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DESIGN AND RESEARCH OF THE GROUND ROBOTIC SYSTEM STRUCTURE FOR WEAPONS REMOTE CONTROL

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During hostilities, ground robotic systems play an important role in minimizing losses of servicemen and suspending the combat capabilities of troops. For firing, robotic complexes are equipped with gun turrets. Researchers are conducting research to improve the performance, reliability and firing accuracy of such turrets. This work describes the design and research of an experimental sample of a ground robotic system, which is equipped with a turret for controlling the position of a machine gun. The description and results of experimental studies of dynamic loads during robot movement at different speeds and road conditions are presented. It was established that the values of the maximum accelerations that must be worked out by the stabilization system during operation for the experimental design of the robot do not exceed 20 rad/s^2. The possibility of using counterweights was considered to reduce the torque of the turret guidance drive while reducing the dimensions of the robotic system structure. The description of the experimental module equipped with a control and measurement system and the results of experimental studies on determining the power of the turret drives during the manipulation of the structure are presented. A procedure of dynamic analysis and the results of modeling the movement of the gun turret in the ANSYS software package are presented. The proposed method for designing the structure ensures the determination of the impact on the structure of the complex shape of loads caused by its manipulation, to compensate for the exciting loads when the robotic system is moved over the terrain. With the help of this method, it is possible to determine and minimize the power, and therefore the energy consumption, of azimuth and lifting electric drives at the design stage

Keywords: gun turret, ground robot, combat module, dynamic analysis, robotics, moment sensor

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1. Introduction

The leading countries of the world, such as the United States of America (USA), Great Britain, countries of the European Union, Japan, Israel, Turkey, South Korea, China have clearly determined that the wars of the future are wars of robots (robotic systems) [1–4]. Therefore, great attention is paid to their design and implementation [1, 5], which is evidenced by US guiding documents [2–4], namely: Integrated Roadmap of Unmanned Systems for 2017–2042, Strategy for Robotic and Autonomous Systems of the US Army, and Operational Concept of the US Army to 2040. According to the documents, special attention in the use of ground forces is directed to minimizing the loss of personnel during the execution of combat tasks by units. For this purpose, the robotization of weapons and military equipment is widely implemented.

Ground robotic system (GRS) [1] is an unmanned robotic platform, related remote control points, control lines, and other elements that make it possible to automate the performance of assigned tasks. For firing, GRS is equipped with gun turrets that appeared in the last two decades due to the significant technological development of mechatronic systems [5, 6].

One of the vivid examples of modern GRS is the combat robotic platform RoBattle LR-3 from the Israeli company IAI [6]. The RoBattle LR-3 GRS is intended for the introduction of active combat operations, reconnaissance, ambushes, and perimeter patrols. It has a wheeled platform weighing 7,000 kg with a diesel power plant. The robot is armed with an ultra-light combat module with remote control Pitbull (weighing 50 kg), developed by General Robotics. In Ukraine, GRSs are manufactured by the companies Temerland and Roboneers. The Ukrainian company Temerland manufactures combat GRS «Laska» [7] weighing 310 kg. «Laska» has a 4-wheel base from an electric quad bike and an automatic firing system based on a turret with a machine gun mounted on it. The Ukrainian company Roboneers designed a multi-functional GRS «Ironclad» [6, 8] (Fig. 1) weighing 1950 kg with a turret for controlling a machine gun.

Many researchers and designers conduct research to improve the technical characteristics of GRS, such as weight, energy consumption, speed, reliability, and accuracy of gun firing. Scientific research into this area is important because the advantage over the enemy will be delivered by those GRSs that are endowed with advanced «artificial intelligence» [9] and improved operational properties. The results of military GRS research can be used to improve civilian robots, the use of which is rapidly increasing every year [5].

Fig. 1. Ukrainian ground robotic system «Ironclad» from Roboneers

2. Literature review and problem statement

The GRS gun turret is a complex mechatronic system consisting of two moving units: an azimuth housing and a suspended elevation housing (swinging part of the gun turret) for height guidance. The azimuth case consists of a bracket, an azimuth electric drive, an electric lift drive, an ammunition belt, an ammunition box, and other additional components. The elevation body consists of a cradle with a gun of a certain caliber and a sighting system installed on it.

When designing, it is important to choose the azimuth and elevation drives so that they provide the necessary torque, speed, and acceleration during the manipulation of the azimuth and suspension bodies during the movement of GRS. At the same time, the design of the turret should be as balanced as possible and with the minimum possible moment of inertia to minimize the power of the drives while ensuring its necessary rigidity and strength. The power of the drives affects the dimensions, weight, and energy consumption of GRS.

To conduct aiming fire when moving on the terrain, a gun aiming stabilization system is used [10, 11]. Under combat conditions, in order to aim and hit the target, the gun turret must change its position as quickly as possible. The speed of the actuators should provide compensation for the change in the position of the gun during the stabilization of aiming and firing during movement. At the same time, the hinges are subjected to forces and moments caused by the influence of the mass and inertia of the moving parts. Thus, the effectiveness of the turret strongly depends on the dynamic response of the GRS structure. In addition, firing accuracy largely depends on the vibration of the GRS structure, which is affected by loads, structure rigidity, mass imbalance, as well as manufacturing tolerances and backlash in gears [10, 11].

During operation, GRS is subject to:

– dynamic loads transmitted from the road during movement;

– the load caused by manipulations with the system;

– loads transmitted from the gun during firing.

These three main sources of loads mainly affect the design of GRS and are the object of research in [12–16].

In [12], a numerical simulation of a virtual prototype of a fixed turret was performed to study the accuracy of its firing depending on the type of gun damper. When describing the assumptions accepted when constructing the mathematical model, the authors note that the effects of the relationship between the vehicle structure, the combat module, and the road surface are extremely complex. Therefore, the research did not take into account the influence of the road surface and the structure of the lower part of the car.

In article [13], a modal dynamic analysis using the finite element method of the influence of firing loads during the development of an air defense gun turret of a military tracked vehicle was carried out. Structural vibration modes were analyzed, and changes were made to the turret design in certain locations to strengthen the mounting assembly and obtain better vibration response. Paper [14] describes the task of integrating 12.7 mm hand-held machine guns on a mobile platform and a simulated machine gun stand on a cradle. Based on the determined internal ballistic parameters, the load from firing on the structure and the rotating bearing was calculated using the finite element method. In works [13, 14] it is shown that to study the dynamic loads from firing on the turret structure, numerical simulation using the finite element method is mainly used.

Work [15] reports the results of research on the experimental determination of the dynamic characteristics of gun turret parts during firing. The paper presents a method of experimentally determining the vibration of mounted parts of a turret on a tracked vehicle, and the excitation force acting on the mount during firing. Excitation forces were measured with the help of force sensors, and the acceleration of the movement of parts was measured with the help of accelerometers.

When improving gun turrets, researchers mainly study the effect of loads on the structure transmitted from the gun during firing [12–15]. But the dynamic loads transmitted from the road during movement and loads caused by manipulations with the system affect the turret design and the required power of the drives to a greater extent. These loads are less studied and depend not only on the design of the turret but also on the structure of the robotic GRS platform and its operating modes. In works [12–15], the effect of dynamic loads on the structure of the turret from firing without taking into account other loads is investigated. A systematic approach taking into account three types of loads is described in [16].

Work [16] is aimed at modeling and optimizing the design of a light U-shaped bracket for a gun turret. The authors conducted optimization studies with varying loads (road excitations and recoil force during firing) and determined the optimal design of the U-shaped bracket using probabilistic analysis and finite element modeling.

But the method of analytical calculation of the system of equations described in [16] is difficult to apply for structures of complex geometric shape. Also, the acceleration values given in [16] when the robot moves over the terrain cannot be used for other GRS designs.

All this allows us to state that there is a need to devise a universal method for determining the impact exerted on the structure of a turret of a complex shape by loads caused by its manipulation, to compensate for exciting loads when GRS is moved over the terrain. This, in combination with well-described methods of studying the impact of loads on the turret structure during firing, will allow taking into account all three main sources of loads on the structure of the complex geometrically shaped GRS.

3. The aim and objectives of the study

The purpose of this work is to devise a universal method for determining the impact of loads on the turret structure caused by its manipulation to compensate for exciting loads when GRS is moved over the terrain. The use of the would-be method in combination with the well-described [12–15] methods for determining loads from a machine gun during firing will allow solving the practical task of optimal selection of azimuth and elevation drives.

To achieve the goal, the following tasks were set:

– to determine the value of the maximum accelerations to determine the maximum dynamic loads when the robot moves under different terrain conditions;

– to devise procedures of analytical and experimental determination of the power of turret drives during manipulation of its structure;

– to determine how it is possible to reduce the dimensions and improve the characteristics of the turret by changing the design;

– to devise a procedure for determining the necessary torques of engines by the method of numerical modeling in the ANSYS software package;

– to analyze the accuracy of determining the required torque of the drive by comparing the data of numerical and experimental studies.

4. The study materials and methods

The object of our study is a prototype of GRS (Fig. 2) weighing 130 kg, which is equipped with a turret for controlling a machine gun.

Fig. 2. An experimental sample of a ground robotic system

It has been found that the effects of the relationship between the vehicle structure, the combat module, and the road surface are extremely complex. But dynamic loads transmitted from the road during movement and loads caused by manipulations with the system have a significant impact on the design of the turret and on the required power of the drives. Approaches to determining the impact of firing are well studied and described in detail, so the loads transmitted from the machine gun during firing were not investigated in this work.

Movement of mobile GRSs takes place under difficult and variable road conditions. When moving GRS under off-road conditions, unevenness of the soil determines the dynamic movements of the chassis and the manipulator (turret). It was established that the dynamic loads when moving GRS on the road depend not only on the type and parameters of the road but also on the design features of the mobile robot. Theoretical and experimental methods are used to study the impact of road conditions on the effectiveness of ground robotic systems. A more accurate experimental method was used in the study of loads from the influence of road conditions on GRS.

The study of dynamic loads during manipulation of the system by the operator can also be carried out by experimental [11, 17–21] or theoretical methods, which in turn can be divided into analytical calculations and numerical modeling by the finite element method [22, 23].

The movement of each point of the robotic system is the result of the reaction of the dynamic system of the complex to all input actions. The main ones are loads in wheel pairs, dynamic disturbances due to drives or the action of shots. The initial parameters of the dynamic GRS system are the movement of a single point in a certain direction. In particular, the output parameter is the horizontal and vertical movements of the barrel, or the movement of the combat module in a certain direction. In the study, the inertial properties of the manipulators were determined taking into account the design features of GRS. To determine the reduced moments of inertia and to determine the required torques of the drives, a method of numerical modeling in the ANSYS software package was used.

The ANSYS software package has proven effective in solving problems of statics and dynamics [22, 23]. The software package makes it possible to solve the problem of modeling the dynamic behavior of the structure, taking into account all possible effects, such as the elastic and inertial properties of the structural elements. Carrying out numerical 3D simulations using the finite element method in modern software packages requires working out the methodology and its verification.

To verify the methodology, the results of numerical modeling were compared with the results of an experimental study on the dynamics of the suspended elevation housing (the rocking part of the gun turret). For this purpose, an experimental module and a control and measurement system were built, the construction principles of which are described in works [11, 17–21].

5. Results of investigating dynamic loads on the gun turret of the ground robotic system

5. 1. Experimental studies of dynamic loads during robot movement

In this study, the experimental operation of the prototype GRS was carried out with three driving scenarios (Fig. 3) with different speeds of the robot and under different road conditions. Experimental operation was carried out to assess the maximum loads transmitted to the system during movement under various conditions.

Angular velocities (pitch, roll, yaw) (Fig. 4) of the movement of GRS during displacement, registered using the IMU sensor and calculated angular accelerations, are illustrated in Fig. 5, 6. IMU sensors are used for self-balancing robots, airplanes, mobile phones, tablets, spacecraft, satellites, and unmanned aerial vehicles for orientation detection, motion tracking, and flight control.

a *b* *c*

Fig. 3. Experimental operation of a prototype of a robotic system with three driving scenarios: *a* – asphalted hard road with potholes; *b* – hard soil and short grass; *c* – sand, sand hills, small stones

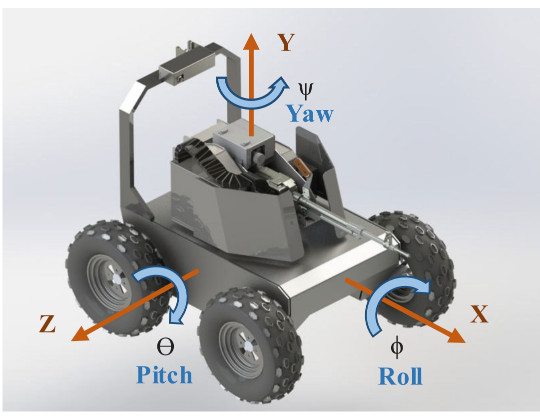


Fig. 4. 3D model of the prototype of the robotic system

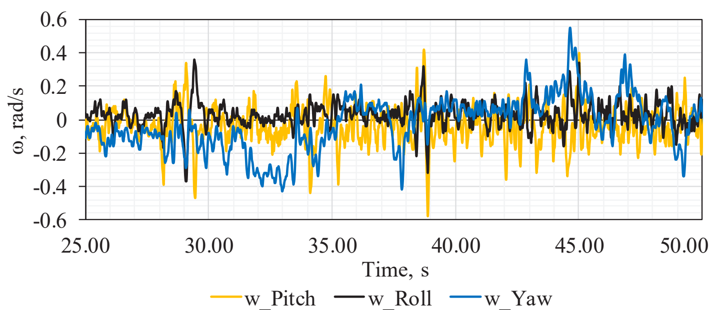
In the experiments, a motion tracking device developed by InvenSense brand MPU-6050 was used, which is an IMU sensor that contains a MEMS (microelectromechanical system) accelerometer and a MEMS gyroscope on a single chip. The main characteristics of the MPU6050 device:

– six 16-bit ADCs (three for accelerometer and three for gyroscopes);
– supply voltage: 3–5 V;
– communication: I2C protocol;
– board size: 20×16 mm.

Each experiment was performed with periodic polling of the sensor using the I2C protocol and subsequent storage of data in text format. The final frequency of determining the position of the robot, taking into account the delay of polling, transmission over the communication channel is 71.42 Hz, the time period, respectively, is about 14 milliseconds between data.

The results of the experiment (angular velocities of pitch, roll, yaw) (Fig. 4) were stored in radians per second using the time stamp of the microprocessor in milliseconds.

Our experimental data (Fig. 5, 6) are unique for this GRS design. These data are necessary because the dynamic response of a turret placed on a ground vehicle is directly related to the speed and dynamic characteristics of the vehicle, which in turn are affected by the nature of the terrain.



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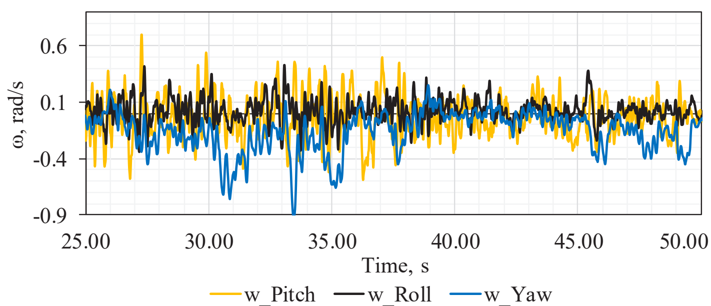

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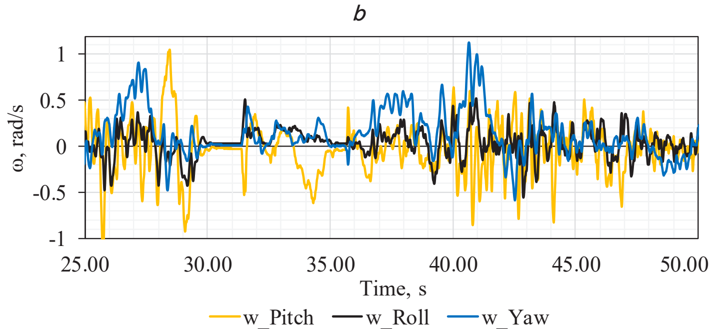
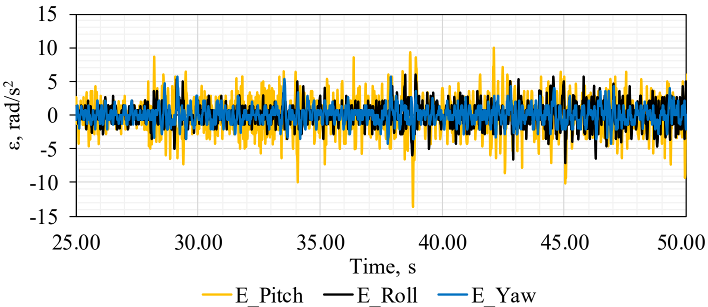
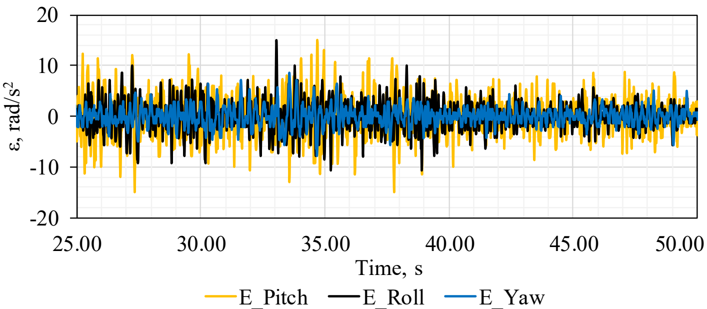


c

Fig. 5. Values of the measured angular velocities of the turret of the experimental prototype of the robotic system around the *Z*(Pitch), *X*(Roll), *Y*(Yaw) axes (Fig. 4) in different traffic scenarios: *a* – asphalted hard road with pits; *b* – hard soil and short grass; *c* – sand, sand hills, small stones



a



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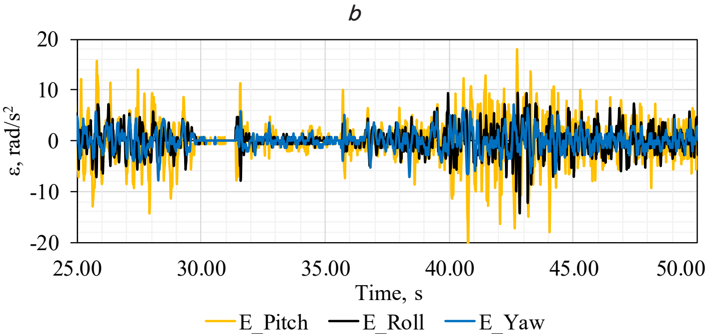

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Fig. 6. Values of the calculated angular accelerations of the turret of the experimental prototype of the robotic system around the *Z*(Pitch), *X*(Roll), *Y*(Yaw) axes (Fig. 4) under different traffic scenarios: *a* – asphalted hard road with pits; *b* – hard soil and short grass; *c* – sand, sand hills, small stones

5. 2. Procedure of analytical determination of the power of turret drives for manipulation of the structure

To estimate the dynamic response of a part of a gun turret, the equations that describe the motion of the mechanism are given under the assumption of rigid body dynamics. The researched system is a stationary fixed azimuth housing of the turret and a movable drive-mounted suspension housing (swinging part of the gun turret) (Fig. 7).

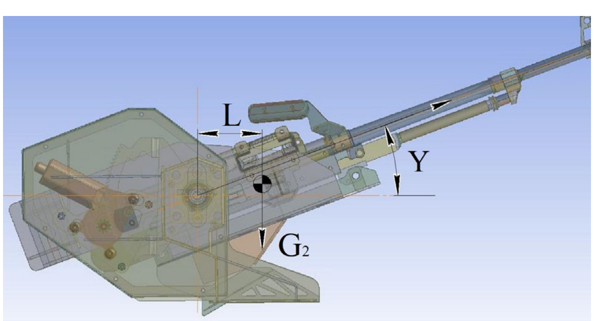

Fig. 7. A prototype turret of a robotic system with a machine gun and counterweights

The power on the drive shaft is determined by the formula:

$$N = w \cdot M, \quad (1)$$

where M is the torque on the drive shaft, Nm; w – angular velocity of shaft rotation, rad/s.

With such a design, the torque on the output shaft of the drive:

$$M = Mw + Mf + Md, \quad (2)$$

where Mw is the moment from the unbalanced weight, Nm; Mf – moment of friction in supports, Nm; Md – dynamic moment, Nm:

$$Md = \varepsilon \cdot J, \quad (3)$$

where ε is the angular acceleration ($\varepsilon = d\omega/dt$), rad/s^2; J is the moment of inertia of the structure relative to the axis of rotation, kg·m^2. The value of the moment of inertia of a turret with a complex geometric shape is obtained from the CAD system:

$$Mw = G_2 \cdot L \cdot \cos\gamma, \quad (4)$$

where G_2 is the force of the weight of the swinging part, H; L is the distance of the center of gravity of the swinging part from the pivot axis, m; γ is the angle of inclination to the horizon.

The friction moment in the supports Mf depends on many factors: the type of bearings, the lubrication technique, contamination and wear of the friction surfaces, the accuracy of the construction, the amount of misalignment and backlash. The value of this moment can be determined experimentally using a torque measuring device [17], or analytically using empirical data from the study of similar supports.

5. 3. Reducing the dimensions of the structure by using counterweights

The use of balancing mechanisms makes it possible to relieve the vertical guidance drive from the action of the weight moment G_2 of the swinging part of the gun turret. This moment arises as a result of the displacement of the trunnion axis of the swinging part from its center of gravity in order to reduce the height of the line of fire (reducing the height of the turret and GRS).

As a result of placing the pivot axis behind the center of gravity of the swinging part of the gun, the gun becomes unbalanced, which is characterized by the fact that the swinging part tries to return relative to the pivot axis under the influence of the weight moment Mw. To partially or completely eliminate the influence of the moment of gravity on the operation of the lifting mechanism, we try to balance the swinging part of the gun. There are two balancing techniques: cargo (natural) and artificial (power). Load balancing consists in the fact that the swinging part is balanced by counterweights. This shifts the center of gravity of the swinging part of the gun to the axis of rotation.

This technique is used for artillery and tank guns that fire on the move. The advantage of cargo balancing is complete balancing of the swinging part of the gun. The disadvantage is an increase in the mass and moment of inertia of the gun.

5. 4. Experimental studies of the power of turret drives for structure manipulation

To work out the procedure of experimental determination of the required power of the vertical guidance drive, the suspended lifting body (experimental module) was equipped with a control and measurement system (Fig. 8). Tests were carried out without a machine gun and with a part of the counterweight to change the value of the moment from the unbalanced weight *Mw*.

The power on the shaft during experimental studies is determined by formula (1).

As a result of the research, the values of the necessary power of the vertical guidance drive were determined to ensure the necessary speed during the manipulation of the structure. Plots of change in the angular speed of movement around the axis of the supports of the rocking part of the gun turret (Fig. 9) and the change in the torque applied by the drive (Fig. 10) as a function of time were also constructed.

Fig. 8. Experimental module of the prototype of the robotic system

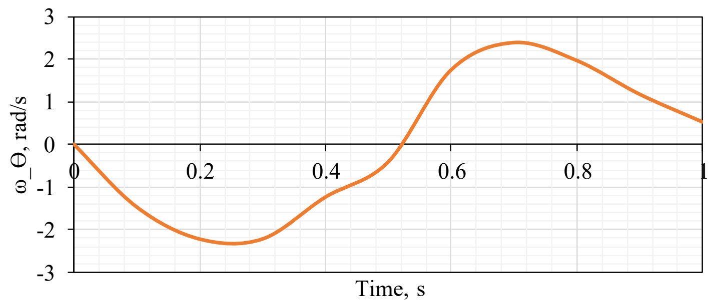

Fig. 9. Change in the measured angular velocity of the swing part of the gun turret

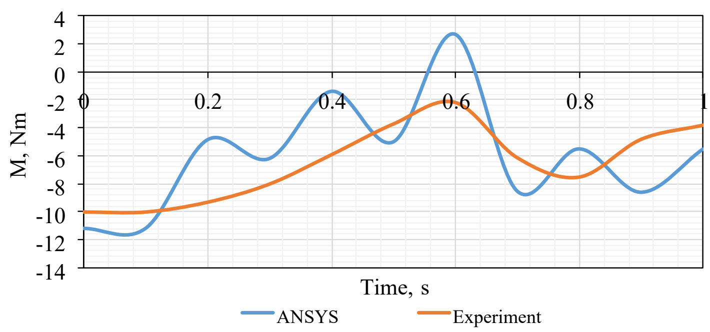

Fig. 10. Comparison of change in the torque applied by the drive over time (when modeling in ANSYS and when experimentally measured)

The experimental module includes the inertial load of the system (suspended elevation case with counterweights without a machine gun), controlling drive (motor with built-in gearbox), fixed azimuth case (bracket).

The control and measurement system consists of an optical encoder LPD3806-600BM and a torque sensor, the design and operation of which is described in detail in [17].

The optical encoder LPD3806-600BM is designed to convert the angular position of the shaft into an electrical signal. The optical encoder has 600 pulses per revolution, which makes it possible to see a shaft displacement of 0.6°. In the study, the encoder was used to obtain the shaft speed. A microcontroller was used for these calculations. When receiving a pulse from the encoder, an interrupt is triggered in the microcontroller, in which the time that passed between two pulses was calculated, that is, the time it took for the shaft to turn by 0.6°, knowing this, we find the angle the shaft will turn in a second. These calculations are carried out when receiving each pulse, that is, every 0.6° by which the shaft was rotated.

The control and measurement system contains software developed by us for monitoring and managing research in real time. The appropriate visual control software of the upper computer sets the polling time of the instruments. The polling time of the torque sensor was 100 milliseconds.

These data were used to create and check the accuracy (Fig. 10) of the methodology for numerical modeling of the movement of the rocking part of the gun turret in the ANSYS software package.

5. 5. Numerical simulation of the dynamics of the gun turret movement

Modeling of the movement of the rocking part of the gun turret (Fig. 11) is carried out in the ANSYS software package using dynamic analysis to study the behavior of structures under the influence of time-varying loads.

During simulation, the type of all bodies was set to Rigid. Thus, the model will be calculated as a mechanism, without calculating the stress state of the constituent elements. Contact pairs were replaced by joints of the mechanism. The body of the bracket was fixed in space, (Body-Ground) connection type – Fixed. The type of joints of the surfaces of the rocking part of the gun turret and the surfaces of the supports of the bracket body is Revolute. In the simulation, free fall acceleration (which acts on all bodies along the *Y* axis) and time-varying relative angular velocity joint_Revolute relative to the *Z* axis were set as loads (Table 1). The values of this angular velocity were measured during experimental studies (Fig. 9).

As a result of our calculations, the movement of the structural system elements under the action of external loads was determined. We also calculated (Table 1) the change in time of torques (Fig. 10) and angular accelerations.

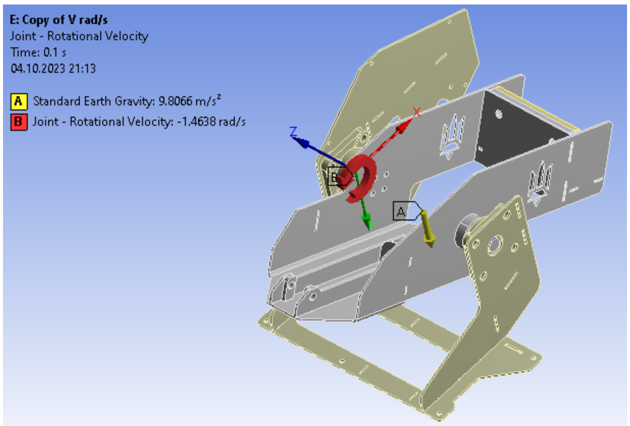

Fig. 11. Load diagram of the model of the rocking part of the gun turret

Table 1

Results of dynamic analysis

Time [s]	Angular velocity around the axis *Z*, [rad/s]	Moment relative to the axis *Z*, [N·m]	Angular acceleration relative to the axis *Z*, [rad/s^2]
0.1	–1.46	–11.2	–14.6
0.2	–2.21	–4.9	–7.5
0.3	–2.21	–6.2	0.0
0.4	–1.24	–1.4	9.8
0.5	–0.42	–5.0	8.2
0.6	1.73	2.7	21.5
0.7	2.37	–8.6	6.4
0.8	1.96	–5.5	–4.2
0.9	1.17	–8.6	–7.9
1	0.52	–5.6	–6.5

When using this approach, it is possible to take into account the inertial properties of the structure and the effects of the accelerated movement of the unbalanced structure.

6. Discussion of results of investigating dynamic loads on the gun turret of the ground robotic system

As a result of experimental studies of dynamic loads during robot movement, the frequency and amplitude of changes in the angular velocities of the turret movement around the *Z*(Pitch), *X*(Roll), *Y*(Yaw) axes were determined (Fig. 4). Using these data, it was established that the maximum values of the angular accelerations of the turret movement around the axes *Z*(Pitch), *X*(Roll), *Y*(Yaw) do not exceed $\varepsilon_{max}=20$ rad/s^2 (Fig. 6) for various driving conditions. This means that the gun turret drive must provide such acceleration while stabilizing guidance when firing while moving. In this case, the dynamic moment *Md* calculated according to formula (3) will arise. The obtained values of the frequency and amplitude of changes in the angular velocities and accelerations of the turret movement can be used to calculate the fatigue strength and durability of structural elements.

Our experimental data (Fig. 5, 6) are unique for this design of GRS moving platform. When designing and optimizing a turret for a new structure of a moving platform, they should be specified according to the methodology given in the work.

As a result of experimental studies of the power of turret drives for the manipulation of the structure, empirical data on the change in the angular velocity of movement around the axis of the supports of the rocking part of the gun turret (Fig. 9) and the change in the torque applied by the drive (Fig. 10) as a function of time were obtained. These data were used to devise a methodology for numerical modeling of the movement of the rocking part of the gun turret in the ANSYS software package using dynamic analysis. A comparison of the moments obtained during simulation in ANSYS and those experimentally measured moments shows that the difference between the maximum moments is 1 Nm. The deviation of the maximum moment determined by the modeling method from the experimental value does not exceed 10 %. To reduce discrepancies between the plots (Fig. 10), it is necessary to reduce the time of polling the sensors to 10 milliseconds.

At this stage, the loads transmitted from the gun during firing were not investigated since when the axis of the gun barrel is located on the axis of rotation (Fig. 7), the forces from firing do not create a torque.

As a result of the research, it was established that when the vertical guidance housing of the turret weighing up to 15 kg is moved with an angular acceleration of up to 20 rad/s^2, moments of more than 10 Nm occur. When manipulating the horizontal guidance body weighing up to 50 kg, moments up to 50 Nm occur. This proves that the dynamic loads transmitted from the road during movement and the loads caused by the manipulation of the system have a significant effect on the turret design and the required power of the actuators.

It is planned to use numerical modeling in the ANSYS software package, according to the described procedure, to conduct optimization studies of the power of the gun turret drives, taking into account all types of dynamic loads that can simultaneously affect GRS turret.

The proposed structure design method, in contrast to those described in works [12–16], ensures the determination of the impact on the structure of the complex shape of the loads caused by its manipulation, to compensate for the exciting loads when GRS is moved over the terrain.

To carry out optimization studies into the design of GRS gun turret, it is necessary to build a mathematical description of the impact of road surface irregularities on its moving platform. To do this, it will be necessary to conduct a survey of GRS with various designs of moving platforms for the accumulation of imperial data according to the described methodology.

7. Conclusions

1. Experimental studies of dynamic loads during robot movement at different speeds and under different road conditions were carried out. The values of the maximum accelerations and displacements, which must be worked out

by the stabilization system, were determined, which made it possible to determine the maximum values of the angular accelerations (ε_{max}=20 rad/s^2) of the displacement for this design of the prototype of GRS.

2. Procedures of analytical and experimental determination of the power of the turret drives when manipulating the structure were devised, and experimental studies were carried out. To this end, a control and measurement system was built, which provides measurement and registration of rapidly changing researched parameters. This made it possible to obtain data for numerical simulation of the movement of the rocking part of the gun turret in the ANSYS software package.

3. To reduce the height of the prototype of GRS, counterweights were used in the design, which made it possible to achieve full balancing of the swinging part of the gun, which made it possible to reduce the required power of the drive. The disadvantage of this approach is the increase in mass and moment of inertia of the swinging part of the gun turret. In the future, to reduce the moment of inertia, it is planned to balance the swinging part of the gun by shifting the position of the machine gun.

4. A procedure for determining the necessary torques of engines by the method of numerical modeling in the ANSYS software package was devised and verified with the help of experimental data. This allows us at the design stage to build a structure that is as balanced as possible and with the minimum possible moment of inertia while ensuring its necessary rigidity and strength.

5. Based on the results of the comparison of experimental and numerically calculated moment values, it can be concluded that the modeling procedure does provide the specified accuracy.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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