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DETERMINATION THE IMPACT OF PARTIAL METRIC IMPROVEMENT ON THE EVALUATION OF UNMANNED GROUND VEHICLE COMPLEX APPLICATION EFFECTIVENESS

Unmanned Systems and Unmanned Ground Vehicles, in particular, have become a crucial element of modern combat operations during the war for Ukraine's independence against the Russian aggressor. A wide spectrum of tasks is assigned to them based on their designated roles: Intelligence, Surveillance, and Reconnaissance, strike (fire support), logistics, medical evacuation, etc.

This article provides an analysis of the most common types of multi-functional Unmanned Ground Vehicles in the Armed Forces of Ukraine, including those that are codified. It outlines the potential and limitations of Unmanned Ground Vehicles, based on an analysis of their Tactical and Technical Characteristics and combat capabilities derived from operational experience.

The key performance indicator for evaluating the combat effectiveness of a Unmanned Ground Vehicle unit is determined and substantiated. This performance indicator integrates aggregate metrics: Functionality/Combat Capabilities, Maneuverability, Survivability/Protection, Autonomy, and a list of partial components.

The influence of improving partial indicators on the Unmanned Ground Vehicles effectiveness assessment is determined using the system sensitivity analysis method.

The article presents an effectiveness evaluation of the designated tasks performed by a modernized combat Unmanned Ground Vehicles, with an illustrative example provided for clarity.

Keywords: *Unmanned Ground Vehicle, UGV, Monitoring, Reconnaissance, Detection, Situational Awareness Tool, Effectiveness Assessment, Sensitivity Analysis Method, Unit Employment.*

Problem Statement

Today, unmanned systems are being implemented across all domains and areas of application within the Armed Forces of Ukraine. According to the "Unmanned Systems" Doctrine, approved in August 2025 [1], the distribution of various types of Unmanned Ground Vehicles (UGVs) occurs across the majority of services (branches) and their subordinate units.

According to the Doctrine [1], an UGV is a complex (system) comprising vehicles, associated Ground Control Stations, command and control (C2) links, and other elements that ensure their functioning.There is rapid development and prototyping of new models by various manufacturers, necessitating standardization and a unified approach to the definition, classification, role, and place of UGVs among other forces and assets of the Armed Forces of Ukraine. The development of new and the improvement of existing doctrinal and regulatory documents are ongoing, and algorithms for the codification of both domestic and foreign platforms have been introduced.

Unmanned Ground Vehicles of various designations are being developed today, but operational experience [2–4] suggests that they are most efficiently used predominantly for logistics, medical evacuation (MEDEVAC), and reconnaissance; while combat modules are utilized only in supportive/accompanying roles. It is necessary to refine specific technical specifications (specs), which requires identifying problematic issues. Currently, there is a range of technical and organizational challenges regarding the deployment of UGVs. Manufacturers and developers continue to refine and modernize their UGV models by improving specific system parameters. It is relevant to investigate how the modernization of a platform's individual characteristics impacts the overall UGV operational effectiveness assessment.

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Analysis of Recent Research and Publications

Domestic military scientists and military experts from leading global nations employ various scientific approaches for evaluating the combat effectiveness of Armaments and Military Equipment models: analysis of Tactical and Technical Characteristics (TTCs); probabilistic (based on the probability of mission success); economic-mathematical (cost-effectiveness analysis); expert-analytical (assessment by a group of specialists in the absence of complete data); simulation-modeling (modeling combat scenarios with varied UGV parameters), etc. [5-10]. Article [11] presents methods for assessing the status of autonomous ground vehicles: perspectives on evaluation objects, key algorithms, and UGV characteristics.

This study selects a multi-criteria evaluation method based on a set of weighted indicators, and the quantitative (numerical) parameter for assessing the effectiveness of UGV models is defined as the Key Performance Indicator (KPI) for employment effectiveness, which is currently the most rational way to compare different types of combat platforms.

A thorough understanding of UGV employment challenges is necessary for a meaningful assessment of their effectiveness. A general overview of sources regarding the creation of ground platforms and their use in combat in Ukraine highlights the capabilities and limitations currently faced by UGVs.

Following the analysis of UGV employment effectiveness in combat based on the experience of the war in Ukraine [12-20], the general problems and weaknesses of UGV deployment can be summarized:

Tactical Effectiveness – whether the UGV achieves its assigned combat/operational tasks (reconnaissance, engagement, MEDEVAC, demining).

Personnel Safety/Force Protection – the extent to which UGVs reduce risk to personnel (the percentage of operations where UGVs replace a human in hazardous actions).

Payload Capacity and Protection – current platforms are still insufficient for heavy combat functions and protective armor.

Maneuverability – difficulty traversing complex terrain (craters, mud, dense foliage); lower effectiveness in urban warfare; impact of weather conditions.

Reliability / Availability – mean Time Between Failures in extreme conditions (dust, water, frost or heat, rough terrain degrade performance); failures; percentage of battlefield availability.

Mission Duration or Power Supply – average battery life (limited operation time-hours, sometimes less, under intensive tasks); logistical burden (charge/ replacement); charging logistics.

Resistance to Countermeasures (EW, Cyberattacks) – probability of losing control under the effect of Electronic Warfare (EW) (interference in control, spoofing, and jamming leave UGVs vulnerable; requires autonomous modes and protected channels). This is one of the most critical threats.

Maintenance Logistics – time and resources for repair/replacement; need for spare parts; many systems are commercial off-the-shelf; complex field repair.

Cost / Cost-Effectiveness – the ratio of effect (saved human resources, accomplished tasks) to overall cost.

Risk of Capture and Enemy Use – technical information and sensors may be copied or used against friendly forces.

Cost and Scalability – large-scale procurement and sustainment require significant resources; concurrently, a need for tens/thousands of units for widespread application.

Thus, existing UGV models require technological enhancements and the elimination of identified deficiencies, leading to the necessity of validating the rationality of implemented modernization.

The Goal of the Article is to conduct a fundamental study on the influence of individual parameters on the overall effectiveness assessment of UGV employment to enhance the functions and capabilities of ground robotic systems.

Presentation of the Main Material

The capabilities of modern UGV designs demonstrate a wide scope for executing combat missions. Specific missions require improved characteristics for relevant partial parameters (e.g., cross-country mobility and autonomy for logistical platforms (fig. 1 *a*), power supply for MEDEVAC platforms (fig. 1 *b*), a high degree of protection for fire support (strike) UGVs (fig. 1 *c*), etc.). A preliminary review indicated that significant improvements are currently needed across a large number of TTCs for models of various types and roles, which requires an analysis of UGV employment experience against specific indicators. Therefore, the analysis of UGV employment effectiveness should also be conducted with consideration of structural and technical features.

A generalized comparative technical analysis of the main characteristics that influence UGV maneuverability and cross-country mobility shows that:

tracked platforms have a larger contact area, which reduces ground pressure and increases cross-country mobility on soft soil types (mud, snow); mass distribution, track width, and ground clearance are critically important here;

the track drive system is more prone to wear when moving on gravel and requires regular tensioning/ section replacement;

the maintenance of a wheeled platform is simpler – in field repair, wheel replacement is faster than track repair;

speed and maneuverability in an Urbanized Area are higher for wheeled platforms – wheeled UGVs are typically faster and more maneuverable in narrow city streets, while tracked UGVs better overcome obstacles, ascents, and trenches.

The sensor and communication system is one of the primary limiting factors for UGV effectiveness (up to 30% of all operational failures); thus, manufacturers and developers are actively refining and improving the characteristics of the C2 infrastructure.

Kinematic and dynamic instability limit the effectiveness of UGVs on the battlefield in Ukraine. Kinematic instability is the unsteady position or trajectory of the UGV caused by features of the chassis design, mass distribution, or control inaccuracy. It manifests as: skidding and loss of trajectory; rocking when moving on uneven surfaces; instability during stopping or firing due to an unfavorable ratio of parameters: wheelbase / track / center of gravity / moment of inertia.

Dynamic instability is the loss of control or stability of the UGV under the influence of external or internal forces acting during movement, acceleration, or braking. It includes: hull oscillations; resonance during movement at certain speeds; oscillation of the gun or manipulator during movement or firing; rollover when overcoming obstacles or rapid changes in speed.

The design and technical solutions of various UGV manufacturers and developers improve the partial indicators of the models, but none accounts for all employment nuances. General recommendations for determining paths and directions for improvement include:

1. Technical problems can be solved by modernizing the design:

platform unification;

enhancement of armor protection;

modernization of the power plant to reduce thermal and acoustic detection by the enemy;

improvement of the running gear and, for example, the use of prospective hybrid bionic chassis.

2. Increasing autonomy and system intellectualization:

integration of Artificial Intelligence;

autonomous navigation;

autonomy.

3. Improving communication means provision:

Use of communications and control means with enhanced jamming resistance (wideband signal).

communication redundancy;

implementation of simultaneous multi-channel communication (radio, satellite, WiFi, 4G/5G);

use of Mobile Ad-hoc Network (MANET) technology to build a communication system within a UGV group.

4. Expanding functionality:

multi-functionality (replacing the combat module with a logistics module, etc.);

increased execution of engineer tasks.

5. Organizational issues:

centralized technical maintenance;

refining the training of operators and technical personnel (improving training quality);

scaling.

Thus, the effectiveness of UGV employment in the context of modern warfare demonstrates high potential but requires systematic improvement. Therefore, it is important to conduct a UGV employment effectiveness assessment and then investigate the impact of the implemented partial improvements on the effectiveness evaluation.

a *b* *c*

Fig. 1. **Domesticaly prodused UGV samples:**

a – TerMIT (TENCORE); *b* –Ardal (BUREVII); *c* – Krampus (Brave1/Deviro)

It is known that, according to the chosen multi-criteria evaluation method with weighted coefficients, the effectiveness of an Armaments and Military Equipment model is determined by assessing its group criteria (evaluation criteria) and studying the impact of partial factors (sub-criteria) that characterize the system. Therefore, the main influence indicators for assessing UGV operational effectiveness are defined as: *Functionality/ Combat Capability* (firepower, accuracy, compatibility, automation); *Maneuverability* (speed, cross-country mobility, range, maneuvers); *Survivability/ Protection* (armor, EW countermeasures, signature/

detectability) and *Autonomy* (power/energy, algorithms, communication).

This list and nomenclature of indicators are not constant and may change depending on the specific conditions under which priority thematic areas for scientific research are determined.

All group criteria represent interconnected constraints that define the UGV's combat readiness in the theater of operations. If one of these components fails to meet mission requirements, the platform's effectiveness falls exponentially, leading to equipment losses, mission failures, increased logistical burden, and the risk of capture/reverse-engineering. These criteria require detailed investigation to define UGV employment effectiveness evaluation criteria.

To ensure simplicity, clarity, and rapid results for assessing the effectiveness of combat UGVs, the Weighted Sum Method is proposed. This method is effective for prioritizing multiple options and allows for ranking options based on their importance or significance relative to defined indicators. The primary indicator for assessing the effectiveness of combat UGVs is defined as the Key Performance Indicator for Employment Effectiveness (KPI-EE) – a consolidated weighted indicator that summarizes several group criteria (combat, technical, operational) into a single numerical value, providing a quantitative assessment even for heterogeneous systems. Its purpose is the objective comparison of UGV employment effectiveness, considering their diversity and broad specialization, such as the degree of automation (remotely-operated, automated, robotic (autonomous) UGVs) or the type of UGV chassis (tracked, wheeled, special), etc.

Procedure for Calculating the Key Performance Indicator for Combat UGV Employment Effectiveness or KPI-EE – E_{tot} **.**

The UGV employment effectiveness is calculated using the relation (1)

$$E_{tot} = \sum_{i=1}^{N} \omega_i E_i \,, \qquad (1)$$

where:

E_i – normalized scores of the group criteria based on a defined experimental scale;

ω_i – weight coefficients of importance (determined by the expert assessment method), where $\sum_{i=1}^{N} \omega_i = 1$;

N – the number of group criteria.

The calculation of the weight coefficients for the combat UGV employment effectiveness indicators is performed using the *Pairwise Comparison Method*. This is done according to standardized algorithms involving competent experts and is not described in this paper.

The *min-max* normalization method is used to allow for the comparison of qualitative values of sub-criteria within a group criterion that have different natures.

In case one or more sub-criterion values are improved (e.g., during model modernization), the *Sensitivity Analysis Method* is used to assess the impact of these improvements on the overall effectiveness indicator of the model.

The sensitivity analysis method allows for assessing the model's robustness against parameter changes and the interrelationship between models. It also helps identify the criteria that most significantly influence effectiveness – for instance, control range or survivability.

In comparative models, the sensitivity method shows how competition between models affects rankings. It accounts for the degradation of one model when another is improved. That is, increasing the indicator of one model (e.g., range or survivability) automatically reduces the relative score of the others.

The quantitative measure of the model's robustness (sensitivity) to changes is the *Sensitivity Coefficient* – E^*_{tot} , which indicates the relative change in the integrated index upon changing a specific criterion. The relation (2) is used to determine the *relative increase*, in percentage

$$E^*_{tot} = \frac{\Delta_E^{Zr}}{E_{tot}^{Zr\_old}} * 100. \qquad (2)$$

where

Δ_E^{Zr} – change in contribution, calculated as $\Delta_E^{Zr} = E_{tot}^{Zr\_new} - E_{tot}^{Zr\_old}$;

$E_{tot}^{Zr\_old}$ – KPI-EE of the non-modernized model;

$E_{tot}^{Zr\_new}$ – new KPI-EE (calculated by the standard method using the new values of the improved sub-criteria, while others are fixed).

It is considered that in the case where $E^*_{tot} > 1$ – the system is highly sensitive (small changes have a strong impact). Conversely, in the case where $E^*_{tot} < 0$, a reverse effect is observed (e.g., improving one parameter causes a relative degradation of the overall index due to weight imbalance or normalization).

Example of Modernized UGV Effectiveness Assessment

To evaluate the impact of improving one or more UGV sub-criterion values on the overall effectiveness indicator E_{tot} of the model using the sensitivity analysis method, the example tests two scenarios: improving one TTC indicator and improving two sub-criteria from different group indicators.

In the first scenario, the sub-criterion "Power/ Energy" from the group criterion "Autonomy" is improved, while the second scenario improves "Accuracy" from the "Combat Capability" group criterion and "EW (Protection against EW influence)" from the "Survivability/ Protection" group criterion.

The following weight coefficients of importance are defined for both scenarios: $\omega_C = 0{,}25$, $\omega_M = 0{,}35$, $\omega_P = 0{,}2$, $\omega_A = 0{,}2$.

The KPI-EE values for the old and new sub-criteria $E_{tot}^{Zr\_old}$ and $E_{tot}^{Zr\_new}$ (for one sub-criterionand for two, respectively) were calculated using the standard method, equation (1), with new values for the improved sub-criteria and others fixed. The relation (2) is used to determine the Relative Increase E_{tot}^{*}, in percentage.

The results and intermediate values of the calculations performed for the UGV model before and after the modernization of specific indicators are presented in the table:

normalized indicators for old and new TTCs ($E_{tot}^{Zr\_old}$, $E_{tot\_1}^{Zr\_new}$ and $E_{tot\_2}^{Zr\_new}$, for one and two sub-criteria improving);

values of the old and new KPI-EE – $E_{tot}^{Zr\_old} = 4{,}7$, $E_{tot\_1}^{Zr\_new} = 4{,}83$ (for one sub-criterion), and $E_{tot\_2}^{Zr\_new} = 4{,}8$ (for two), respectively;

the value of the relative KPI-EE increase E_{tot}^{*} in conventional units (c.u.) and percentages (%) for one and two indicators, respectively.

Table

Effectiveness Assessment of a Modernized Model using Sensitivity Analysis

Indicators		Normalized indicators, rank		Relative Increase		Normalized indicators, rank	Relative Increase	
				c.u.	%		c.u.	%
Group Criterion	Sub-criterion	$E_{tot}^{Zr\_old}$	$E_{tot\_1}^{Zr\_new}$	$E_{tot\_1}^{*}$		$E_{tot\_2}^{Zr\_new}$	$E_{tot\_2}^{*}$	
Functionality/ Combat Capability, (C)	Firepower	6	6			6		
	Accuracy	6	6			7 (+1)	0,01	1,27
	Compatibility	7	7			7		
	Automation	5	5			5		
Maneuverability, (M)	Speed	5	5			4 (-1)	-0,02	-1,78
	Cross-country mobility	5	5			5		
	Operational Range	5	5			5		
	Maneuvers	4	4			4		
Survivability/ Protection, (P)	Armor	2	2			3 (+1)	0,01	1,35
	Signature/Detectability	3	3			3		
	EW (Protection against EW)	3	3			3		
Autonomy, (A)	Energy	5	7 (+2)	0,03	2,71	5		
	Algorithms	5	5			5		
	Communication	5	5			5		
	KPI-EE, c.u.	**4,70**	**4,83**		**2,71**	**4,80**		**0,85**

The analysis of the obtained data shows that for the defined weight coefficients of the chosen group criteria, upon improvement:

change in contribution for both tests $\Delta_{E_A}^{Zr} = 0.13$ and $\Delta_{E_{БЗ}}^{Zr} = 0.1$;

the sub-criterion "Power/Energy" from the group criterion "Autonomy" by 2 points results in a relative KPI-EE increase of $E_{tot\_1}^{*} = 2{,}71$ %.

the sub-criteria "Accuracy" from the "Combat Capability" group criterion by 1 point and "Armor" from the "Survivability/Protection" group criterion by 1 point results in a relative KPI-EE increase of $E_{tot\_2}^{*} = 0{,}85$ %, accounting for the loss of maneuverability due to the increased weight of the armor after modernization (speed reduced by 1 point).

The value of the relative KPI-EE increase indicates that the system is highly sensitive to changes.

The research results clearly demonstrate how the improvement of partial TTCs of a model can negatively affect the values of other indicators and the assessment of the overall UGV employment effectiveness indicator.

Future plans include conducting an analysis of the influence of modernized partial characteristics on the UGV employment effectiveness assessment in comparative models of competing platforms.

Conclusions

1. The analysis of sources regarding UGV employment experience in modern warfare reveals the high potential of contemporary designs, yet necessitates their systematic improvement. In this regard, studying the impact of implemented partial improvements on the UGV employment effectiveness assessment is relevant.

2. The example provided assessed the impact of improving one and several (two) UGV sub-criterion values on the overall effectiveness indicator E_{tot} of the model using the sensitivity analysis method. Two modernization options were tested. It was determined that, for the defined weight estimates of the selected group criteria, upon improvement:

the sub-criterion "Power/Energy" from the group criterion "Autonomy" by 2 points results in a relative KPI-EE increase of $E^{*}_{tot\_1} = 2{,}71$ %, which indicates the system's high sensitivity to change.

the sub-criteria "Accuracy" from the "Combat Capability" group criterion by 1 point and "Armor" from the "Survivability/Protection" group criterion by 1 point results in a relative KPI-EE increase of $E^{*}_{tot\_2} = 0{,}85$ %, accounting for the loss of maneuverability due to the increased weight of the armor after modernization.

3. The results of the conducted study clearly demonstrate that improving the partial TTCs of a model can negatively impact the values of other indicators and the assessment of the overall UGV employment effectiveness indicator.

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ВИЗНАЧЕННЯ ВПЛИВУ ПОКРАЩЕННЯ ЧАСТКОВИХ ПОКАЗНИКІВ НА ОЦІНКУ ЕФЕКТИВНОСТІ ЗАСТОСУВАННЯ БЕЗЕКІПАЖНОГО НАЗЕМНОГО КОМПЛЕКСУ

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У ході війни за незалежність України проти російського загарбника безпілотні системи, зокрема безекіпажні наземні комплекси, стали важливим елементом ведення бойових дій, на них покладається широкий спектр завдань, виходячи з їх призначення: розвідувальні, ударні (вогневі), логістичні, евакуаційні тощо.

У статті проаналізовано найбільш поширені у Збройних Силах України зразки багатофункціональних безекіпажних наземних комплексів різних типів, зокрема кодифікованих. З огляду на аналіз тактико-технічних характеристик і бойових можливостей за досвідом застосування окреслено потенціал та обмеження безекіпажних наземних комплексів.

Визначено й обґрунтовано показник оцінювання ефективності застосування підрозділу безекіпажних наземних комплексів, який включає групові показники: функціональність/бойові спроможності, маневреність, захищеність, автономність та перелік часткових складових.

Наведено визначення впливу покращення часткових показників на оцінку ефективності застосування безекіпажного наземного комплексу методом аналізу чутливості системи.

Проведено оцінювання ефективності виконання завдань за призначенням модернізованим бойовим безекіпажним наземним комплексом, для наочності наведено приклад.

Ключові слова: *безекіпажний наземний комплекс, моніторинг, розвідка, виявлення, засіб ситуаційної обізнаності, оцінювання ефективності, метод аналізу чутливості, застосування підрозділу.*