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RESEARCH ON THE POSSIBILITY OF CARRYING OUT CONVOY DRIVING MISSIONS USING VEHICLES WITH VARYING DEGREES OF AUTONOMY

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Abstract:

The objective of this work is to assess the possibility of driving unmanned vehicles in a convoy, depending on the vehicle type (wheeled or tracked, level 0, according to SAE J3016), and the mutual coincidence with a human-controlled vehicle in accordance with the driving scenario adopted. The assessment is based on tests carried out while driving the vehicles along a designated route and measuring the physical quantities that describe the vehicles' motion, such as the components of the velocity vectors and distances between the vehicles. The tests were carried out on a safe training ground, using inertial-satellite devices mounted on the vehicles; they provide a good basis for planning the minimum passage corridor for a column of vehicles. During the tests, the expected distances between the vehicles were recorded and analyzed depending on the above-mentioned types of the vehicles; based on that, the possibility of using the technology in the carrying out of various missions for the needs of the tactical level units of the Polish Armed Forces was preliminarily assessed. The required lane width for the safe passage of Target 1, Hunter and Target 2 vehicles along the designated routes was calculated, taking into account the external dimensions of the vehicles, the additional widths associated with the vehicles' yaw angles and the maximum lateral distances between the vehicles. During tests of a convoy of remote-controlled vehicles, maintaining a speed of 1.5 m/s and a distance of 10 m, the requirements for the lane width for safe passage were analyzed. The largest lateral gaps were observed between Target 2 and Hunter vehicles, which may affect the planning of the convoy route. The differences in lane width between the two tests were due to the yaw angles of the vehicles and their different dimensions and drive types. In the first test, the lane width for Target 1 and Hunter was 5.50 m and for Target 2 3.70 m; in the second test it was reduced to 3.73 m and increased to 3.75 m, respectively.

Keywords: *automated vehicles, unmanned ground vehicles, driving in a column, wheeled vehicles, tracked vehicles, minimal distance between vehicles, platooning*

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1. Introduction

It is assumed that the rapid development of unmanned ground vehicles (UGV) began over 20 years ago (Łopatka 2020). However, the first works on remote operation of a moving vehicle were carried out much earlier, in the 19th century. In 1898, Nikola Tesla built two remotely operated boats (Czapla et al. 2013). These boats were made of metal and provided with power batteries, radio receiver, mechanism connected to the propeller and the directional rudder, and lighting system that could also be turned on and off remotely. The boats were controlled via encrypted communication. Tesla patented his invention under the number US613809A (Tesla 1898). In result of the World War II, effective combat use of unmanned-vehicle technologies was developed; such technologies were implemented e.g. in German vehicles such as Sd.Kfz.302, 303, "Goliath"(Lewiński 2022). Reconnaissance UAVs together with satellite means have taken over the domain of modern military reconnaissance in armed conflicts, build situational awareness, shape the course of operations, indicate targets, and determine scenarios for the use of combat resources (Czarnowski et al. 2018). Hitting the enemy is often done using UAVs. From a technical point of view, the use and the efficient and effective operation of an unmanned land platform (UGV) in the field is much more difficult than the operation of an air platform (UAV) or a marine platform in their "natural" environments. This is directly due to the occurrence of a whole range of terrain obstacles that must be recognized and assessed and of the resulting necessity to set correctly the vehicle motion parameters in real time for the obstacles to be effectively overcome. The widespread adoption of UGVs is also limited by safety including fire protection (Guzek et al. 2024), which remains an obstacle to bringing truly autonomous vehicles (AVs) into service (Autonomous Vehicles in the US military 2022).

2. Literature review

The assisted column driving system (also known as Platooning or C-ACC - Cooperative Adaptive Cruise Control) allows vehicles to be automatically kept at the correct distances and to move safely in a convoy. The main components of this system include (Prochowski et al. 2022):

- ACC - Adaptive Cruise Control;
- V2V - Vehicle-to-Vehicle Communication;
- sensors: such as: LiDAR, radar, GPS/IMU, cameras;
- Lane Keeping Assist;
- Distance Keeping System;
- AEB - Autonomous Emergency Braking;
- HMI - Human-Machine Interface;
- V2I - Vehicle-to-Infrastructure.

Adaptive cruise control is the core component of the system, which automatically adjusts the vehicle's speed to maintain a safe distance from the vehicle ahead. Automated vehicles perceive their environment through sensors (LiDAR, GPS/IMU), and the cameras. The LiDAR object detection is handled in multiple stages: point cloud frame transformation, filtering and down-sampling, ground segmentation, and clustering. The tracking algorithm uses the clustering information to provide position and velocity of the Lead vehicle which allows for vehicle platooning. Test results illustrate that The LiDAR object detection and tracking algorithms as well as the autonomous platooning control algorithms works correctly (Alzu'bi 2020). Suitable image analysis enables automated vehicles to perceive their surroundings, especially identifying areas where they can and cannot move. Cameras are used to recognize the surroundings and ensure that the vehicle remains in the correct lane and to recognize obstacles. Semantic segmentation, which divides an image into homogeneous areas regarding specific properties, involves assigning each pixel in the image a particular label associated with the corresponding class allows for a much more complete understanding of the scene presented in the image, which is crucial for correctly determining a passable route for an Autonomous Vehicles (Małek et al. 2024). The improvement of the transport efficiency of vehicles moving in a convoy can also be improved by forecasting traffic flow and traffic congestion. Machine learning (ML), and particularly recurrent neural networks (RNNs), emerge as powerful tools for effectively addressing these urban complexities (Durlik et al. 2024). V2V systems allow the exchange of real-time information such as speed, braking, acceleration and lane change information. This allows the vehicles in the column to react faster than if only sensor data is used. V2V systems also provide remote information on planned maneuvers, which increases traffic synchronization and minimizes the risk of collisions. Lane Keeping Assist ensures that vehicles move into the correct lane by adjusting their path according to the road markings. This is particularly important when driving in a column to ensure that all vehicles move in a coordinated manner and maintain the correct position on the road. The Distance Keeping System allows the distance between vehicles in a column to be kept constant. It works on the basis of radar, camera and V2V data, adjusting the speed of each vehicle to maintain an appropriate space (usually around a few meters, depending on the setting and road conditions). A certain extension of the system could be the use of 4WS steering, which at low speeds can significantly reduce the width of the traffic corridor, while at higher speeds it increases vehicle stability and thus safety (Dębowski et al. 2024, Faryński et al. 2023). Autonomous Emergency Braking reacts to sudden changes in speed in the column, for example when the vehicle in front brakes suddenly, which is typical on motorways (Jurecki et al. 2021). Thanks to V2V communication and radar data, vehicles can synchronize braking more effectively than a traditional braking system. The vehicles in the column automatically adjust their acceleration and braking based on information from other vehicles and sensor data. This allows each vehicle in the convoy to precisely adapt its movements to the traffic situation. HMI - Human-Machine Interface enables the driver to control and monitor the operation of the platooning system. The driver can activate or deactivate the system, receive information on the status of the column and alerts on emergency situations. V2I - Vehicle-to-Infrastructure is a system that allows vehicles to communicate with road infrastructure such as traffic lights, road signs or guardrails. This allows speed optimization and synchronization of vehicles in a column, which can improve efficiency and safety.

The platooning system is based on the integration of advanced sensors, vehicle-to-vehicle communication and traffic planning algorithms. It aims to improve safety, fuel efficiency and traffic flow by automating driving in a group of vehicles. By synchronizing traffic and reacting quickly to changing conditions, the system represents a significant step towards full driving autonomy.

It should be noted that the follow-me missions (platooning) will be a common scenario for the use of UGVs; therefore, research to assess the feasibility of using platforms of this type is highly justified. Automated vehicle connectivity (AV) can improve the safety, performance, and energy efficiency of surface transportation systems by reducing or eliminating human involvement in driving tasks (Salek et al. 2024). The platooning brings also many benefits, namely: lower fuel consumption on the highway (Borhan et al. 2021), which is beneficial in terms of aerodynamics; better smoothness of traffic; less space taken up on the road; increased efficiency due to the fact that the vehicles can cover longer distances at a time, causing fewer road accidents; moreover, drivers gain time to rest during the trip. However, there are several problems associated with vehicle platoons including complicated vehicle driving conditions in or between platoon columns, a high degree of mutual influence, dynamic optimization of the platoon, and difficulty in the cooperative control of lane change (Yan et al. 2023). Important aspects of the development of the above-mentioned systems are: mutual cooperation of moving vehicles, especially vehicles with different degrees of autonomy; maintaining the assumed spacing and speed; and assessing the possibility of driving the vehicles in a convoy, depending on the vehicle type (wheeled or tracked) and the degree of individual vehicles' autonomy, in accordance with the scenario adopted. The work in this direction has been carried out for many years, esp. within projects and programs of the European Defense Agency. An example of such work is the MUSICODE project, i.e. Unmanned Ground Platform for multi-sensor remote detection of components of improvised explosive devices. The project included the development of a remotely operated vehicle (UGV) that moves in front of the control vehicle (Szynkarczyk et al. 2022). While the vehicles themselves have reached technology readiness level VII to IX, the simulated drive in a column is currently the testing of system operation at technology readiness level V. A schematic concept of vehicle cooperation in the project and an example column of vehicles are shown in Fig. 1.

The efficiency or safety of driving an automated or autonomous vehicle is assessed taking into account many normative documents (standards: ISO, Euro NCAP, NHTSA, SAE, UN/ECE Regulations), where many test scenarios are adopted. Typical experimental research scenarios chiefly include lane keeping (Kang et al. 2015), vehicle behavior in urban areas (Wu et al. 2012), and research on avoiding suddenly appearing obstacles (Li et al. 2010). The normative scenarios are most often implemented on test tracks/proving grounds provided with the necessary infrastructure. The scenarios selected make it possible to carry out the tests on public roads. The prescriptive test scenarios focus on testing off-the-shelf automated vehicles systems, such as e.g. driver warning, emergency braking, and lane keeping systems. The effectiveness of these systems is assessed in terms of vehicle's reaction to the threat detected (only the effect of the system's reaction is assessed). The non-normative scenarios should focus on the cognitive aspects of the operation of automated vehicles. The non-normative scenarios include, among others: mapping a path using recorded inertial data (Pusty 2022, Guzek et al. 2002), following the preceding vehicle, and avoiding a suddenly appearing obstacle in a critical situation (Prochowski et al. 2018).

In the practice of testing the systems provided in vehicles moving in a convoy, the test scenario should:

- make it possible to test the data transmission technologies, communications, detectors, artificial intelligence, and heightened situational awareness;
- be multi-variant and take into account the course of the mission divided into sections, e.g. in the territory controlled by own forces and in the territory where direct contact with the enemy is possible.

The mission test scenarios should take into account the cooperation within the marching group of manned vehicles (e.g. two armored personnel carriers) and unmanned vehicles (wheeled and tracked) of various categories, e.g. UGVs for logistic purposes (carrying cargo), serving as medical support, or armed to engage in combat in contact with the enemy in order to protect the remaining vehicles of the group and to gain passage. Moreover, in order to raise situational awareness, the vehicles moving in the group should have continuous communication with the remote command post that cooperates with the group and from which the intelligence information obtained from other sources is transmitted to the convoy. It is assumed that the vehicles will be able to operate at such a distance from own troops that they will still be within the support range of own artillery assets and will be able to provide the appropriate coordinates for fire assets necessary to destroy the indicated targets. The COMMANDS (Convoy Operations with Manned-Unmanned Systems) project, launched in 2021 as part of the European Defense Fund, with the participation of 21 entities from 10 EU countries, attempts to use the latest, currently developed technologies related to individual capabilities in order to provide a tactical advantage to the user in the field during the mission (Edfcommands 2024): formation of a supply convoy as well as configuration and reconfiguration of the convoy supported by artificial intelligence (avoiding objects and threats, determining the adaptive routes).

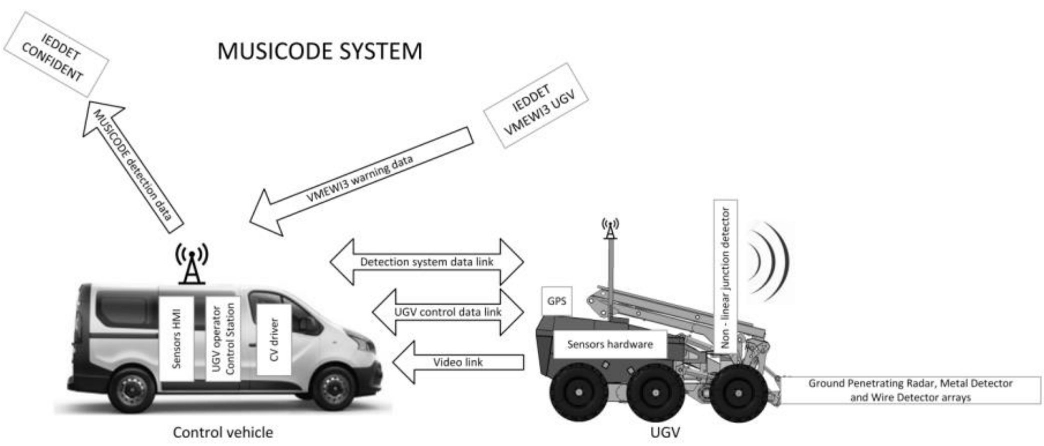

Fig.1. The concept of vehicle cooperation in the MUSICODE System project (Szynkarczyk et al. 2022)

A matter of crucial importance here is also the reliability of unmanned systems, also understood as the probability of failure-free execution of the task by the UGV, which in the authors' opinion remains a critical factor. The reliability of the technical device results from its design and operational features (Pszczółkowski et el. 2023) and adaptation to a given mission, which was assessed during the research and is very important on the modern battlefield, in particular in relation to unmanned systems.
The topic of processing data from sensors and modeling traffic flows is well known in the literature, however, there is a gap in work related to research on convoy vehicles with various degrees of autonomy, including remotely controlled vehicles and their relationship with vehicles controlled directly by a human.

3. Purpose of the work

The work is aimed at assessing the possibility of driving vehicles in a convoy depending on the vehicle type (wheeled or tracked) and the degree of vehicle's autonomy (human-driven, remotely controlled, level 0, according to SAE J3016). The results of the work can be used to plan the minimum passage corridor for a column of vehicles and the expected distances between the vehicles depending on the above types and degrees of autonomy of the vehicles, as well as a preliminary assessment of the possibility of using the technology in carrying out various missions for the tactical level units of the Polish Armed Forces.

4. Scope of the work

The scope of the work includes checking the ability of vehicles formed in a convoy to maintain the preplanned track while negotiating a track with permanent obstacles. The test consists of the following stages:
- forming a convoy of vehicles at 10 m intervals (the convoy does not move);
- starting a drive of all the vehicles along the predefined track (the convoy is moving), keeping the vehicle spacing as assumed;
- stopping the convoy at a marked place, keeping the vehicle spacing as assumed.

Obviously, the aforementioned applications that make it possible to determine the distance between vehicles in a column or traffic corridor are highly dependent on the dynamics of the vehicles, whose weight may vary depending on the load they are carrying. This is very important especially to find an energy minimizing route for the given environment (Jaroszek et al. 2014). To minimize this impact, a low traffic speed was chosen, i.e. 1.5 m/s.

5. Measuring equipment and vehicles used

Three OXTS RT measurement sets, power batteries, and computers recording the results were used for the tests. During the field tests on a closed track, the signal recording frequency was set to 100 Hz. These sets recorded, inter alia, the following quantities:
- geographical coordinates;
- three mutually perpendicular components of the linear acceleration vector;
- three mutually perpendicular components of the angular velocity vector;
- angles of rotation of the vehicle body solid around three mutually perpendicular axes.

Three vehicles are the objects under test:
- remotely controlled off-road – Target 1;
- remotely controlled wheeled vehicle – Hunter;
- Manned Tracked Platform – human-controlled Command and Staff Vehicle – Target 2.

During the analysis of the results of the experimental research, the vehicle kinematics model was used, in which right-handed coordinate systems were used: two global and two local coordinate systems. Local coordinate systems, rigidly associated with the car body. Coordinate systems were used:
- local coordinate system, rigidly associated with the car body. The Oxyz coordinate system has an O origin at the center of the measuring equipment, the Ox axis is parallel to the longitudinal axis of the vehicle. In the local coordinate system Oxyz, the components of the acceleration vector (ax, ay, az) and the components of the angular velocity vector of the car body (P, Q, R) were recorded;
- local horizontal coordinate system, rigidly associated with the car body. The OxPyPzP coordinate system has an O origin at the measuring equipment, the OxP axis is parallel to the longitudinal axis of the vehicle;
- $O_GX_GY_GZ_G$ global coordinate system related to road. The $O_GX_GY_GZ_G$ plane of this system is on a horizontal roadway, and the O_GZ_G axis is directed vertically upwards. The speed vector of the car is parallel to the O_GX_G axis before starting the measurements;

– global reference system rigidly connected to the Earth (the northern axis (N), with its direction towards the north pole, is perpendicular to the direction of the gravity vector and tangent to the Earth's surface; the eastern axis (E), pointing east, is perpendicular to the direction of the gravity vector and perpendicular to the northern axis; and the downward axis (D) runs along the gravity vector);

Vehicle movement is identified, among others. in relation to the road infrastructure, the location of which is described in the global coordinate system. Therefore, it is necessary to transform the measurement results from the local components of the acceleration vector (a_x, a_y, a_z) into the global system (a_X, a_Y, a_Z). The angular velocities of the car body in the global coordinate system are described by the expression:

$$\begin{bmatrix}\dot{\Phi}\\ \dot{\Theta}\\ \dot{\Psi}\end{bmatrix}=\begin{bmatrix}1 & \sin\Phi\,\mathrm{tg}\Theta & \cos\Phi\,\mathrm{tg}\Theta\\ 0 & \cos\Phi & -\sin\Phi\\ 0 & \frac{\sin\Phi}{\cos\Theta} & \frac{\cos\Phi}{\cos\Theta}\end{bmatrix}\begin{bmatrix}P\\ Q\\ R\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}a_{xP}\\ a_{yP}\\ a_{zP}\end{bmatrix}=\begin{bmatrix}\cos\Theta & \sin\Theta\sin\Phi & \sin\Theta\cos\Phi\\ 0 & \cos\Phi & -\sin\Phi\\ -\sin\Theta & \cos\Theta\sin\Phi & \cos\Theta\cos\Phi\end{bmatrix}\begin{bmatrix}a_x\\ a_y\\ a_z\end{bmatrix} \quad (2)$$

$$\begin{bmatrix}a_{Gx}\\ a_{Gy}\\ a_{Gz}\end{bmatrix}=\begin{bmatrix}\cos\Psi & -\sin\Psi & 0\\ \sin\Psi & \cos\Psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}a_{xP}\\ a_{yP}\\ a_{zP}\end{bmatrix} \quad (3)$$

where:

Ψ, Θ, Φ – quasi-Euler angles, defining the orientation of the local system $\{C_s\}$ relative to the global system $\{O\}$;

P, Q, R – components of the angular velocity vector of the body in local coordinate systems.

To achieve the planned aim of this work, a different rout was set up, during which the acceleration and angular velocity waveforms were recorded in the local reference system. The waveforms of accelerations and angular velocities have been centered by removing the so-called offset and exported with a cutoff frequency of 20 Hz. The OXTS RT measuring set was placed inside the test objects: Target 1 and Target 2 and outside the test object Hunter. The determined acceleration of the center of measuring equipment in the global system a_{Gx}, a_{Gy}, a_{Gz} was used to determine the coordinates of the center of measuring equipment by double numerical integration. The results of the calculations are presented in Figures 4 and 6 in the form of the trajectories of the vehicles.

The view of the vehicles is shown in Fig.2.

6. Test results

6.1. Calculation method adopted

The readings of the systems installed on the vehicles were determined in relation to the vehicle taken as a reference. The reference vehicle is Hunter (moving second in the column), while the other vehicles, named Target 1 and Target 2, moved first and last in the column, respectively. The measuring systems used made it possible to determine:

– vehicle trajectories in the global reference system (NED);
– time histories of the relative yaw angles of the Target 1 and Target 2 vehicles, distances between these vehicles and the reference one, and vehicles' velocities in the local Hunter coordinate system.

Then, time histories of the distances of the Target 1 and Target 2 vehicles from the reference one were determined in the local Hunter coordinate system (in the longitudinal and lateral directions). For the analysis, straight sections of the route were selected, which were covered by the convoy under test in the different time intervals depending on the type of test (driving in a straight line avoiding one obstacle, driving in a curvy line avoiding a lot of obstacle**.** The following quantities characterizing the relative motion of these vehicles were analyzed:

– angles of deviation of the longitudinal axes of the Target 1 and Target 2 vehicles from the longitudinal axis of the Hunter vehicle (relative yaw angles – see Figure 3);
– longitudinal and lateral distances of the Target 1 and Target 2 vehicles from the Hunter vehicle in the local coordinate system;

longitudinal and lateral components of the velocities of the Target 1 and Target 2 vehicles relative to the Hunter vehicle in the local coordinate system.

Fig. 2. Photos of the object under test: a) Target 2, b) Target 1, c) Hunter, d) vehicles while forming a convoy, e) OXTS in the Target 1, f) OXTS on the Hunter , g) OXTS in the Target 2, h) all vehicles after the test (source: materials provided by WITPiS, i.e. the Military Institute of Armor and Automotive Technology).

The distances between the Hunter vehicle and the Target 1 and Target 2 vehicles were calculated based on vehicles' instantaneous positions in time. The distance values determined and the relative velocity components in the local Hunter coordinate system refer to the mounting points of the measuring equipment. The Range system calculates the distance (range) to the Targets and resolves this into forward and lateral measurements in the Hunter vehicle's coordinate frame. Range calculations are carried out in the Hunter vehicle's frame of reference, i.e. forward and lateral with reference to the Hunter, regardless of the orientation of the Targets. The resultant distance between the Hunter vehicle and Targets vehicles can be calculated from their instantaneous positions. This can then be decomposed into a lateral and forward component relative to the Hunter. Description of the adopted markings is shown in Fig. 3.

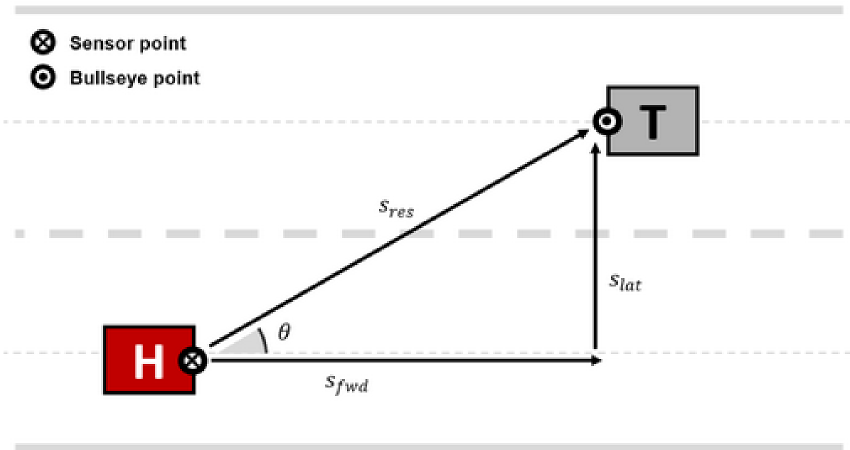

Fig. 3. Description of the adopted markings (Support OXTS, 2024), where: T – Target; H – Hunter; Φ – yaw angle of the Target 1 and 2 relative to the Hunter vehicle [deg]; s_{fwd} – range forward of the Target 1 and 2 relative to the Hunter vehicle [m]; s_{lat} – range lateral of the Target 1 and 2 relative to the Hunter vehicle [m].

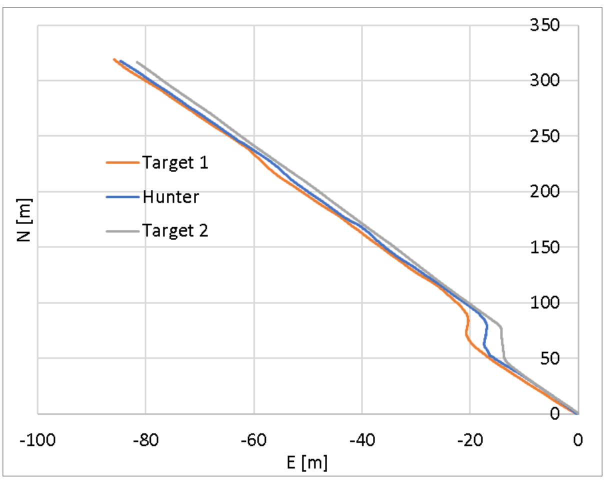

Fig. 4. Vehicle trajectories in the global reference system (NED) during driving in a straight line avoiding one obstacle

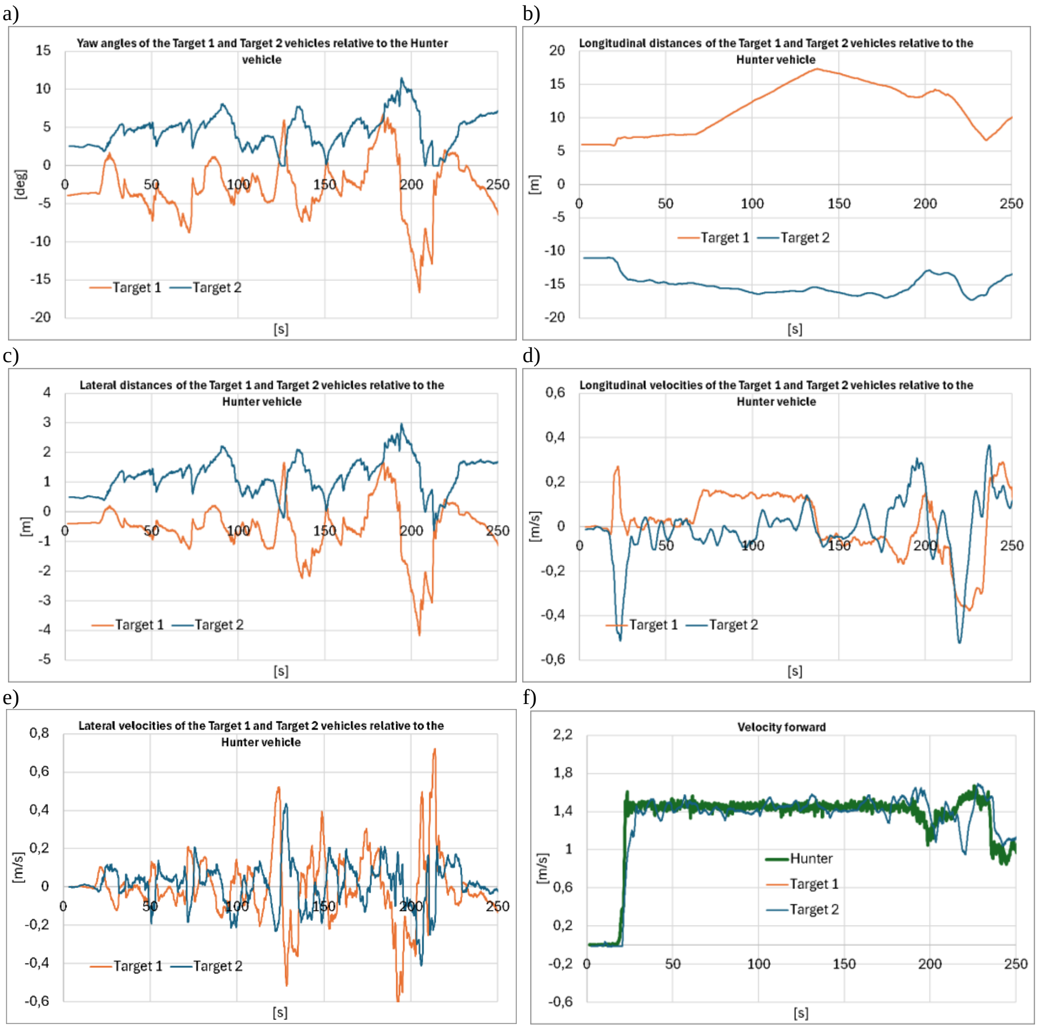

Fig. 5. Results of calculations of the quantities that characterized the relative vehicles' motion driving in a straight line avoiding one obstacle

When calculating the relative velocities of the Hunter and Targets the next step included lateral and forward velocity differences between the Targets and the Hunter, arranged such that when the Hunter is gaining on the Targets these values ought to be negative. The forward velocity of the Target 1 and 2 relative to the Hunter velocity can be given by taking the difference in distance divided by the difference in time for a given time step.

$$v_{fwd} = \frac{\Delta s_{fwd}}{\Delta t} \tag{5}$$

where:
t – time [s].

From the presented time histories of the quantities that characterized the relative vehicles' motion, the arithmetic mean values were determined and the extreme values were indicated.

6.2. Driving in a straight line avoiding one obstacle

Vehicle trajectories in the global reference system (NED) during driving in a straight line avoiding one obstacle is shown in Fig. 4. Results of calculations of the quantities that characterized the relative vehicles' motion driving in a straight line avoiding one obstacle is shown in Figure 5. Values of the arithmetic mean of the quantities under analysis in the time intervals as specified during driving in a straight line avoiding one obstacle is shown in Table 1.

6.3. Driving in a curvy line avoiding a lot of obstacle

Vehicle trajectories in the global reference system (NED) during driving in a curvy line avoiding a lot of obstacle is shown in Fig. 6. The results of calculations of the quantities that characterized the relative vehicles' motion are shown in Fig. 7a-7f. Values of the arithmetic mean of the quantities under analysis in the time intervals as specified during driving in a curvy line avoiding a lot of obstacle is shown in Table 2.

Table 1. Values of the arithmetic mean of the quantities under analysis in the time intervals as specified during driving in a straight line avoiding one obstacle

	Time interval 0–250 s		
	Arithmetic mean	**Minimum value**	**Maximum value**
Φ Target 1 [deg]	-8,4	-12,8	-3,9
Φ Target 2 [deg]	4,0	2,6	5,4
s_{fwd} Target 1 [m]	6,3	6,0	6,6
s_{fwd} Target 2 [m]	-12,2	-13,4	-11,0
s_{lat} Target 1 m]	-1,0	-1,5	-0,4
s_{lat} Target 2 [m]	0,88	0,50	1,26
vfwd Target 1 [m/s]	-0,01	-0,01	0,00
vfwd Target 2 [m/s]	0,1	0,0	0,3

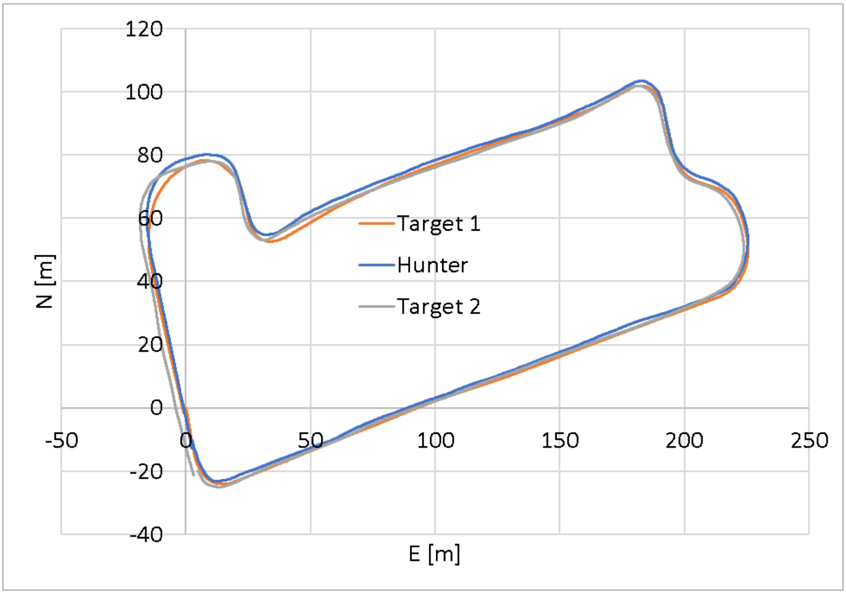

Fig.6. Vehicle trajectories in the global reference system (NED) during driving in a curvy line avoiding a lot of obstacle

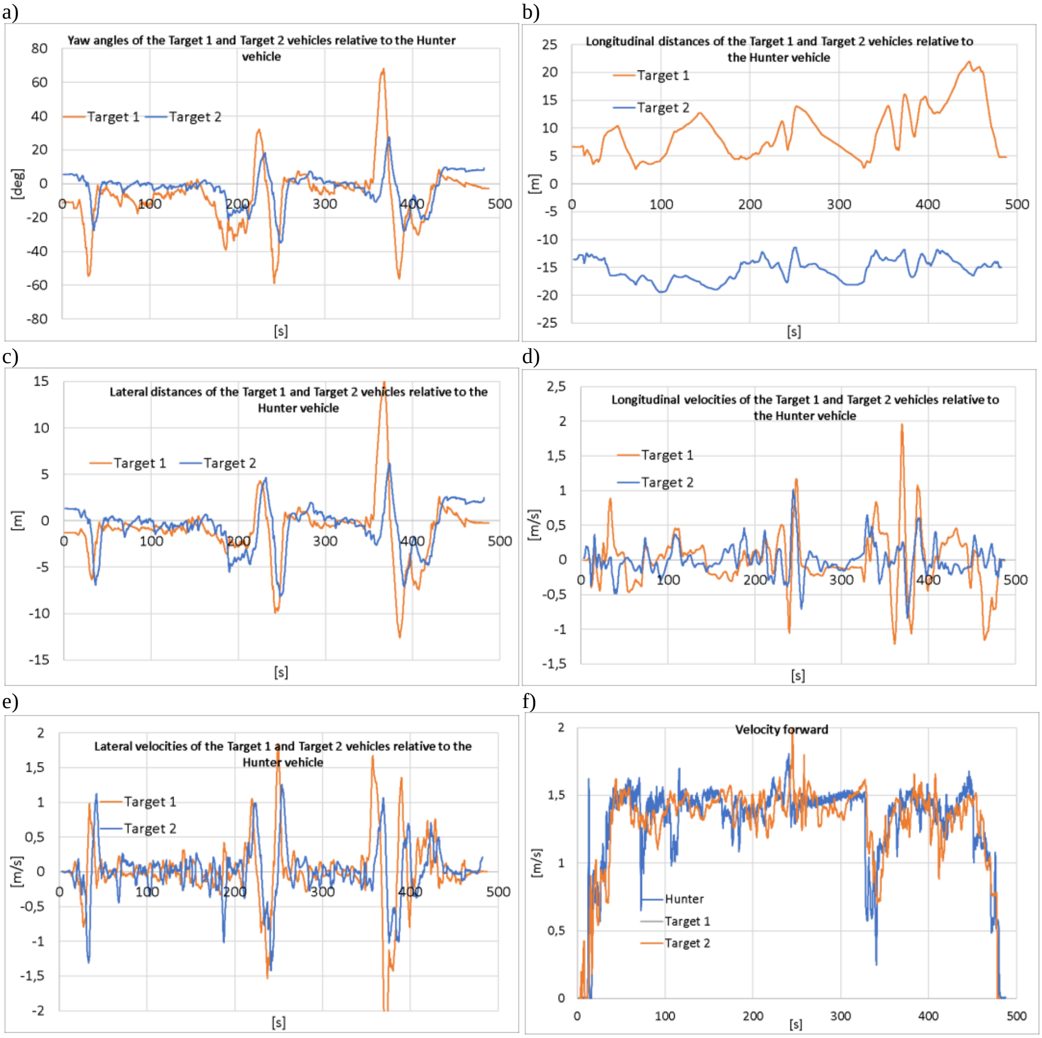

Fig. 7. Results of calculations of the quantities that characterized the relative vehicles' motion (source: authors' own study)

All the vehicles maintained continuous communication with the remote control station that cooperated with the group, this being an important element in assessing the reliability of the control system. It is possible to carry out a convoy mission along a designated route using a manned vehicle and unmanned vehicles with various autonomy levels, in conditions similar to real ones with an assumed distance between the vehicles of 10 m and a speed of 1.5 m/s. The biggest lateral distances, which may have a considerable impact on planning the path for the vehicle column, were observed between the Target 2 and Hunter vehicles. In subsequent studies, it should be assessed whether driver's decisions or different dimensions and designs of the running gear of the Target 2 and Hunter vehicles (a tracked and a small-size wheeled one, respectively) may affect the temporarily increased value of the lateral distance between the vehicles. The obtained average mission speed of 1.5 m/s should be considered low; it should be increased in subsequent tests, monitoring its impact on other parameters describing the vehicles' motion, e.g. the distance or relative yaw angles between the vehicles. Detailed conclusions:

- the maximum value of the modulus of the Target 1 and Target 2 vehicles' yaw angles relative to the Hunter – Hunter was, 12.8° and 5.4° (first test Target 1 and Target 2), 2.1° and 5.8° (second test Target 1 and Target 2), respectively.
- the longitudinal distances of the Target 1 and Target 2 vehicles relative to the Hunter vehicle were 6.0-6.6 m and 11-11.4 m (first test Target 1 and Target 2) 10.4–12.2 m and 13.4–18.5 m (second test Target 1 and Target 2), respectively.
- the lateral distances of the Target 1 and Target 2 vehicles relative to the Hunter vehicle were 0.4-1.5 m (first test Target 1 and Target 2), 0.1–0.4 m and 0.0–1.4 m (second test Target 1 and Target 2), respectively.
- the longitudinal velocities of the Target 1 and Target 2 vehicles relative to the Hunter vehicle were 0.0-0.3 m/s (first test Target 1 and Target 2), 0.1–0.4 m/s and 0.0–0.1 m/s (second test Target 1 and Target 2), respectively.

To calculate the required lane width for Target 1, Target 2 and Hunter vehicles, taking into account yaw angles, longitudinal and lateral distances and speeds, several factors need to be considered:
- the yaw angle of the vehicles relative to the Hunter (yaw angle) - the angle at which the Target 1 and Target 2 vehicles are positioned relative to the Hunter affects the lane width, as the vehicles are not moving in a straight line but may occupy more lateral space.

- lateral distances between vehicles - indicate how far apart the vehicles are on the road, which directly affects the lane width needed.
- longitudinal distances - indicate differences in vehicle positions relative to the Hunter vehicle in the direction of travel, but do not directly affect lane width.
- relative speeds - as speeds are very low, lane widths are not expected to be significantly affected. Vehicles are moving at almost the same rate.

To calculate the lane width needed for the safe passage of Target 1, Hunter and Target 2 vehicles along the designated routes, the external dimensions of the vehicles were taken into account (Target 1: length 3.5 m, width 2.0 m; Hunter: length 1.5 m, width 1.2 m; Target 2: length 7.4 m, width 3.0 m), the additional widths associated with the yaw angles of the vehicles and the maximum lateral distances between the vehicles. The additional width associated with the yaw angle was determined from the relationship:

$$\begin{gathered} lane\ width = \\ vehicle\ length \times \tan\,(yaw\ angle) \end{gathered} \tag{5}$$

For the first test:

- Target 1: Deflection angle 12.8°, additional width = 3.5m×tan(12.8°)≈0.80 m;
- Target 2: Deviation angle 5.4°, additional width = 7.4m×tan(5.4°)≈0.70 m.

For the second test:

- Target 1: Deviation angle 2.1°, additional width = 3.5m×tan(2.1°)≈0.13 m;
- Target 2: Deviation angle 5.8°, additional width = 7.4m×tan(5.8°)≈0.75 m.

Table 2. Values of the arithmetic mean of the quantities under analysis in the time intervals as specified during driving in a curvy line avoiding a lot of obstacle

	Time interval 50–150 s			**Time interval 260–360 s**		
	Arithmetic mean	**Minimum value**	**Maximum value**	**Arithmetic mean**	**Minimum value**	**Maximum value**
Φ Target 1 [deg]	−1,8	−2,1	−1,5	0,7	−0,3	1,7
Φ Target 2 [deg]	−0,1	−0,1	0,0	−1,8	−5,8	2,2
s_{fwd} Target 1 [m]	10,9	10,4	11,5	11,4	10,7	12,2
s_{fwd} Target 2 [m]	−17,4	−18,5	−16,4	−13,9	−14,5	−13,4
s_{lat} Target 1 m]	−0,3	−0,4	−0,3	0,2	−0,1	0,4
s_{lat} Target 2 [m]	−0,02	−0,03	0,00	−0,4	−1,4	0,6
vfwd Target 1 [m/s]	−0,1	−0,2	0,1	0,1	−0,2	0,4
vfwd Target 2 [m/s]	−0,1	−0,1	0,0	0,0	−0,1	0,1

For the first test:
Target 1: vehicle width: 2.0 m, additional width associated with yaw: 0.80 m, maximum lateral distance relative to Hunter: 1,5 m. Total width occupied by Target 1: 4.30 m.
Hunter: vehicle width: 1.2 m, total lane width for Target 1 and Hunter: 5.50 m
Target 2: vehicle width: 3.0 m, additional width associated with deviation: 0.70 m, total width occupied by Target 2: 3.70 m
For the second test:
Target 1: vehicle width: 2.0 m, additional width associated with yaw: 0.13 m, maximum lateral distance relative to Hunter: 0.4 m. Total width occupied by Target 1: 2.53 m,
Hunter: Vehicle width: 1.2 m, total lane width for Target 1 and Hunter: 3.73 m
Target 2: Vehicle width: 3.0 m, additional width associated with deviation: 0.75 m, total width occupied by Target 2: 3.75 m
Thus, the lane widths in:
- first test for Target 1 and Hunter is: 5,50 m.
- the second test for Target 1 and Hunter is: 3,73 m.
- the first test for Target 2 is: 3,70 m.
- the second test for Target 2 is: 3,75 m.

7. Summary and conclusions

Greater longitudinal distances between vehicles were recorded in the second test, which may have contributed to a more stable ride. The yaw angles of the Target 1 vehicle were smaller in the second test, suggesting better vehicle control in this test. Lateral distances in the second test were more predictable, which may have been due to better coordination of the control systems. The low relative speeds indicate that the Hunter vehicle successfully maintained a pace similar to the Hunter vehicle in both tests, which is beneficial from a safety perspective.
These findings may suggest that the conditions or control of the vehicles were more optimal in the second test, resulting in a more stable and predictable behavior of the Target 1 and Target 2 vehicles relative to the Hunter.
The external dimensions of Target 2's greater width have the effect of increasing the total lane width in both tests, particularly in test two, where the additional width resulting from the angle of deflection is greater.
The work describes the results of research into the possibility of conducting missions in convoys with vehicles with varying degrees of autonomy. Included were tests of the possibility of driving a convoy of two remotely controlled vehicles and one tracked vehicle driven directly by a human. The scope of the tests included checking the convoy's ability to move on a straight section of road with one fixed obstacle and on a winding path with numerous fixed obstacles. Research should be continued, especially in fully autonomous vehicle variants, with higher travel speeds and moving obstacles.

References

1. Alzu'bi, H., Tasky, T., (2020). LiDAR-Based Urban Autonomous Platooning Simulation, *SAE Technical Paper,* 2020-01-0717. https://doi.org/10.4271/2020-01-0717
2. Borhan, H., Lammert, M., Kelly, K., Zhang, C. (2021). Advancing Platooning with ADAS Control Integration and Assessment Test Results, *SAE Int. J. Adv. & Curr. Prac. in Mobility* 3(4),1969-1975. https://doi.org/10.4271/2021-01-0429
3. Czapla, T., Wrona, J. (2013). Technology Development of Military Applications of Unmanned Ground Vehicles, *Vision Based Systems for UAV Applications*, *Studies in Computational Intelligence*. 481(1), 239-309. https://doi.org/10.1007/978-3-319-00369-6_19
4. Czarnowski, J., Dąbrowski, A., Maciaś, M., Główka, J., Wrona, J. (2018). Technology gaps in Human-Machine Interfaces for autonomous construction robots, *Automation in Construction,* 94, 179-190. https://doi.org/10.1016/j.autcon.2018.06.014
5. Dębowski, A., Faryński, J.J., Żardecki, D.P. (2024). Reference Models of 4WS Vehicle Lateral Dynamics for the Synthesis of Steering Algorithms. In: Awrejcewicz, J. (eds) Perspectives in Dynamical Systems II — Numerical and Analytical Approaches. DSTA 2021. *Springer Proceedings in Mathematics & Statistics*. Springer, Cham. 454. https://doi.org/10.1007/978-3-031-56496-3_11

6. Durlik, I., Miller, T., Kostecka, E., Pusty, T., Łobodzińska, A. (2024). Utilizing recurrent neural networks in sustainable urban transport and logistics. *Scientific Journals of the Maritime University of Szczecin*, 78(150), 131-149. https://doi.org/10.17402/609
7. Faryński J., Żardecki D., Dębowski A. (2023). Method of Autonomous Vehicle Control Using Simplified Reference Models and Regulators. *Problems of Mechatronics Armament Aviation Safety Engineering*. 14(4), 37-58. https://doi.org/10.5604/01.3001.0054.1647.
8. Guzek M., Jackowski J., Jurecki R. S., Szumska E. M, Zdanowicz P., Żmuda M. (2024). Electric Vehicles—An Overview of Current Issues—Part 1—Environmental Impact, Source of Energy, Recycling, and Second Life of Battery, *Energies, MDPI*. 17 (1), 249, 1-25. https://doi.org/10.3390/en17010249
9. Guzek M., Jackowski J., Jurecki R. S., Szumska E. M, Zdanowicz P., Żmuda M. (2024). Electric Vehicles—An Overview of Current Issues— Part 2—Infrastructure and Road Safety, *Energies, MDPI*. 17 (2), 495, 1-29. https://doi.org/10.3390/en17020495
10. Guzek, M., Lozia, Z. (2002). Possible Errors occurring during Accident Reconstruction based on Car "Black Box" Records. *SAE Technical Paper*, 2002-02-0549, 90920. https://doi.org/10.4271/2002-01-0549
11. J3016_201806; Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles *SAE International*, J3016_201806. https://www.sae.org/standards/content/j3016_201806
12. Jaroszek, P., Trojnacki M. (2014). Model-Based Energy Efficient Global Path Planning for a Four-Wheeled Mobile Robot, *Control and Cybernetics*, 43(2) 337-363. http://yadda.icm.edu.pl/yadda//element/bwmeta1.element.ekon-element-000171510722?printView=true
13. Jurecki, R.S.; Stańczyk, T.L. (2021) A Methodology for Evaluating Driving Styles in Various Road Conditions. *Energies*, 14, 3570. https://doi.org/10.3390/en14123570
14. Kang, C.M., Lee, J., Yi, S.G., Jeon, S.J., Son, Y.S., Kim, W., Lee, S.-H., Chung, C.C. (2015). Lateral Control for Autonomous Lane Keeping System on Highways. *In Proceedings of the 2015, 15th International Conference on Control, Automation and Systems (ICCAS)*, Busan, Korea (South), 1728-1733. https://doi.org/10.1109/ICCAS.2015.7364643
15. Lewiński, R. (2022). Unmanned land vehicles – directions of research and development, *WIEDZA OBRONNA*, 280(3), 287-312. https://doi.org/10.34752/2022-n280
16. Li, X., Sun, Z., He, Z., Zhu, Q., Liu, D. (2015). A Practical Trajectory Planning Framework for Autonomous Ground Vehicles Driving in Urban Environments. *In Proceedings of the 2015 IEEE Intelligent Vehicles Symposium (IV)*, Seoul, Korea (South), 1160-1166. https://doi.org/10.1109/IVS.2015.7225840
17. Łopatka, M. (2020). UGV for Close Support Dismounted Operations – Current Possibility to Fulfil Military Demand, *Proceedings of 2nd International Conference CND GS'2020*, 2020(1), 16-23. https://doi.org/10.47459/cndcgs.2020.2
18. Małek, K., Dybała, J., Kordecki, A., Hondra, P., Kijania, K. (2024). OffRoadSynth Open Dataset for Semantic Segmentation using Synthetic-Data-Based Weight Initialization for Autonomous UGV in Off-Road Environments, *Journal of Intelligent & Robotic Systems*, 110 (76). https://doi.org/10.1007/s10846-024-02114-2
19. Prochowski, L.; Szwajkowski, P.; Ziubiński, M. (2022). Research Scenarios of Autonomous Vehicles, the Sensors and Measurement Systems Used in Experiments. *Sensors*, 22, 6586. https://doi.org/10.3390/s22176586
20. Prochowski, L., Pusty, T., Gidlewski, M., Jemioł, L. (2018). Experimental studies of the car-trailer system when passing by a suddenly appearing obstacle in the aspect of active safety of autonomous vehicles. *IOP Conference Series: Materials Science and Engineering*, 421, 032024. https://doi.org/10.1088/1757-899X/421/3/032024
21. Pszczółkowski, J., Goliasz, T. (2023). Analysis and evaluation of the technical equipment maintenance system in the Polish Army. *Military Logistics Systems*. 59(2), 73-102. https://doi.org/10.37055/slw/186384

22. Pusty, T. (2022). Determining the trajectory of the vehicle motion on the basis of the recorded physical quantities describing its dynamics during double lane change maneuvers, *The Archives of Automotive Engineering*, 96(2), 96-102. https://doi.org/10.14669/AM/151703
23. Salek, M. S., Thakur, M., B., Ala, P., S., K., Chowdhury, M., Schmid, M., Murray-Tuite, P., Khan, S., Krovi, V. (2024). An Overview of Automated Vehicle Platooning Strategies Published in *arXiv.org 8 March 2024 Engineering, Computer Science/ Systems and Control.* https://doi.org/10.48550/arXiv.2403.05415
24. Szynkarczyk, P., Wrona, J., Pasternak, M., Rubiec A., Serafin, P. (2022). Unmanned Ground Vehicle Equipped with Ground Penetrating Radar for Improvised Explosives Detection. *Journal of Automation, Mobile Robotics and Intelligent Systems*, 15(2), 20-31. http://dx.doi.org/10.14313/jamris/2-2021/10
25. Support OXTS https://support.oxts.com/hc/en-us/articles/115002772345-RT-Range-Measurements. accessed: 2024-02-05.
26. Tesla, N. (1898). Method of and apparatus for controlling mechanism of moving vessels or vehicles, Patent no US613809A.
27. Yan, D., Zhao, Z., Liang, K., and Yu, Q. (2023).Cooperative Lane Change Control Based on Null-Space-Behavior for a Dual-Column Intelligent Vehicle Platoon, *SAE Technical Paper,* 2023-01-7064. https://doi.org/10.4271/2023-01-7064
28. Wu, C. -F., Lin, C. -J., Lee, C.-Y. (2012). Applying a Functional Neuro-fuzzy Network to Real-Time Lane Detection and Front-Vehicle Distance Measurement; *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 42(4), 577-589. https://doi.org/10.1109/TSMCC.2011.2166067