure 10: The MAUGV model in RecurDyn.

During the test, MAUGV was able to climb a slope with an angle of 30°, cross a 400 m-wide moat, and overcome a 200-mm-high step.

The results of comparing the theoretical calculations with the test results of the prototype are shown in Table 6.

In general, there are minor discrepancies between the theoretical model and the capabilities of the prototype MAUGV. The largest difference was recorded at the crossing of the moat—the difference was 18%. The reasons for the discrepancy may be inaccuracy of the theoretical model, surface unevenness, measurement errors, and other factors [22].

6. Discussion of the Study Results on the Development and Performance Evaluation of the MAUGV

During the study, various aspects of the functioning and management of the MAUGV were considered, which made it possible to achieve results in each of the tasks set.

The analysis of the structure and principles of control (Figure 2) showed that the efficiency of the MAUGV directly depends on the integration of modern control algorithms and adaptation to changing environmental conditions.

The obtained results are underpinned by a calculation of the drive power and traction capabilities of the MAUGV, factoring in the vehicle's weight, desired speed, motor characteristics, and drive systems. These calculations, outlined by formulas (1)–(8), address the counteracting forces such as rolling resistance, slope resistance, and aerodynamic forces, which are basic for determining the necessary technical specs of the engine to ensure effective propulsion across different terrains.

Table 3 illustrates how traction requirements escalate with the angle of incline, highlighting the critical angle of 35° for the vehicle's performance. This analysis demonstrates the importance of selecting an engine with sufficient power (chosen as 350 W) and optimizing the vehicle's design to maintain balance between power output and the challenges posed by various environmental conditions. The approach ensures the MAUGV is equipped to navigate and perform in its operational landscape.

The calculation of traction characteristics for turning illustrates the MAUGV's ability to maintain necessary thrust

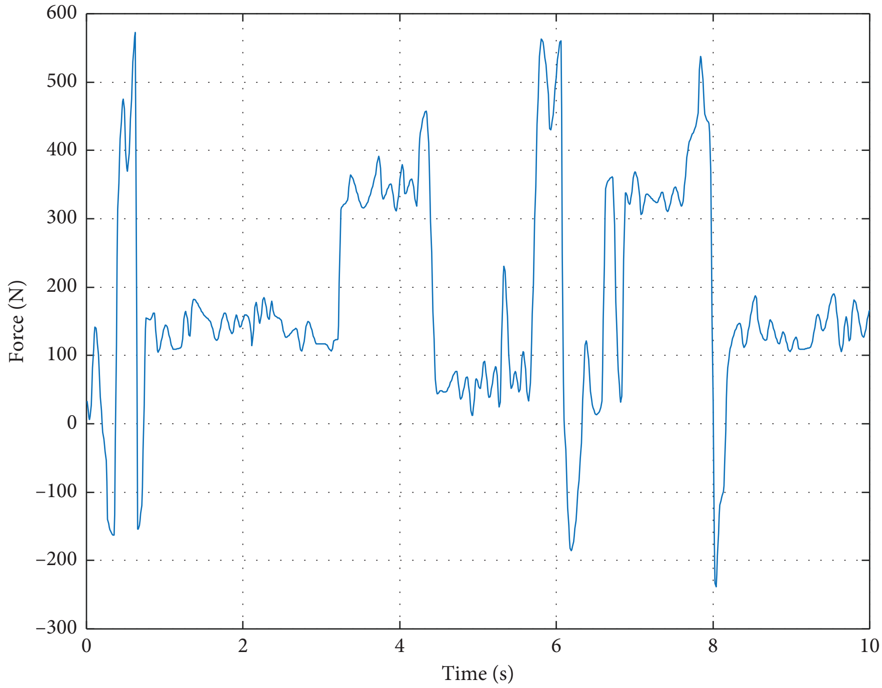

Figure 11: Profile of traction forces during the movement of the MAUGV.

(a) (b)

Figure 12: MAUGV test stage (climbing the steps): (a) MAUGV overcomes the middle of the stairs; (b) MAUGV overcomes the last step of the stairs.

Table 6: Results of comparison of theoretical calculations with the test results of the prototype

Results of modeling	Results of the test subject	Discrepancy
Maximum lifting angle 34° (from calculations of traction characteristics)	About 30°	4° (12%)
The maximum height of the obstacle 204 mm	About 200 mm	4 mm (or 2%)
Maximum width of the moat 485 mm	About 400 mm	85 mm (or 18%)

levels during maneuvers. This involves assessing factors like track design, vehicle weight, and friction. Important outcomes include optimizing design for maneuverability and planning vehicle behavior. Formulas (9)–(21) quantify these aspects, such as pressure exerted by tracks (9) and (10), external force components (11) and (12), and traction forces

(16), crucial for understanding vehicle dynamics during turns. Table 4 shows that traction varies with surface inclination, impacting turn radius and vehicle stability. This analysis aids in ensuring the MAUGV's design meets operational demands for varied terrains.

The cross-country and obstacle analysis of the MAUGV assesses its capability to navigate different terrains and surmount barriers, considering factors like size, weight, track design, and surface types. This analysis aids in identifying design limitations and informs adjustments in the UGV's tracks, suspension, and drive control for enhanced agility. Important formulas and figures (Figures 4 and 5) illustrate the forces at play and the impact of the vehicle's geometry on its ability to tackle inclines and obstacles. The outcomes, encapsulated by formulas (24)–(29) and visualized in Figures 5, 6, 7, and 8, highlight the vehicle's engineered capacity to climb angles up to 39°, clear heights up to 204 mm, and cross ditches up to 485 mm wide, showcasing a tailored approach to optimizing its design for robust off-road performance.

The results obtained from the comparative analysis of RecurDyn simulations and prototype testing of the MAUGV are explained through a blend of graphical representations, numerical data, and the correlation of theoretical calculations with practical outcomes. Figures 10 and 11 visually depict the simulation environment and the MAUGV's traction performance across various terrains, respectively, demonstrating an increase in traction force in challenging conditions. Table 3, while not detailed here, likely validates the engine choice and vehicle dimensions against simulation results. Table 6 compares theoretical predictions with prototype test results, showing minor discrepancies in capabilities such as climbing angles and overcoming obstacles, which emphasize the model's accuracy and highlight areas for refinement. These elements collectively validate the MAUGV's design and operational effectiveness, bridging theoretical planning and real-world application.

The proposed method and results of the study stand out due to their comprehensive approach towards enhancing the cross-country ability and operational efficiency of UGVs. Unlike existing works, such as the disaster detection vehicle system outlined in [6], which focuses on gas detection and disaster area surveillance, our study delves into a broader spectrum of obstacle-overcoming capabilities, optimizing motor characteristics, and ensuring adaptability across various terrains.

Our UGV model incorporates advanced control mechanisms and modular design principles, allowing for a more versatile application in comparison to the serial manipulator UGV discussed in [4]. This contrasts with the specific focus on control mechanisms seen in previous research, emphasizing our model's adaptability and multifunctional capabilities.

In comparison to [6], which centers on reducing ground-induced vibrations, our study provides a more holistic approach to UGV design, encompassing not only the structural but also the functional aspects, thereby addressing a wider range of operational challenges.

Our research contributes significant advancements in UGV development by integrating comprehensive cross-country analysis, modular design for adaptability, and enhanced control models, setting a new benchmark for future developments in UGV technology. Unlike a remotely controlled mobile robot (patent RU 2473863 C1, F41A 7/00, F42B 12/00, F41C 27/06, 01/27/2013) and a mobile robotic complex (patent RU 2364500, IPC B251 5/00 dated 10/31/2007), which have insufficient chassis patency and lack of navigation system, MAUGV has an advanced control and navigation system. This was made possible thanks to the integration of modern sensors and algorithms, which ensures high accuracy of orientation in difficult conditions and improved cross-country ability.

The robotic reconnaissance and fire support complex (patent RU 2548207, IPC F41H 7/00 dated 04/20/2015), which serves as the closest prototype, is limited in functionality and scope due to the lack of the possibility of replacing replaceable payload modules. In contrast, the MAUGV is designed with a modular architecture in mind, which allows you to quickly change the equipment of the device depending on current tasks and requirements, which ensures its high adaptability and a wide range of applications.

Thus, the important advantages of the MAUGV are its improved cross-country ability and navigation and the modularity of the design. These features not only provide superiority over known analogues but also expand the potential applications of the device, including performing specialized tasks in various operating conditions.

It should be noted that this study has a number of limitations. The proposed solutions and results are tailored to a specific MAUGV design, which may limit their direct applicability to vehicles with different designs or operational requirements without adaptations. Moreover, the study assumes certain environmental conditions for the MAUGV's operations. Performance variations under drastically different conditions (extreme temperatures, varied terrains not tested, etc.) are not fully explored. The research is based on simulations and prototype testing within a specific range of operational conditions and scenarios. The results' adequacy outside these parameters is not guaranteed.

One of the disadvantages of the study is that the current mathematical models and simulations might not fully capture the complexities of real-world terrains and operational scenarios. Future research could incorporate machine learning and artificial intelligence to develop adaptive models that can generalize across a broader range of conditions [23].

The prototype testing covered a limited set of terrains and obstacles. Expanding the testing to include a wider variety of environmental conditions and operational tasks will help identify additional limitations and refine the vehicle's design. Also, the study does not extensively address the integration of the MAUGV with other unmanned systems or command and control infrastructures. Future research could explore interoperability aspects and the development of standardized communication protocols for enhanced operational capabilities in multiagent scenarios.

In addition, less attention was paid to energy efficiency aspects, which is critical for long-term operations. Future studies could integrate comprehensive energy management strategies and renewable energy sources to enhance the MAUGV's operational endurance.

The future development of this study on the MAUGV could involve advancing autonomy through AI and machine learning for dynamic decision-making and improved navigation across complex environments [24]. Challenges include developing algorithms that can reliably interpret complex sensory data and make decisions in real-time, ensuring safety and effectiveness, also enabling coordinated operations with other unmanned systems (aerial and ground) for complex missions. This involves developing standardized communication protocols and control strategies, facing difficulties in ensuring reliable data exchange and synchronized actions among heterogeneous systems.

7. Conclusions

1. The development of the MAUGV control model has improved its operational capabilities. The integration of control algorithms, along with a modular and versatile platform design, facilitates maneuverability and adaptability across diverse environmental conditions. The MAUGV, equipped with interchangeable payload modules, can perform a range of tasks, such as firefighting support in inaccessible areas, reconnaissance, surveillance, and ordnance disposal under various climatic conditions. This modular design approach allows for rapid adaptation to mission-specific requirements, reducing material and time investments. Additionally, the automatic navigation system enhances the MAUGV's ability to autonomously navigate predetermined routes with high accuracy, ensuring effective execution of complex tasks in both open terrains and confined spaces.
2. Analyzing the motor characteristics and optimizing drive parameters of the MAUGV highlighted the critical balance between power efficiency and the vehicle's operational range. Optimized engine selection, considering forces like rolling resistance and slope resistance, enhanced MAUGV's adaptability to different terrains. Calculations showed the MAUGV's capability to handle various incline angles with sufficient traction, with a performance in managing slopes up to 35° before traction limits were reached. This analysis not only underscores the importance of considering environmental factors in design but also contributes to the development of more robust and versatile UGVs.
3. The results summarized in Table 5 illustrate the significant impact of soft soil characteristics, such as soil cohesion and internal friction angle, on the maximum tangential stress and corresponding traction forces achievable by the MAUGV.

   Specifically, increasing soil cohesion from 10 to 40 kPa and the internal friction angle from 25° to 40° leads to nearly a four-fold increase in maximum tangential stress (from 11.35 to 42.43 kPa) and subsequently raises the maximum achievable tangential force from 3845.4 to 14,375.3 N. This highlights the considerable influence that soil parameters have on the MAUGV's capability to generate traction forces on soft, deformable terrains.

   Under the most realistic operational conditions considered (cohesion 20 kPa and internal friction angle 30°), the MAUGV achieves a maximum tangential force of approximately 7341.8 N, substantially exceeding the earlier calculated traction requirement (approximately 760 N).
4. The cross-country analysis of the MAUGV has demonstrated an advancement in overcoming diverse terrains and obstacles, reflecting its robust design and versatile functionality. Through mathematical modeling and optimization of its track system, the MAUGV has shown a capability to tackle inclines up to 39°, surmount obstacles up to 204 mm in height, and traverse ditches up to 485 mm wide. This level of performance enhances the MAUGV's operational scope across various environmental conditions.
5. The integration of a rapid module change capability through a bayonet connection system significantly enhances the MAUGV's adaptability across different missions. This system allows for the quick and secure attachment and detachment of various payload modules, enabling the MAUGV to efficiently switch roles in the field. The bayonet connection system not only reduces the time required for module changes but also ensures robustness and reliability in harsh operational environments.
6. The comparative analysis between the mathematical modeling and prototype testing of the MAUGV underscores the reliability of the theoretical models used in predicting the vehicle's performance across challenging terrains. Despite minor discrepancies, notably an 18% difference in the moat crossing capability, the simulation data closely aligns with real-world testing results. These findings validate the effectiveness of the developed models in forecasting the operational capabilities of the MAUGV, establishing a foundation for future enhancements. The variances observed can be attributed to the theoretical model's limitations, variations in terrain surface, and potential measurement errors, pointing towards areas for further refinement in model accuracy and real-world applicability.

7.1. Limitations of the Study

- The current prototype tests covered only a select number of terrains and obstacle types, such as inclined surfaces, stair climbing, and ditches. Extensive testing on varied terrains, including mud, snow, rocky landscapes, aquatic environments, and complex, uneven

ground, has not yet been conducted, limiting the full assessment of MAUGV performance in diverse real-world scenarios.
- The study did not analyze the effects of varying environmental conditions such as temperature extremes, humidity fluctuations, precipitation, and other weather-related impacts, potentially affecting the general applicability of the MAUGV under challenging or extreme conditions.
- The possibility and economic viability of scaling the MAUGV for serial production and widespread practical implementation were not fully examined. Further research is required to optimize production costs and assess the feasibility of mass manufacturing, considering factors such as material availability, production processes, and market demands.

7.2. Future Research Directions

- Upgrading sensor arrays and incorporating advanced artificial intelligence algorithms can significantly improve autonomous navigation, decision-making capabilities, and adaptability of the MAUGV to dynamically changing environments.
- Conducting field tests across diverse and challenging terrains, including mud, snow, sand, rock, aquatic environments, and varied weather conditions, is crucial to increase the robustness, reliability, and generalizability of the vehicle's operational capabilities.
- Integrating advanced energy management solutions, including renewable energy sources, hybrid power systems, and battery management technologies, can enhance operational endurance and efficiency, thereby extending MAUGV mission durations.
- Conducting field trials and practical validations of the MAUGV through military exercises, proving-ground testing, tactical scenario simulations, and joint operations with specialized units (e.g., firefighting brigades, explosive ordnance disposal teams, and search-and-rescue groups) can provide critical insights into its operational performance.

The authors confirm that they did not use artificial intelligence technologies in the creation of the current work and the manuscript does not contain related data.

Data Availability Statement

The authors confirm that the manuscript does not contain related data.

Conflicts of Interest

The authors declare no conflicts of interest.

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