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V. Kryvtsun

IMPROVEMENT OF THE CLASSIFICATION OF REMOTE-CONTROLED (ROBOTIC) MEANS (COMPLEXES) OF DEMINING

The results of theoretical studies on improving the classification of remotely controlled (robotic) means (complexes) of demining are presented. The analysis of scientific approaches to the development of the classification of weapons and military equipment, in particular ground remote-controlled (robotic) means (complexes), was carried out. The advantages and disadvantages of object classification methods are defined, the expediency of their application is substantiated depending on the purpose of classification. Based on the faceted method, an improved classification of remotely controlled (robotic) means (complexes) of demining is proposed.

Keywords: *demining, classification, classification features, classification methods, remote-controlled (robotic) means (complexes) of demining.*

Statement of the problem. Modern conflicts and the war of the Russian Federation (RF) against Ukraine testify to the ever-growing role of mine weapons, which puts forward new requirements for demining means (complexes), which are primarily due to the expanded list of tasks that rely on them. The experience of conducting combat operations during the counteroffensive of the Defense Forces of Ukraine in the summer of 2023 showed that one of the most difficult tasks turned out to be overcoming the enemy's deeply echeloned system of mine-explosive barriers (MEB), in particular, making passages through them [1]. It should be noted that during the fire damage by the enemy, it was the means (complexes) of overcoming the MEB and demining groups of our units that became their primary targets.

However, there is another side to the use of mine weapons and other ammunition – the war of the Russian Federation against Ukraine led to the fact that our country turned out to be one of the most polluted by explosive objects (EO) among the countries of the world, about a third of the territory is covered by the so-called "mine pollution" [2].

In developed countries, due to the fact that mine danger has become a global problem, the priority issue of the development of means of combating mine weapons in the last two decades is the creation of remotely controlled (robotic) means (complexes) of demining (RCRMCD), as well as increasing the efficiency of conducting reconnaissance for the presence of EO and their identification using unmanned aerial vehicles (UAVs).

The implementation of the specified requirements leads to the emergence of new combinations of properties and methods of application of RCRMCD, which must be reflected by appropriate classification features. However, in Ukraine, the active development of demining equipment began only after the large-scale aggression of the Russian Federation, and as a result, there is currently a lack of adopted domestic anti-mine weapons, as well as a unified classification of these equipment.

It should be emphasized that the large nomenclature of existing RCRMCD provided by partner countries and prospective RCRMCD determines the need for their grouping by functional purpose in order to further ensure the maximum possible correspondence of the characteristics of the samples to their functional purpose. Such a generalization ensures the determination of the achieved level of development of the RCRMCD, reveals the structure in the general population of samples and determines their place in the weapons system.

Thus, there is a need for improvement classifications of the RCRMCD to consider classification features that reflect the essence of demining tasks that are actually being solved.

Analysis of recent research and publications. The analysis of the available sources of information revealed that little attention was paid to the issue of developing (refining) the classification of RCRMCD. This is also confirmed by the lack of such a class of weapons and military equipment (WME) in the governing documents [3]. The main attention was paid to the general classification of

robotic complexes, in particular ground ones [4–7]. In general, it should be noted that today there is a lack of a single, generally accepted view regarding the classification of robotic complexes and the conceptual apparatus in the field of robotics.

For example, in work [4], during the classification of robotic systems for military purposes, in particular, sapper systems, a matrix approach in the form of a table is proposed, which makes it possible to understand and classify robots, in order to implement a more balanced approach to their use in military operations. However, such a system can be much more complex depending on the level of detail and difficult to understand. In the article [5], based on the analysis of the "Concept of the use of ground robotic complexes for the fulfillment of the tasks of the Armed Forces of Ukraine for the period up to 2020 and the future perspective", a general classification of ground robotic complexes at the first stage is proposed according to the principle of the well-known "hierarchy ideas" with a multi-level distribution of entities, for example, into groups, classes, types, modifications. In the future, the classification of terrestrial robotic complexes is proposed to be carried out on the basis of intentional type research.

The publication [6] gives the classification of ground robots according to the ROS program (robot operating system) of Stanford University in terms of mass-dimensional characteristics and the level of autonomy as the main characteristics and properties. In work [7], it is proposed to solve the issue of classification of combat wheeled vehicles by using methods of cluster analysis. Therefore, the analysis of the works in the specified subject area shows that they are directed mainly to the general classification of robotic complexes and do not consider the specifics of their functional purpose, in particular demining, which determines the need to improve the classification of existing and prospective RCRMCD.

The purpose of the article is to develop proposals for improving the classification of remotely controlled (robotic) means (complexes) of demining.

Summary of the main material. The execution of demining tasks can be conditionally divided into three stages: reconnaissance of the MEB (localities, objects for the presence of EO), development of passages in the MEB, continuous demining of the area (combat, humanitarian) [8].

In connection with the great danger to the personnel of demining groups both during hostilities and in peacetime, special attention is paid to the creation of remote-controlled (robotic) demining tools (complexes) in the world. Under these conditions, the developers of the RCRMCD are constantly looking for a place for them in the process of performing demining tasks. Considering the above, the tasks of developing and systematizing the requirements for the RCRMCD arise, one of the stages of which is the clarification of the classification of the specified type of WME.

It should be noted that classification is, in the general sense, the division of objects into groups according to certain characteristics [9] . During the classification of a certain group of objects, in particular RCRMCD, it is necessary to clearly outline its purpose and scope of application, for example accounting, application or creation (constructive-functional classification), etc. Also, an important factor is the depth (detailedness) of the classification within the limits of "reasonable" sufficiency, otherwise this process can be endless. The most important factor when creating a classification of objects is the choice of a classification method.

The classification method is method of unification objects of classification into classification groups, which must satisfy certain requirements [9]. Based on the analysis of the works on the classification of RCRMCD, it can be noted that the main methods are hierarchical, facet and cluster analysis.

The hierarchical method of classification consists in the fact that the initial set of RCRMCD objects is successively divided into groups (classes) of the first level of division, then into groups of the next level, etc. A peculiarity of the hierarchical method is the close connection between individual classification groups due to the commonality and divergence of the main features. The basis of the division of the set into subsets , the main feature for this stage, is the degree of classification, that is, the stage of classification in the hierarchical method, which results in a set of classification groups. Each degree and grouping is highlighted by its own sign. Differences between groups consist of various features. In this regard, the selection of the main features is a responsible operation of the distribution of the set, on which the final result largely depends. This choice should be based on the intended purpose of the classification. At the same time, the number of signs and degrees determines the depth of classification. An example of such a classification of RCRMCD is shown in Figure 1.

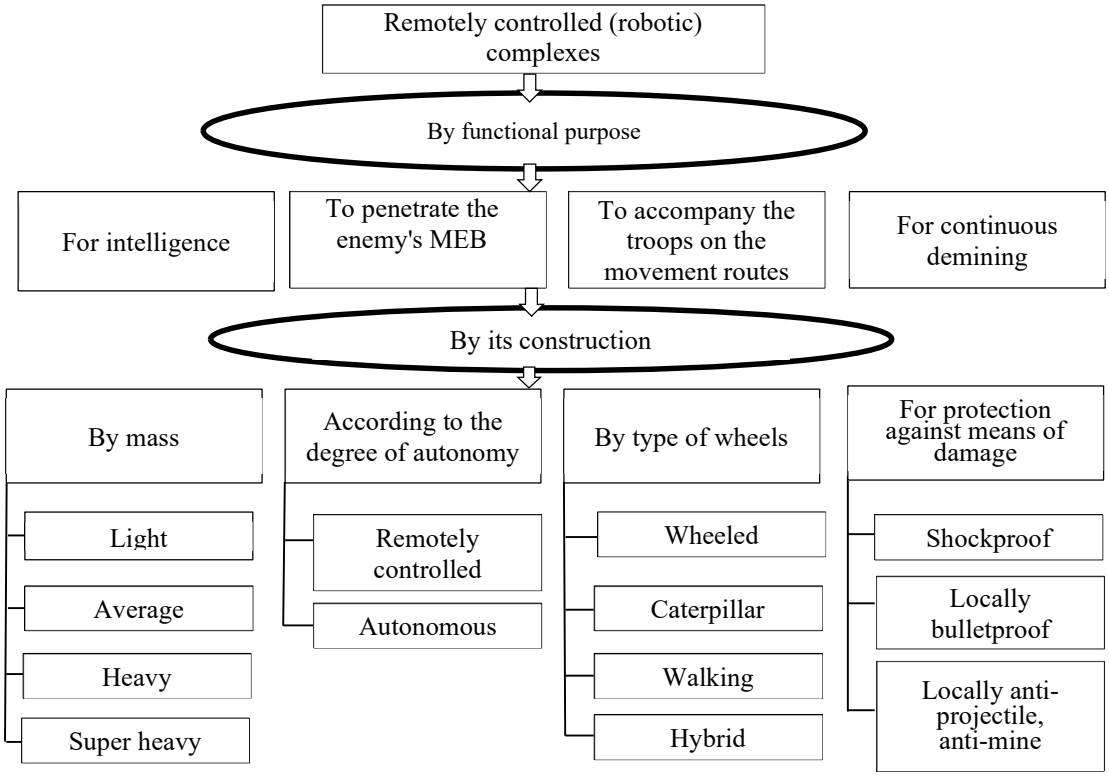

Figure 1 – Classification of remote-controlled (robotic) means (complexes) of demining by the hierarchical method

In contrast to the hierarchical method, the faceted method consists in the equal division of objects into independent classification groups. The peculiarity of the facet method is that the various signs are not related to each other. Thanks to this, the faceted system is characterized by great flexibility, the ability to limit the number of signs and groups, which creates certain conveniences during use. At the same time, its information capacity can be increased by selecting general and partial classification groups. Each feature of the faceted classification corresponds to a facet, which is a list of values of the named feature of the classification. So, the classification system can be represented by a list of independent facets (lists) that contain the values of the classification features.

An example of the classification of RCRMCD by the facet method is shown in Figure 2.

It should be noted that these methods belong to the group of heuristics. To obtain a rational classification result, their implementation requires the involvement of qualified experts.

In contrast to hierarchic and facet methods, cluster analysis does not require a priori assumptions about the definition of data, does not impose restrictions, and makes it possible to analyze indicators of various types of data (interval data, frequencies, binary data) [7]. At the same time, it should be emphasized that the variables should be measured in comparable scales. The criterion for determining the similarity and difference of clusters is the distance between the points on the scatter diagram, it is equal to the distance between the points on the graph. There are few ways to determine the measure of the distance between clusters, which is also called the measure of closeness. The most common way is to calculate the Euclidean distance (Euclidean metric) between two points *i* and *j* on the plane, when their coordinates *X* and *Y* are known [7] :

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \,. \qquad (1)$$

The distance between points in three-dimensional space (Figure 3) is determined by the following expression (Euclidean metric):

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \,. \quad (2)$$

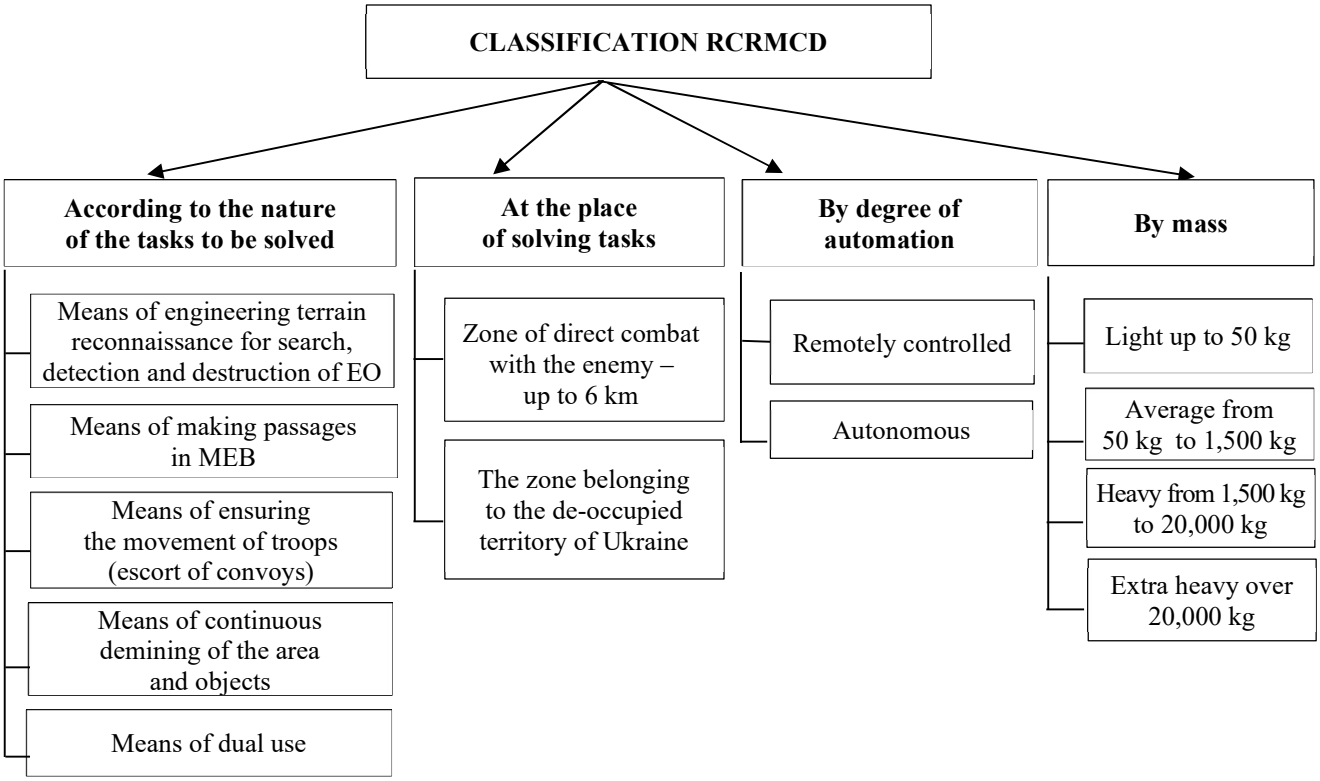

Figure 2 – Classification of remotely controlled (robotic) means (complexes) of demining by the facet method

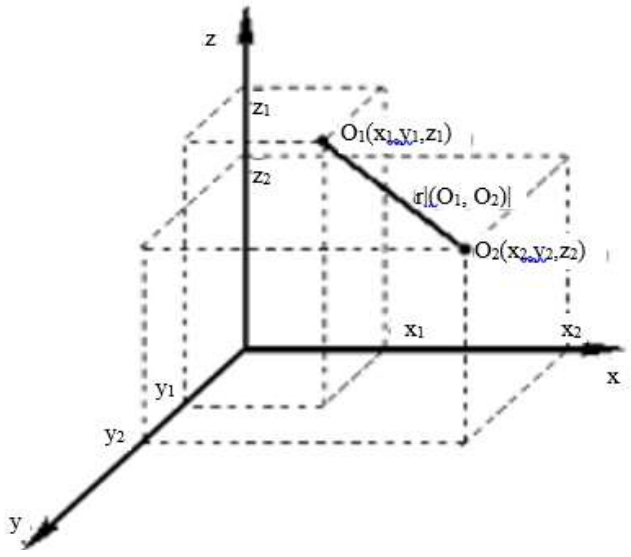

Figure 3 – Distance between two points in three-dimensional space

There are two groups of cluster analysis methods – hierarchical (sequential) and non-hierarchical (fuzzy), which contain many approaches and algorithms. Using different methods of cluster analysis allows you to get different solutions for the same data, which is a normal phenomenon.

During the classification of objects using the hierarchical method in [7], data analysis is proposed to be carried out by sequential clustering and to obtain a dendrogram that unambiguously describes the matrix of distances between elements. If $X=\{x_1,...x_n\}$ – is a set of n samples of RCRMCD, each of which is characterized by t features, then each of the samples can be considered as a point in the t – dimensional space. In this case, the output data can be presented in the form of a matrix:

$$X=\begin{pmatrix} x_1^1 & x_1^2 & \cdots & x_1^m \\ x_2^1 & x_2^2 & \cdots & x_2^m \\ \cdots & \cdots & \cdots & \cdots \\ x_n^1 & x_n^2 & \cdots & x_n^m \end{pmatrix}, \quad (3)$$

where x_n^m – the value of the m-th characteristic of the n-th sample of the RCRMCD.

Proximity between samples of the set X can be represented in the form of a matrix:

$$X=\begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{p1} & d_{p2} & \cdots & d_{pn} \end{pmatrix}, \quad (4)$$

where d_{pn} – sample proximity x_i and x_j.

The Euclidean metric is used to characterize the closeness.

To build a dendrogram, it is advisable to use SPSS software products, *STATISTICA* – when using agglomerative methods (unification methods) and STATGRAF – when using divisive methods (division methods).

To eliminate the bias caused by the influence of those features that have a larger range of values, the variables are standardized [7] :

$$x_i^{st} = (x_i - \bar{x}) / \left((n-1)^{-1} \sum_n [\bar{x} - x_i]^2 \right), \qquad (5)$$

where $\bar{x} = n^{-1} \sum_n x_n$ – the average value of the feature.

An example of the grouping of RCRMCD by the method of cluster analysis with obtaining a dendrogram is shown in Figure 4.

However, the results obtained in the monograph [7] during the application of the hierarchical method indicate the incorrectness of the obtained results in dendrograms, namely the combination of samples with significant differences in characteristics and purposes. All this requires revision of the number of clusters, which is possible through heuristic procedures and formal tests. In this regard, in order to obtain an acceptable result after determining the number of clusters, it is advisable to use methods of non-hierarchical (fuzzy) clustering, which, in contrast to the hierarchical one, weaken the strict requirement for the uniqueness of the clustering of elements (samples). Data clustering is an effective method of data preparation for further use by an expert group.

So, after considering the methods used to classify objects, in particular the RCRMCD, it can be noted that they have both advantages and disadvantages (Table 1).

On the basis of the analysis of the methods used during the classification of objects, the author of the article proposes an algorithm for developing the classification of the RCRMCD, shown in Figure 5.

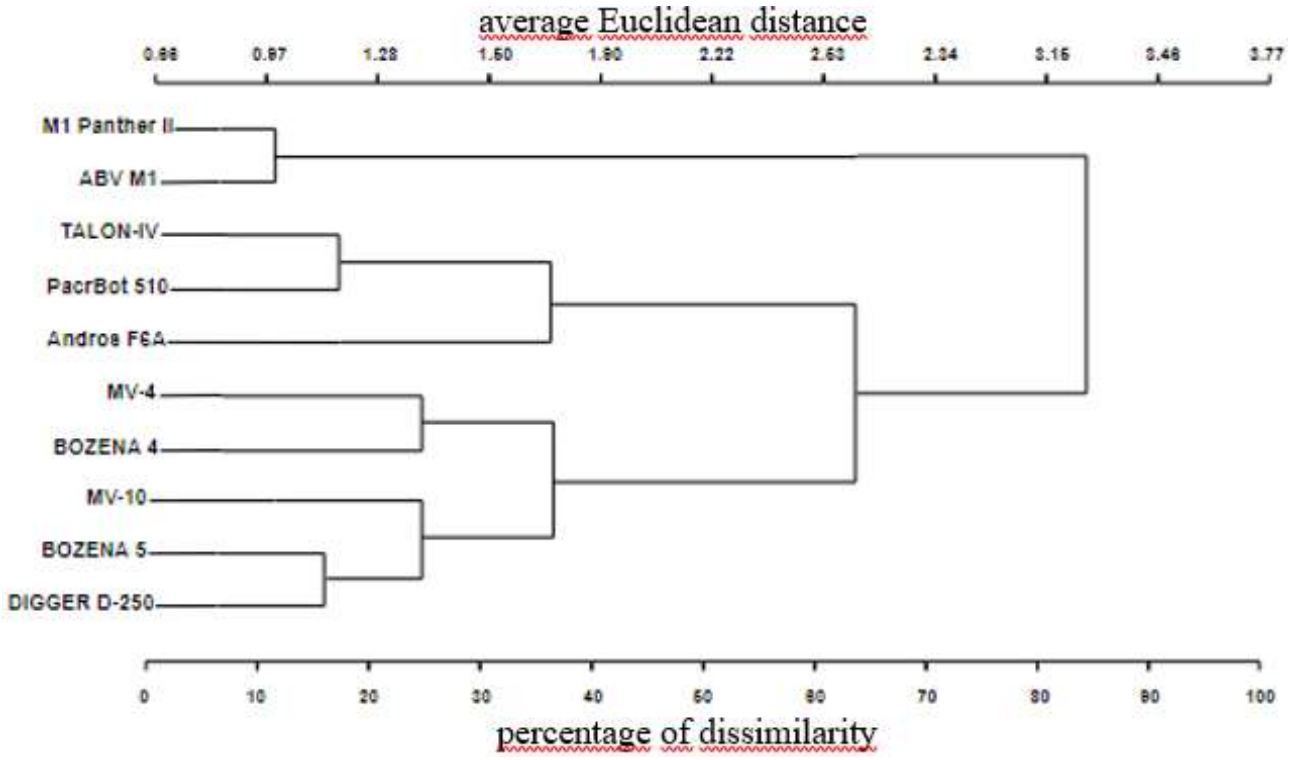

Figure 4 – Dendrogram for data of the main characteristics of 10 samples of remote-controlled (robotic) means (complexes) of demining

Table 1 – Advantages and disadvantages of classification methods

Methods of classification	Advantages	Disadvantages
Hierarchical	1. The logic of construction. 2. Clarity of identifying signs, a large amount of information. 3. Ease of use, visibility. 4. Each level of classification is a set of objects similar in one feature. 5. Differences between objects at different levels of classification are recorded	1. Rigid structure. 2. Lack of reserve volume. 3. For great depth: excessive bulkiness, high, not always justified costs, difficulties in use. 4. At a shallow depth: insufficient information, incomplete coverage of objects and features
Faceted	1. Flexibility of the building structure. 2. Possibility of aggregation of objects. 3. Ease of use. 4. The possibility of limiting the number of signs without losing the adequacy of object coverage	1. Incomplete capacity utilization. 2. Non-traditional , and sometimes difficult to use. 3. Impossibility of distinguishing commonalities and differences between objects in different classification groups
Cluster analysis	1. Visibility. 2. Allows you to identify similarities between objects and combine them into a group, which can be useful for further analysis. 3. Makes it possible to reduce the dimensionality of the data, which facilitates their further analysis. 4. Makes it possible to reveal complex relationships between objects that may be invisible during ordinary analysis and be used to develop promising samples	1. Sensitivity to the choice of initial parameters, which can lead to different results. 2. Susceptibility to data noise and outliers, which can lead to incorrect results. 3. The lack of possibility to take into account the qualitative criterion during implementation on a computer. 4. The need to review the results by qualified experts

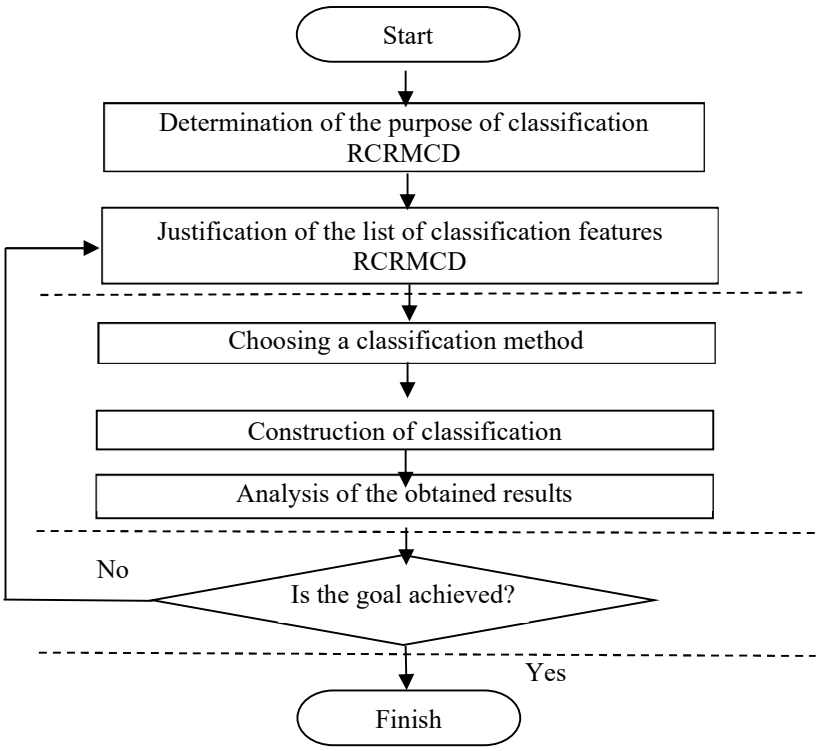

Figure 5 – Algorithm for developing the classification of remote-controlled (robotic) demining tools (complexes)

The most complete and meaningful issue of the development of robotic models, their nomenclature, tactical and technical parameters and the vision of the prospects for their use are reflected in the guiding documents and programs of the US Ministry of Defense [10].

Considering the views and methods of classification (their advantages and disadvantages) of RCRMCD, in the work the author proposes an improved classification of RCRMCD based on the facet method (Table 2), shown in tabular form.

For greater detail, it is possible to divide each group (class) into subgroups (subclass). The proposed classification of the RCRMCD is justified by the following provisions:

– the class of light demining anti-terrorist vehicles is determined by the possibility of transportation by dismounted servicemen during reconnaissance, search, detection, inspection and destruction of mines, improvised explosive devices and other explosive devices both in the areas where combat missions are carried out by units and units, and on troop movement routes;

– medium RCRMCD demining is determined by the possibility of their transportation on available cars with high cross-country ability (especially armored ones) and their use for searching, surveying and neutralizing IEDs, making passages in the MEB by explosive means;

– heavy RCRMCD is determined by the possibility of performing tasks of conducting reconnaissance, searching for and neutralizing EO on troop movement routes, demining the areas where troops (forces) are located, making passages by explosive means;

– super-heavy demining means are conditioned by the need to make passages in the MEB in the areas of hostilities during an offensive (counteroffensive), as well as for reconnaissance in an unknown area.

Table 2 – Classification of land-based remote-controlled (robotic) means (complexes) of demining

Group (class)	Weight, kg	Payload mass, kg	Way delivery	Protection level	Ability to perform tasks *
I (light)	Up to 50	10–15 % of the mass of the base platform	Portable	Shockproof	1,2
II (medium)	50–1,500		Portable, self-propelled	Local, bulletproof	1–5
III (heavy)	1,500–20,000	From 200 to 7000	Self-propelled	Anti-bullet, anti-splinter, anti-mine	1–5
IV (super heavy)	More 20,000	More than 5000	Self-propelled	Anti-bullet, anti-shell, anti-mine	2–5

** List of possibilities of RCRMCD.*

1. Conducting search, detection and destruction of mines, improvised explosive devices and other explosive devices.
2. Inspection and clearance of mines, improvised explosive devices and other IED routes (paths) for the movement of troops (forces).
3. Demining in the areas of hostilities and location of units.
4. Ensuring the overcoming of the MAZ, making passages in the minefields in front of the front edge and in the depth of the enemy's defenses.
5. Humanitarian and military demining.

Thus, based on the analysis of the tasks performed by demining units and the analysis of existing approaches to the classification of WME, the article proposes an improved classification of RCRMCD based on the faceted method, which will further provide an opportunity to justify the need of various demining units for such tools.

Conclusions

On the basis of the analysis of existing approaches to the classification of weapons and military equipment, the main methods have been determined: hierarchical, faceted and cluster analysis. The purpose of classification is the basis for making a decision on the application of these methods. Hierarchical and faceted methods or their combination should be applied for the purpose of further consideration in accounting documents, presentation materials, and cluster analysis methods – during the detection of regularities when justifying the parameters of prospective samples.

The work offers an improved classification of remotely controlled (robotic) means (complexes) of demining by the faceted method, considering the main classification features: the nature of the tasks to be solved, the mass, the degree of protection. The specified classification can be used to clarify the guiding documents for determining the nomenclature of engineering property, as well as the needs of engineering units of the Defense Forces for such equipment.

Direction of further research there may be a substantiation of the structure and parameters of promising remote-controlled (robotic) means (complexes) of demining.

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В. І. Кривцун

УДОСКОНАЛЕННЯ КЛАСИФІКАЦІЇ ДИСТАНЦІЙНО-КЕРОВАНИХ (РОБОТИЗОВАНИХ) ЗАСОБІВ (КОМПЛЕКСІВ) РОЗМІНУВАННЯ

Наведено результати теоретичних досліджень щодо вдосконалення класифікації дистанційно-керованих (роботизованих) засобів (комплексів) розмінування. Проведено аналіз наукових підходів до розроблення класифікації озброєння та військової техніки, зокрема наземних дистанційно-керованих (роботизованих) засобів (комплексів). Визначено переваги та недоліки методів класифікації об'єктів, обґрунтовано доцільність їх застосування залежно від мети класифікації. Розглянуто ознаки, які необхідно враховувати у класифікації дистанційно-керованих (роботизованих) засобів (комплексів) під час виконання основних завдань інженерної розвідки місцевості (об'єктів) на наявність вибухонебезпечних предметів, подолання мінних загороджень в умовах бойових дій та під час військового чи гуманітарного розмінування. Установлено, що наявна класифікація є загальною і не враховує класифікаційних ознак, які відображають сутність бойових завдань, що реально вирішуються дистанційно-керованими (роботизованими) засобами (комплексами) розмінування у сучасних воєнних конфліктах.

На основі аналізу методів класифікації об'єктів й особливостей процесу виконання завдань з подолання мінних полів противника та суцільного розмінування запропоновано вдосконалену класифікацію засобів (комплексів) дистанційного керування (роботизованого) розмінування на основі фасетного методу. Враховано чинники, що впливають на класифікаційні ознаки, згідно з якими запропоновано класифікувати дистанційно-керовані (роботизовані) засоби (комплекси) розмінування за чотирма категоріями: легкі, середні, важкі та надважкі.

Ключові слова: *розмінування, класифікація, класифікаційні ознаки, методи класифікації, дистанційно-керовані (роботизовані) засоби (комплекси) розмінування.*

Kryvtsun Volodymyr – Candidate of Technical Sciences, Senior Researcher, Doctoral Student of the National Academy of Land Forces named after Hetman Petro Sahaidachny
https://orcid.org/0000-0002-3907-5320