UDC 004.896:623.368 **doi: 10.32620/reks.2023.2.12**

Gennadiy FEDORENKO[1], Herman FESENKO[1], Vyacheslav KHARCHENKO[1], Ihor KLIUSHNIKOV[1], Ihor TOLKUNOV[2]

[1] ***National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine***
[2] ***National University of Civil Defence of Ukraine, Kharkiv, Ukraine***

ROBOTIC-BIOLOGICAL SYSTEMS FOR DETECTION AND IDENTIFICATION OF EXPLOSIVE ORDNANCE: CONCEPT, GENERAL STRUCTURE, AND MODELS

The subject *of this study is systems for detection and identification (D&I) of explosive ordnance (EO).* ***The aim*** *of this study is to develop a concept, general structure, and models of a robotic-biological system for D&I of EO (RBS-D&I).* ***The objectives*** *are as follows: 1) to classify mobile systems for D&I of EO and suggest a concept of RBS-D&I; 2) to develop the general structure of RBS-D&I consisting of robotic (flying and ground) and biological subsystems; 3) to develop models of RBS-D&I including automaton, hierarchical, and operational ones; 4) to describe tasks and planned results of the article-related scientific project; and 5) to discuss research results. The following* ***results*** *were obtained. 1) The general structure of the RBS-D&I. The structure comprises the following levels: control and processing centres (mobile ground control and processing centre (MGCPC) and virtual control and processing centre); forces for detection and identification (fleet of unmanned aerial vehicles (FoU), biological detection information subsystem (BDIS), and robotic detection information subsystem (RDIS)); interference; natural covers and a bedding surface; and target objects (all munitions containing explosives, nuclear fission or fusion materials and biological and chemical agents). 2) A concept of RBS-D&I. The concept is based on RBS-D&I description, analysis, development, and operation as an integrated complex cyber-physical and cyber-biological system running in changing physical and information environments. 3) The RBS-D&I automata model. The model describes RBS-D&I operating in two modes. In mode 1, FoU and BDIS operate separately and interact through the MGCPC only. In mode 2, depending on the specifics of the tasks performed, FoU and RDIS can directly interact among themselves or through the MGCPC. 4) hierarchical model. The model has two sets of vertices: EO detection and platforms equipped with the necessary sensors. 5) An operational cycle model. The model describes land release operations via a methodology of functional modeling and graphic description of IDEF0 processes.* ***Conclusions****. The proposed concept and RBS-D&I solutions can provide high-performance and guaranteed EO detection in designated areas by the implementation of an intelligent platform and tools for planning the use of multifunctional fleets of UAVs and other RBS-D&I subsystems.*

Keywords: *robotic-biological system; detection and identification; explosive ordnance; technical survey; non-technical survey; clearance; demining; hazardous area.*

Introduction

One of the biggest challenges for Ukraine, which is waging a long-term war of liberation against the Russian aggressor, and dozens of countries that have been engulfed in armed conflicts and wars over the past ten years, is the contamination of territories with various explosive ordnance (EO) [1, 2]. The need for an effective and safe search, identification and removal, and/or disposal of EO is an indisputable condition for the restoration and further development of territories in accordance with their purpose (residential areas, industrial enterprises, and territories of agricultural production, recreation areas, national parks and reserves, coastal territories and marine water areas, etc.).

The task of cleaning up areas contaminated by EO is expensive, time-consuming, and dangerous. According to the data analyzed in [3], the pace of cleaning the territory of Ukraine in 2015-2021 ranged from 30 to 870 square kilometers per year. During this time, from 50,000 to 170,000 units of EO were disposed of annually. It is clear that the volume of demining tasks during and after the end of the Russian-Ukrainian war increased by two orders of magnitude. Unfortunately, world statistics were also and are sad in this sense, which is confirmed by the growing number of international, national, state, and private organizations and companies that take care of various aspects of EO disposal.

This determines the intensive development of methods and technologies for demining using robotic systems, in particular, unmanned aerial vehicles [4, 5], ground [6], sea and underwater [7] robots, and other technical means.

The diversity of EO, their possible deepening relative to the surface of the territory, the presence of vegetation, trees, and other natural obstacles,

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

interference, and destruction, and the need for quick and high-quality demining in different climatic and seasonal conditions significantly complicate the creation and use of such systems and cause the development and implementation of new mobile means, which are based on technologies of artificial intelligence, augmented reality, big data, etc.

It is extremely important to look for integrated solutions that are based on the application of various concepts, methods, and technologies that complement each other, and thus increase the reliability and productivity of the EO detection with the unconditional fulfillment of security requirements. These are solutions based on modern information, communication, and robotics technologies, as well as traditional methods that use biological component - trained animals (dogs, rats, etc.) working under the guidance of qualified instructors [8-10]. In many cases, it is impossible to achieve the goal of demining without traditional bioinformatics technologies for detecting EO. Therefore, within the framework of this study, the authors emphasize such a complex approach to the construction and use of demining systems as complex robotic-biological systems.

1. State of the art

1.1. Analysis of article-related standards

The United Nations together with representatives from the mine action sector developed the International Mine Action Standards (IMAS) framework that covers a wide range of topics so that mine action programs are carried out in a consistent and professional manner: operational procedures, quality management, training and competencies, safety and risk management, and information management. Taking into account the topic of this article and the stated aim of the study, let's focus on standards that concern information management [11], general issues of demining [12-16], and issues of using animals for detection and identification of EO [17,18].

The standard [11] establishes general principles and guidelines that when followed ensure quality management of information in mine action programs. The goal of information management is to supply stakeholders with timely, accurate and relevant information products that meet agreed requirements. The standard also shows a structure that organizations and programs may use to store the minimum required data in a database.

The standard [12] establishes principles and provides guidance for the effective management of land release and residual contamination operations. Land release is the process of applying reasonable efforts to identify, define and remove all presence and suspicion of mines/explosive remnants of war (ERW) through non-technical survey, technical survey and/or clearance.

The standard [13] establishes principles and provides guidance on the conduct of non-technical surveys and details the responsibilities and obligations of the organizations. Non-technical surveys are typically the starting point for the assessment of land, its categorization as a suspected or confirmed hazardous area (SHA/CHA), and the associated processes of cancelling, reducing, or clearing land for productive use. It involves a thorough investigation of new information about possible EO contamination or a previously recorded hazardous area, generally without the use of mine action assets inside the suspected area.

The standard [14] establishes principles and provides guidance on the conduct of non-technical survey and details responsibilities and obligations of the organisations involved. The purpose of technical survey is to provide evidence for analysis to support the land release decision-making process. It is an intrusive process, using survey and clearance assets, typically into a suspected or confirmed hazardous area, although it may also be used as a method for the initial investigation of areas under some circumstances.

The standard [15] defines 'clearance' as part of the land release process and specifies the quality system (i.e. the organisation, procedures and responsibilities) necessary to determine that land has been cleared by the demining organisation in accordance with its contractual obligations. The aim of clearance is the identification and removal or destruction of all mines and ERW hazards, (including unexploded sub-munitions), from a specified area to a specified depth to ensure the land is safe for land users.

The standard [16] provides specifications and guidelines for the safe conduct of explosive ordnance disposal (EOD) operations as part of a mine action program. The standard [17] sets out fundamental principles and specified requirements relating to the use of Animal Detection System (ADS) in mine action programs. The term ‘Animal Detection System’ refers to the combination of animals, handlers, supervisors, managers, equipment, facilities, policies, procedures and other associated functions, which interact to provide a tool intended to detect vapour from EO. ‘Vapour’ may include vapour from the case material and other substances as well as from explosives.

The standard [18] considers procedures to be applied as part of using ADS operationally. They include but are not limited to operational planning and preparation for ADS, search procedures, environmental factors affecting ADS, rest and rotation of ADS units (animals and their handlers (under the direction and monitoring of team/site management)) and target indications for technical survey and clearance.

1.2. Methods of explosive ordnance detection

Currently, various methods are used to detect EO, which differ in physical principles, the complexity of implementation, and the interpretation of results.

Mechanical methods. When utilizing mechanical methods, EO detection and disposal are performed directly by a person or special machines. Modern demining machines are safer and more effective in demining EO with an explosive content of up to 15 kg (for example, mines, improvised explosive devices, and cluster munitions). The working element of demining machines is driven with hooks, cutters, cultivators, and special grippers [19]. To improve the quality of demining, combined systems are used, for example, a cultivator and a hoe. Such platforms are multifunctional, and various tools, search systems, navigation systems, and remote control systems can be installed on them.

An example of a system implementing mechanical methods is the MineWolf MW370 from Pearson Engineering: weight 23 t, clearing width 2.75 m, clearing depth up to 350 mm, clearing speed up to 2.3 km/h, demining productivity up to 30,000 m²/day, fuel consumption of 40–50 l/h and a remote control distance of up to 1000 m [20].

The mechanical method of detection and disposal is simple but provides a high probability of detection and neutralization of EO, and powerful armoured protection and remote control systems reduce the risk of injury to technical personnel. The disadvantages of mechanical methods include: low productivity and limited use depending on the terrain (impossibility to work on wet and stony ground, on slopes of more than 35°); the impossibility of use in forests; the high cost of equipment and costs for the performance of works; and certain environmental damage.

Electromagnetic methods. Electromagnetic methods are the general name of a group of methods that work in different frequency ranges and are widely used to detect, construct images and determine the properties of objects located, in particular, in optically opaque media, such as soil, concrete, brickwork, asphalt, stone, wood, and ice. EO detection using electromagnetic methods is based on differences in the electromagnetic properties of objects and obstacles. Systems created based on these methods differ in operating frequency, electromagnetic spectrum band, type of transmitted signals, interpretation of reflected signals, type of transmitter and receiver, and processing algorithms.

An example of means using the electromagnetic method is metal detectors (electromagnetic induction devices), which are now one of the primary means used in mine countermeasures. The advantages of the method are the ability to detect metal objects smaller than 1 cm at a depth of 50 cm [21]; all-weather; and low-cost.

The disadvantages of the method and the inability to detect EO with a small metal content (for example, in a plastic case); the inability to distinguish between EO and metal fragments, which causes a high percentage of false alarms; and the short search distance. Another example of the use of EMM is the Electrical Impedance Tomography Mine Detection System, which uses the technology of displaying the distribution of electrical conductivity of the medium-surface [22]. The system uses low-level currents to probe the earth surface through electrodes. Anomalies in the electrical conductivity of the environment perform the detection of mines. The main advantage is the possibility of detecting EO, including plastic ones, located under the water's surface.

The radio wave method is the most common detection method. Ground penetrating radars (GPRs), microwave radars (MWRs), and millimeter range radars (MMWRs) were built based on these methods. GPR systems (subsurface sounding radars or subsurface radars) are the general name of radar devices that implement technologies using electromagnetic waves to construct images and determine the properties of objects located in optically opaque environments such as soil, concrete, brick, asphalt, stone, wood, and ice. Typically, a radar of this type with a range of 1 m operates in the frequency range from 300 MHz to 3300 MHz [23].

The advantages include the ability to detect non-metallic objects and have low sensitivity to small metal objects, which reduces the number of false positives and provides information about the depth of the location of the potential EO. To increase the probability of detection and minimize false positives, a combination of GPR and highly sensitive metal detector is used.

These technologies are successfully used to create hand-held mobile devices, examples of which are the AN/PSS-14, which was specially developed for the US Army, in which information processing algorithms were additionally applied for providing high technical characteristics under the condition of low weight: the probability detection up to 98.7%, EO detection depth up to 300 mm, search speed 3.2 m/min, and scanning distance up to 10 cm [24]. Microwave radars operate in the microwave range of the electromagnetic spectrum and are suitable for detecting EO installed on the surface of the earth, even covered with small vegetation, or shallowly buried (up to a depth of several centimeters). Reflections occur at the boundaries of materials with different dielectric constants. An increase in the transmission frequency ensures an increase in resolution, but at the same time, the interference losses also increase, so frequencies up to 10 GHz are usually used.

Microwave radiometers are also used, which work as receivers of microwave radiation based on the high emissivity and low reflectivity of the soil, and conversely the low emissivity and high reflectivity of metal EO [25].

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Optical methods. Radiation in the optical range (wavelength 380–780 nm, frequency 7.89·1014–3.84·1014Hz) is conventionally divided into ultraviolet, visible, and infrared. Methods using the physical properties of this radiation have been successfully used to detect and identify EO. The ultraviolet radiation covers the wavelength range of 100–400 nm. In this range, direct unmasking signs of EO are not detected, but in the process of applying a certain external influence, additional unmasking signs may appear.

For example, in the case of spraying a special strain of bacteria over a contaminated area that germinates in a few hours and fluoresces under ultraviolet radiation in the presence of explosive substances in the soil [26]. The visible radiation used to detect EO involves capturing light in the visible wavelength range using an imaging optical system. The use of modern wide-format multi-spectral cameras makes it possible to survey large areas in a short time. The speed of the examination is determined by the speed of the platform on which the optical sensors are located.

In the case of using an aircraft, the inspection speed may exceed 100 km/h. The US Navy has demonstrated a prototype of a single multi-purpose aerial mine detection (SMAMD) system developed by BAE Systems. The SMAMD system uses a set of onboard optical sensors placed on board the MQ_8C Fire Scout unmanned aerial vehicle (UAV) [27].

The limitation of these methods is that only EO located on the soil surface can be detected. Weather and the presence of masking factors (camouflage, and vegetation) also affect the quality of detection. The use of infrared radiation to detect EO is based on the presence of a difference in thermal characteristics between buried objects and the surrounding soil, which leads to a temperature difference between the buried object and the soil. This temperature contrast is measured using a thermographic camera that detects radiation in the infrared range of the electromagnetic spectrum.

The advantages of optical methods include their passive nature, which means they have no impact on the EO control systems, which can result in an explosion, and their ability to boost survey speed and productivity by employing a UAV as a platform. The disadvantages of optical methods are that environmental parameters (sunlight, rain, etc.) and obstacles (soil cover, vegetation, etc.) affect the detection quality. This significantly narrows the possibilities of application.

Acoustic/seismic methods. Acoustic waves can be an effective tool for detecting and identifying land mines. Ultrasonic and acoustic-to-seismic (A/S) methods are common acoustic detection methods. These methods are based on mechanical properties. The disadvantages of these methods are low resolution and dependence on soil density. Therefore, this method has little efficiency in searching for EO, especially in the presence of several obstacles with different properties, for example, air-ground.

Currently, work is actively being carried out on the development and implementation of means implementing nuclear-physical methods. Bulk Explosive Detection Systems use the principle of Nuclear Quadrupole resonance, which allows the detection of chemical elements with an electric Quadrupole moment, which includes Nitrogen-14. The essence of the methods is that under the influence of radio frequency, approximately in the range from 0.5 to 6 MHz, the alignment of nitrogen nuclei changes, and after the termination of this frequency simulation, the nuclei return to their initial state and generate a specific radio signal that indicates the presence of nitrogen [28].

Neutron-based methods use the excitation of nitrogen, carbon, and oxygen nuclei by neutrons emitted by the system. The stay of atoms in an excited state is short-lived, and during the return to the normal state, gamma rays are emitted, the analysis of which allows determining the proportions of elements (C, N, O), as well as the presence of EO. The disadvantages of these systems are the high probability of false alarms and complexity of the analysis.

Biophysical methods. Biophysical methods are used to detect the remains of explosive substances. Trace Explosive Detection Systems use methods for chemical identification of microscopic residues of explosive substances in the form of vapours and (or) particles. This method is mostly used to reduce the area that needs to be surveyed.

It is based on the detection and quantitative assessment of specific chemical explosives and their components, which are contained in EO and diffuse into the surrounding environment. Nomadics Fido is a device whose action is based on the use of a highly sensitive chemosensor and photopolymer films that change their fluorescence when interacting with nitro compounds [29].

Biosensor systems are also used for these purposes, an example of which is BIOSENS - a Swedish project based on a change in the weight of the sensor due to the release of antigens in the presence of traces of explosive material, which leads to a change in the frequency at the output of the device. It is necessary to emphasize the successful use of animals to detect EO by chemical signs. Mine detection dogs (MDD) were used to detect mines even during the Second World War. In addition to dogs, research is being conducted in various countries on the use of other animals to detect EO, which are more suitable for certain areas and allow reducing the costs of cultivation and training [30]. Under the HeroRATs program, work is being conducted on the use of African giant bag-shaped rats (Mine detection rat, MDR), which help to find land mines [31]. Trained rats can survey an area the size of a tennis court (23.77 x 10.97 m) in 30 min.

Peculiarities of the utilization of other animals and insects to detect EO are also being studied. Note that animals have better gas analytical abilities than electronic gas analyzers. This makes it possible to detect explosives at lower concentrations and with greater probability. According to Marshall Legacy Institute (MLI) [32], MDD teams typically detect not only 30 times faster than teams using manual search methods but also safer. None of the MDD specialists died during demining operations. Artificial vapor detection competes with or is used in conjunction with animals.

However, animals are more sensitive and can detect different smells at the same time, which is quite difficult to reproduce artificially. Separately, it is necessary to emphasize the prospects of using animals in the creation of intelligent automated systems for the detection and disposal of EO. The concept is based on an animal-mounted mobile intelligent system that provides navigation, remote guidance, and surveillance. Such systems increase the probability of the detection of EO.

1.3. Comparative analysis of the EO detection methods

The results of the analysis of EO detection methods according to the main characteristics are shown in Table 1.

The examined methods only included those used in operational or experimental samples (systems). Based on the results presented in Table 1, the following conclusions can be drawn:

Table 1

Results of analysis of EO detection methods by main characteristics

Characteristic	**Mechanical**	**Electromagnetic**			**Optical**	**Acoustic/ Seismic**	**Nuclear-Physical**		**Biophysical**			
		GPR	**Electrical Impedance Tomography**	**Electro-Magnetic**			**Nuclear Quadropole Resonance**	**Neuron-based**	**Trace Explosive Detection**	**Bio-sensorical**	**Dogs**	**Other animals**
Type of intera-ction with EO (A – active, P – passive)	A	P	P	P	P	A	A	A	P	P	P	P
Platform type (S – stationary, M – mobile)	M	M	M	M	M	S	M	M	M	M	M	M
Potential pro-ductivity (Mdm – Medium)	Mdm	High	Mdm	High	High	Low	Mdm	Mdm	Mdm	Mdm	High	High
Data processing and storage	-	+	+	+	+	+	+	+	+	+	-	-
Network access and coverage	-	+	+	+	+	-	+	+	+	+	-	-
Real-time data transfer	-	+	+	+	+	-	+	+	+	+	-	-
Safety	Mdm	High	High	Low	High	Mdm	High	High	High	High	Low	Low
Probability of detection	High	High	High	Mdm	Low	Mdm	High	High	High	High	Mdm	Mdm
Resolution (selectivity)	Low	Low	High	Low	Mdm	Low	High	High	High	Low	Low	Low
Reliability	High	High	High	Mdm	High	Mdm	High	High	Low	Low	Mdm	Mdm
Cost	Mdm	Mdm	Mdm	Low	Mdm	Mdm	High	High	High	High	Mdm	Mdm

Radioelectronic and Computer Systems, 2023, no. 2(106)
ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Continuation of Table 1

Characteristic	Mechanical	Electromagnetic			Optical	Acoustic/ Seismic	Nuclear-Physical		Biophysical			
		GPR	Electrical Impedance Tomography	Electro-Magnetic			Nuclear Quadropole Resonance	Neuron-based	Trace Explosive Detection	Bio-sensorical	Dogs	Other animals
Pros	simplicity and high detection probability	the ability to detect non-metallic EO	detection of EO under the water surface	all-weather and low cost	high survey speed	the possibility of working in wet soils	high detection probability	high detection probability	the possibility of reducing the survey area	the possibility of reducing the survey area	high accuracy, safety and reliability	high accuracy, safety and reliability
Cons	low performance and restrictions on terms of use	low resolution	limited performance	the ability to detect only metal EO	restrictions on terms of use	high rate of false alarms	high cost and large equipment size	high cost and large equipment size	low performance and high false alarms	low performance and high false alarms	the need for long-term training	complexity of data preparation and interpretation

- nuclear-physical methods are the most accurate and reliable, but their implementation is currently very expensive;
- electromagnetic methods have good characteristics, but low selectivity;
- biophysical methods based on the use of animals allow for reducing the cost but have average values of the probability of detection and reliability.

Thus, to build effective and relatively inexpensive systems, it is advisable to integrate various methods, for example, biophysical and optical.

Table 1 also reveals that to provide high/required values of system characteristics, trustworthiness, safety, and reliability, it is necessary to use a few different methods and corresponding means. Hence, it's required to apply a fleet of UAVs of various types that could be transposed detection platforms of different configurations. Besides, the optimal or rational decision must be made considering cost, autonomy/power consumption issues.

2. Objectives and approach

The analysis of publications allows concluding that for the search and detection of EO using mobile systems, it is necessary to combine various methods, including biological ones, to strengthen them with means of artificial intelligence, as well as to find reasonable solutions for creating and implementing demining complexes.

The aim of this study is to develop a concept, general structure, and models of a robotic-biological system for D&I of EO (RBS-D&I).

The objectives of the investigation are the following:

- to classify mobile systems for D&I of EO and suggest a concept of RBS-D&I (Section 3);
- to develop the general structure of RBS-D&I consisting of robotic (flying and ground) and biological subsystems (Section 4);
- to develop models of RBS-D&I including automaton, hierarchical, and operational ones (Section 5);
- to describe tasks and planned results of the article-related scientific project (Section 6), and
- to discuss the research results (Section 7).

The approach to conducting research is based on system analysis of the:

- demining tasks and the land release operational cycle;
- physical and information environments of RBS-D&I application;
- robotic, biological, and cyber components of RBS-D&I;
- set of models describing principles of D&I of EO, models of functioning, and operation modes in changing conditions.

3. The concept of robotic-biological system for detection and identification of EO

The existing systems that are used to perform land release (demining) at its various stages, including the stage of search, detection, and identification, are built on different principles, considering the methods and means analyzed in section 1. They can be classified according to several characteristics, namely:

- according to the environment of application: air, surface (land and surface), underwater, complex, which work in several environments;

- by the nature of the means used: robotic, manual (a person with appropriate means), biological, mixed;

- type of cooperation depending on the nature of the means:

a) homogeneous (fleet, swarm, flock of UAVs (airborne); fleet, swarm, flock of UAVs (surface, underwater); teams of ground robots; collectives of biological systems (several sappers with dogs or Gambian rats);

b) mixed: robotic (based on various combinations of ground, air, surface, and underwater means) and robotic;

- type of systems management and digital infrastructure.

Next, a class of robotic-biological systems is developed and investigated.

The concept of RBS-D&I is based on its description, analysis, development, and operation as an integrated complex cyber-physical and cyber-biological system running in changing physical and information environments. This concept is presented by the system model of RBS RBS-D&I:

$$M_{RBS\text{-}D\&I} = \{M_C, M_O, M_{EN}\},$$

where $M_C = \{C_R, C_C, C_B, F_C\}$ is a model of RBS-D&I described by the sets of robotic C_R, cyber C_C, and biological C_B subsystems and components. Operator F_C describes interconnections between subsystems;

$M_O = \{O_S, O_{EO}, F_O\}$ is a model of the object presented by two or three dimension space for land release (demining) O_S, a set of explosive ordnance O_{EO} located in space O_S according to coordinates described by reflection F_O;

$M_{EN} = \{EN_{In}, EN_{Ph}, F_{EN,C}, F_{EN,O}\}$ is a model of physical EN_{Ph} and information EN_{In} environments described by the corresponding factors and parameters of influence on RBS-D&I components $F_{EN,C}$ and object $F_{EN,O}$.

4. General structure

A general structure of the RBS-D&I obtained on the basis of model (1) is presented in Fig. 1.

The structure comprises the following levels:

1. Control and processing centres.
2. Forces for detection and identification.
3. Interference.
4. Natural covers and a bedding surface.
5. Target objects.

Let us consider each level of the models in detail.

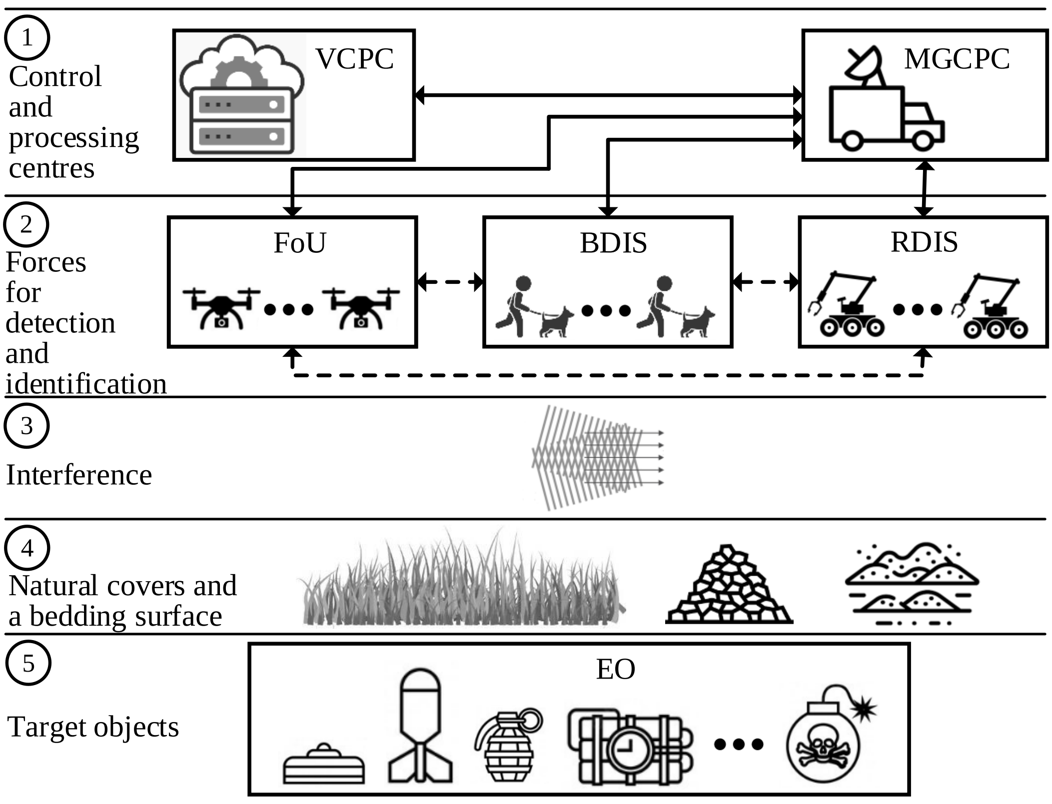

Fig. 1. General model of the robotic-biological system for detection and identification of EO

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Control and processing centres. The control and processing centres are the following: mobile ground control and processing centre (MGCPC) and virtual control and processing centre (VCPC). The MGCPC includes a management team of demining sub-unit that is operationally accredited to conduct one or more prescribed demining activities [12], UAV and robot operators, and appropriate hardware and software. The MGCPC performs the following functions:

- effectively plan, coordinate, and oversee the operations and activities performed by the forces for detection and identification;
- receives and processes data from the forces for detection and identification;
- sends the most significant data processing results to VCPC for backup storage or for processing and analysis by a group of experts.

The VCPC is designed to support the decision-making process in MGCPC by involving a group of experts in demining, including experts on the use of UAVs, robots, and animals to detect and identify EO. The VCPC can be built using Infrastructure as a Service (IaaS) offerings from cloud providers. This involves deploying virtual machines, networks, storage, and other resources on the cloud provider's infrastructure. The VCPC performs the following functions:

- receives data from the MGCPC that should be processed utilizing the IaaS capabilities;
- sends the results of data processing to the MGCPC;
- receives the most significant results of data processing from the MGCPC and ensures their storage;
- provides access to the data to a group of experts engaged by the MGCPC management.

Forces for detection and identification. The forces for detection and identification comprise a fleet of UAVs (FoU), biological detection information system (BDIS), and robotic detection information system (RDIS)).

The FoU consists of UAVs of the same or different types with onboard equipment for the detection and identification of EO. Each UAV is controlled either directly from the MGCPC or in the fully autonomous mode, which provides its greater distance. Depending on the specific equipment, sensors, and technologies UAVs are equipped with, the FoU can:

- conduct aerial surveillance of an area suspected of containing EO by capturing high-resolution images or video footage;
- identify anomalies in the ground or objects that may indicate explosives by utilizing thermal imaging cameras or ground-penetrating radar;
- gather more detailed information about detected explosive ordnances by capturing images or video footage from different angles;
- collect air samples and analyse them in real time to identify any chemical signatures of explosive ordnances by utilizing chemical sensors capable of detecting traces of explosive materials or volatile compounds associated with explosives;
- transmit the collected data, including images, video, sensor readings, and other relevant information to the MGCPC;
- assist in controlled detonation of explosive ordnances by utilizing specialized on-board equipment such as disruptors or explosive charges;
- create detailed maps of the area, marking the locations of detected EO.

The BDIS comprises animals specifically trained to detect and indicate EO, normally in a minefield environment/setting [17,18], EO disposal operators performing the roles of handlers (operators-handlers), and special equipment for collecting data and transmitting them to the MGCPC.

Depending on the specific equipment and sensors, operators-handlers and animals are equipped with and the technologies used, the BDIS can:

- find potential EO sites by using animals trained to detect the odor of explosives;
- visually identify potential explosive devices or suspicious objects using animals trained to recognize specific shapes, colors, or patterns associated with EO;
- identifying potential explosive ordnances by using animals trained to display distinct behaviours, such as agitation, freezing, or pointing, in the presence of explosives;
- transmit the collected data and other relevant information to MGCPC.

The RDIS consists of robots of the same or different types equipped for the detection and identification of EO. Each robot is controlled either directly from the MGCPC or in the fully autonomous mode.

Depending on the specific equipment, sensors, and technologies RDIS are equipped with, the RDIS can:

- scan objects, surfaces or the environment to identify suspicious items or materials associated with explosives by utilizing various sensors such as metal detectors, chemical sensors, or X-ray scanners;
- visually inspect and identify explosive devices or components by capturing high-resolution images or video footage;
- transport EO by utilizing specialized robotic arms or manipulators;
- transmit collected data, such as sensor readings, images, or video feeds to MGCPC;
- perform controlled disposal or neutralization of explosive ordnances by specialized tools or equipment to safely disarm or render the explosive devices inert;
- create detailed maps or 3D models of the environment, marking the locations of detected EO.

Interference. Interference refers to the presence of unwanted signals or objects that can affect the detection of EO. Interference can arise from various sources and can have different forms. Here are a few examples:

- electromagnetic signals from external sources, such as power lines, radio transmitters, or electronic equipment, interfere with detection systems used in demining. These signals can create false readings or mask the presence of buried explosives, making it difficult to accurately identify and locate mines;
- metallic clutter (scrap metal, discarded objects, or remnants of previous conflicts) in the area where EO detection and identification activities are occurring. The metallic clutter can confuse or obscure the signals produced by metal detectors, making it challenging to distinguish between harmless debris and buried mines.

Natural covers and bedding surface. Natural covers, such as vegetation or foliage can:

- effectively conceal EO, making them difficult to detect visually;
- generate false signals or noise that can interfere with detection equipment used in demining;
- restrict physical access to needed areas.

A bedding surface, such as a layer of gravel, sand, or soil, can:

- effectively mask the presence of EO beneath it;
- introduce false signals or noise that can confuse detection equipment used in demining. For example, certain types of gravel or rock formations can generate metallic reflections or electromagnetic interference, leading to false positives or misleading readings.

Target objects. Target objects are specified objects that the robotic-biological system is required to detect and identify. In this study, such objects are EO. According to [16], EO are all munitions containing explosives, nuclear fission or fusion materials and biological and chemical agents. This includes bombs and warheads; guided and ballistic missiles; artillery, mortar, rocket and small arms ammunition; all mines, torpedoes and depth charges; pyrotechnics; cluster bombs and dispensers; cartridge and propellant actuated devices; electro-explosive devices; clandestine and improvised explosive devices; and all similar or related items or components explosive in nature.

5. Models

5.1. Automata model

Let, according to the general structure of the system, the D&I of EO are carried out by two subsystems - FoU and BDIS. These subsystems can work sequentially and in parallel in two modes.

Mode 1: FoU and BDIS operate separately and interact through the MGCPC only. Their operation is synchronized at the planning stage and can be independently corrected during work (Fig. 2).

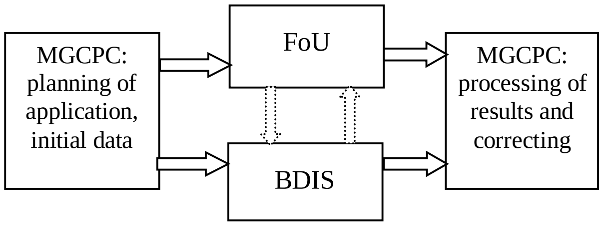

Fig. 2. Scheme of interaction subsystems UAVF and BDIS

Mode 2: FoU and RDIS can directly interact among themselves or through the MGCPC depending on the specifics of the tasks performed, conditions, and results of operation.,.

This interaction is shown by dashed arrows between blocks FoU and BDIS in Fig.2.

Interaction of the MGCPC, FoU, and BDIS can be described by scheme of composition automaton (Fig. 3).

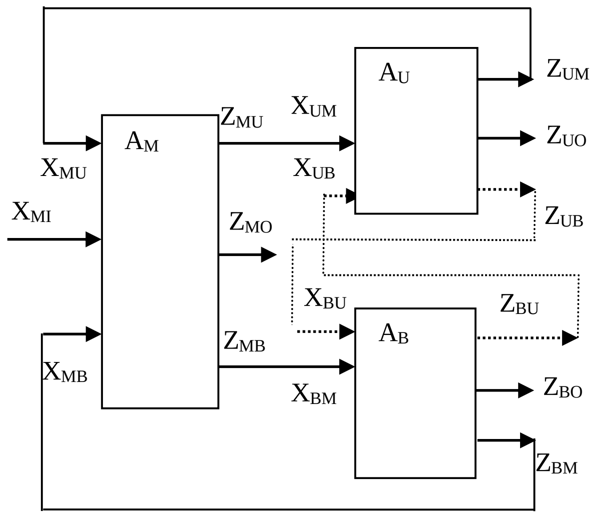

Fig. 3. Scheme of BRS-D&I composition automaton

In these modes, the operation of RBS can be described by automaton models AC_1 and AC_2 that are composed of three sequential automata A_{Ui}, A_{Bi}, A_{Mi}, i = {1,2}, for the FoU, BDIS, MGCPC, correspondingly:

$$AC_1 = \{A_{U1}, A_{B1}, A_{M1}\},$$

$$AC_2 = \{A_{U2}, A_{B2}, A_{M2}\},$$

where

$A_{U1} = \{y_{U10}, t, X_{U1}, Z_{U1}, Y_{U1}, FT_{U1}, FO_{U1}\}$,
FT_{U1}: $Y_{U1}(t+1) = FT_{U1}(Y_{U1}(t), Z_{U1}(t))$,
FO_{U1}: $Z_{U1}(t) = FO_{U1}(Y_{U1}(t))$;
$A_{B1} = \{y_{B10}, t, X_{B1}, Z_{B1}, Y_{B1}, FT_{B1}, FO_{B1}\}$,
FT_{B1}: $Y_{B1}(t+1) = FT_{B1}(Y_{B1}(t), Z_{B1}(t))$,

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

FO_{B1}: $Z_{B1}(t) = FO_{B1}(Y_{B1}(t))$;
$A_{M1} = \{y_{M10}, t, X_{M1}, Z_{M1}, Y_{M1}, FT_{M1}, FO_{M1}\}$,
FT_{M1}: $Y_{M1}(t+1) = FT_{M1}(Y_{M1}(t), Z_{M1}(t))$,
FO_{M1}: $Z_{M1}(t) = FO_{M1}(Y_{M1}(t))$;

$A_{U2} = \{y_{U20}, t, X_{U2}, Z_{U2}, Y_{U2}, FT_{U2}, FO_{U2}\}$,
FT_{U2}: $Y_{U2}(t+1) = FT_{U2}(Y_{U2}(t), Z_{U2}(t))$,
FO_{U2}: $Z_{U2}(t) = FO_{U2}(Y_{U2}(t))$;
$A_{B2} = \{y_{B20}, t, X_{B2}, Z_{B2}, Y_{B2}, FT_{B2}, FO_{B2}\}$,
FT_{B2}: $Y_{B2}(t+1) = FT_{B2}(Y_{B2}(t), Z_{B2}(t))$,
FO_{B2}: $Z_{B2}(t) = FO_{B2}(Y_{B2}(t))$;
$A_{M2} = \{y_{M20}, t, X_{M2}, Z_{M2}, Y_{M2}, FT_{M2}, FO_{M2}\}$,
FT_{M2}: $Y_{M2}(t+1) = FT_{M2}(Y_{M2}(t), Z_{M2}(t))$,
FO_{M2}: $Z_{M2}(t) = FO_{M2}(Y_{M2}(t))$;

$$X_{U2} = X_{U1} U X_{UB},\ Z_{U2} = Z_{U1} U Z_{UB};$$

$$X_{B2} = X_{B1} U X_{BU},\ Z_{B2} = Z_{B1} U Z_{BU};$$

$$X_{M2} = X_{M1},\ Z_{M2} = Z_{M1},$$

where

X_{U1}, X_{B1}, X_{M1}, X_{U2}, X_{B2}, X_{M2}, X_{UB}, X_{BU} are alphabets of corresponding input signals;

Z_{U1}, Z_{B1}, Z_{M1}, Z_{U2}, Z_{B2}, Z_{M2}, Z_{UB}, Z_{BU} are alphabets of corresponding output signals;

Y_{U1}, Y_{B1}, Y_{M1}, Y_{U2}, Y_{B2}, Y_{M2} are alphabets of corresponding memory states;

FT_{U1}, FT_{B1}, FT_{M1}, FT_{U2}, FT_{B2}, FT_{M2} are corresponding functions of transitions;

FO_{U1}, FO_{B1}, FO_{M1}, FO_{U2}, FO_{B2}, FO_{M2} are corresponding functions of outputs;

y_{U10}, y_{B10}, y_{M10}, y_{U20}, y_{B20}, y_{M20} are initial states of corresponding automata:

t is a discrete automaton time.

The automata model is the abstract presentation of the system. Based on this model, RBS-D&I components and subsystems can be further described and synthesized.

5.2. Model of detection and identification of EO

According to the results of the analysis performed in Sections 3, 4, two main tasks for building a mathematical model of the EO search and detection system should be identified:

1) determination of coordinates and type of EO;

2) optimal selection and configuration of search engine platforms with the calculation of routes for surveying.

To solve these problems, a hierarchical model is proposed, which has two sets of vertices: EO detection (I) and platforms equipped with the necessary sensors (P).

The mathematical model is illustrated in Fig. 4 and consists of the following elements:

U_i – unmasking signs of EO;

ω_i – interference caused by the covering layer of ground (G) and the surrounding environment (A);

M_i – methods of detection that are applied using information and measurement tools (sensors);

P_i – the platforms on which information-measuring means of D&I (sensors) are located.

Maps – digital maps of contaminated areas;

AI algorithms - recognition algorithms based on artificial intelligence;

Cognitive algorithms – cognitive calculations that use human experience and expertise;

Actor is an expert person;

D – EO image datasets for training mathematical models;

I – presumably detected EO and their types.

The proposed mathematical model for D&I of EO is probabilistic in nature and depends on how fully the proposed analytical dependencies describe the physical phenomena that occur during the interaction of unmasking features with the methods of D&I of EO, considering nonlinear distortions due to the influence of interference caused by covering soil and the surrounding environment (atmosphere).

Each type of EO has certain unmasking signs [33], which can be due to the following:

- appearance (color, shape, size);
- physical properties (mass, density, viscosity, electromagnetic conductivity);
- radiation (luminosity, radioactivity, electromagnetic radiation);
- chemical properties (chemical composition, acidity).

Thus, by unmasking the signs and characteristics of obstacles, they determine methods of detection and recognition and condition a set of information and measurement tools.

According to the model (Fig. 4), the initial data for training the models of the AIS means for EO identification using UISs and a two-level distributed architecture of edge computing and a private protected cloud system are formalized [34] and AI quality models are developed and profiled [35]. Further, artificial intelligence methods and tools have been developed for EO identification, as well as methods, algorithms, and tools for evaluating and visualizing the compliance of UISs with requirements for trustworthiness, resiliency, reliability, and safety [36, 37].

5.3. Operational cycle

To describe the processes of system functioning, we will use the methodologies of functional modelling and

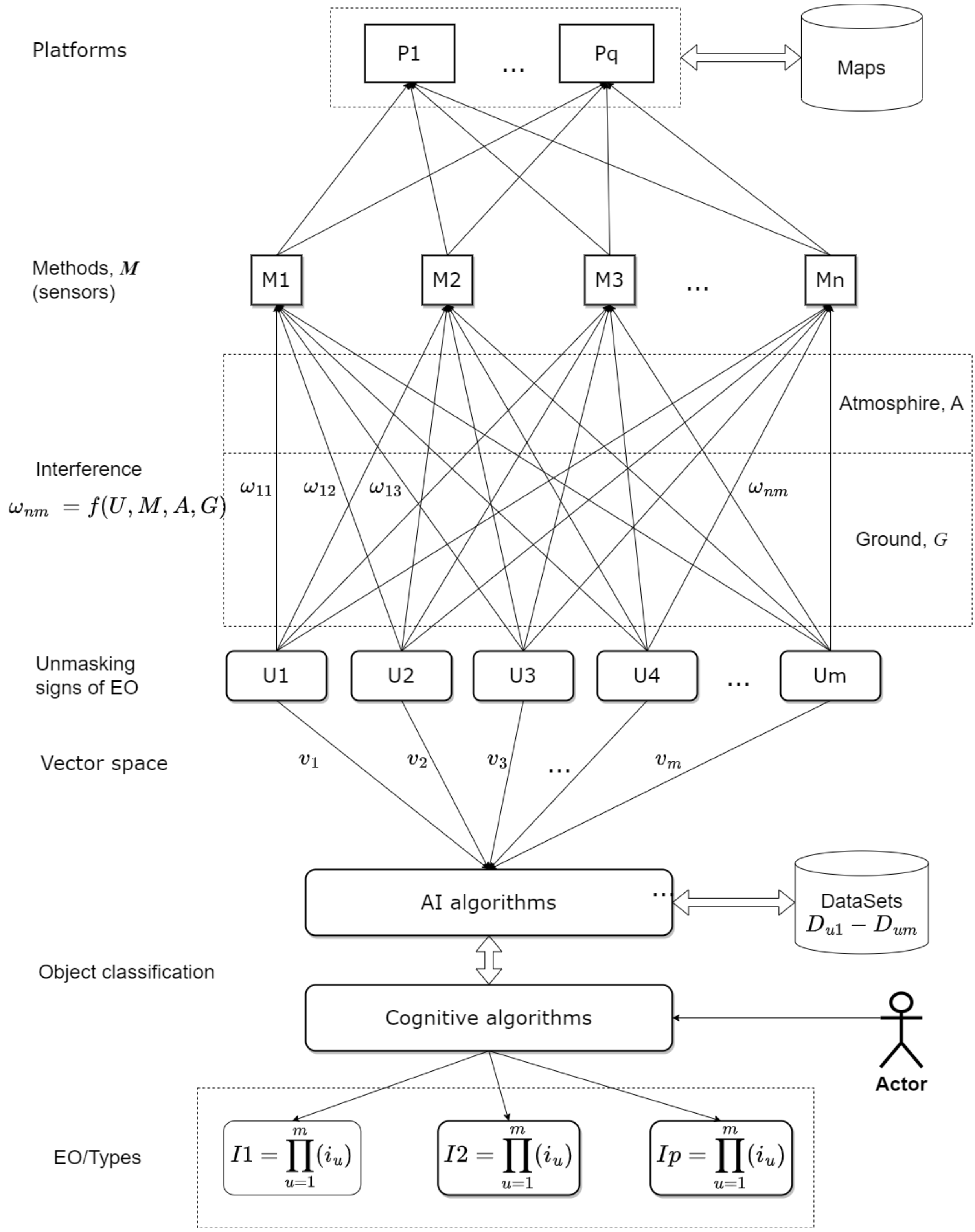

Fig.4. Structure of mathematical model

graphic description of IDEF0 processes. We will start the construction of the IDEF0 model from the context diagram A0 (Fig. 5), which consists of one functional block “Land release” with interface arcs that determine the connection with the external environment, as well as Input (Area potentially contaminated with EO), Outputs (Area cleared of EO, Acts of the performed works), Control (GIS data, EO database, Legislative acts, Orders, Evidence), and Mechanism (IT infrastructure, Sensors, Platforms, Algorithms).

Context diagram A1 (Fig. 6) consists of four blocks, the purpose and results of which are as follows.

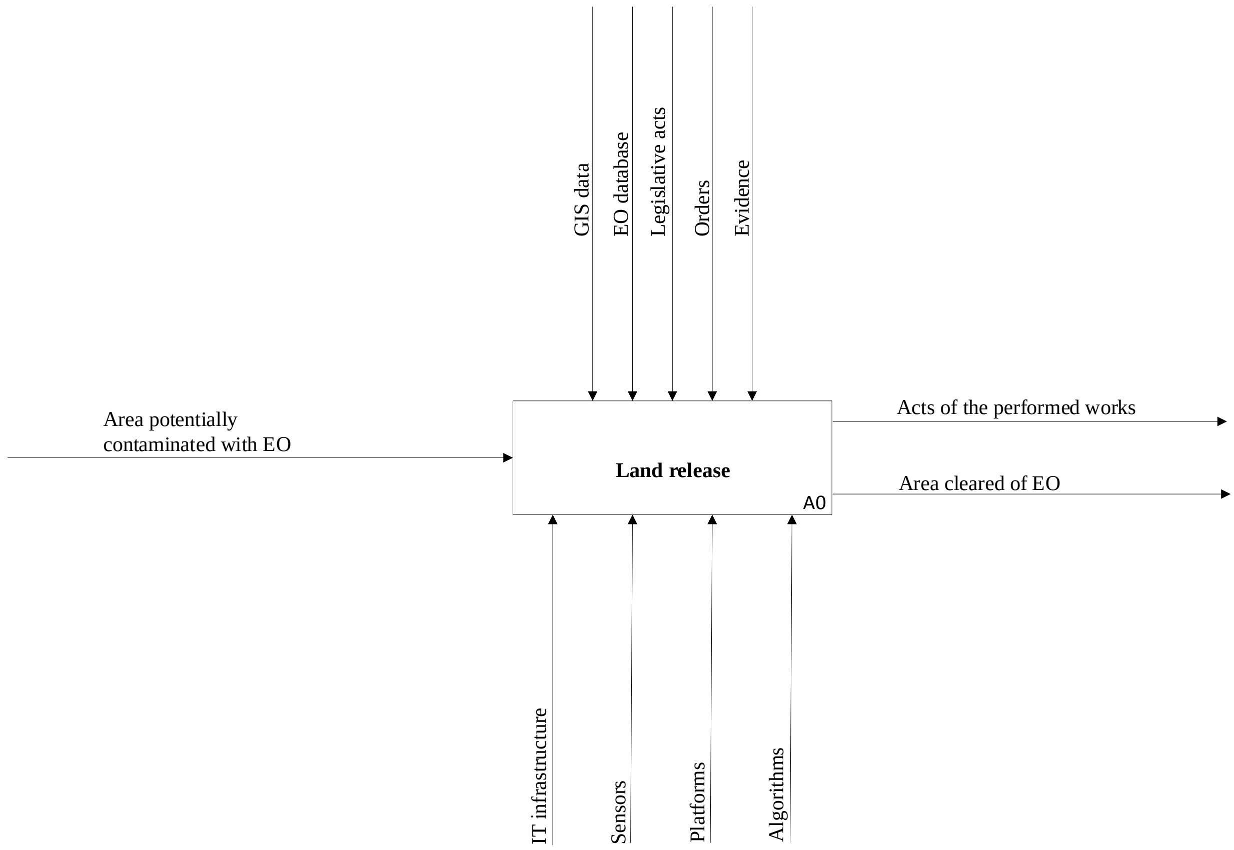

Fig. 5. Context diagram A0

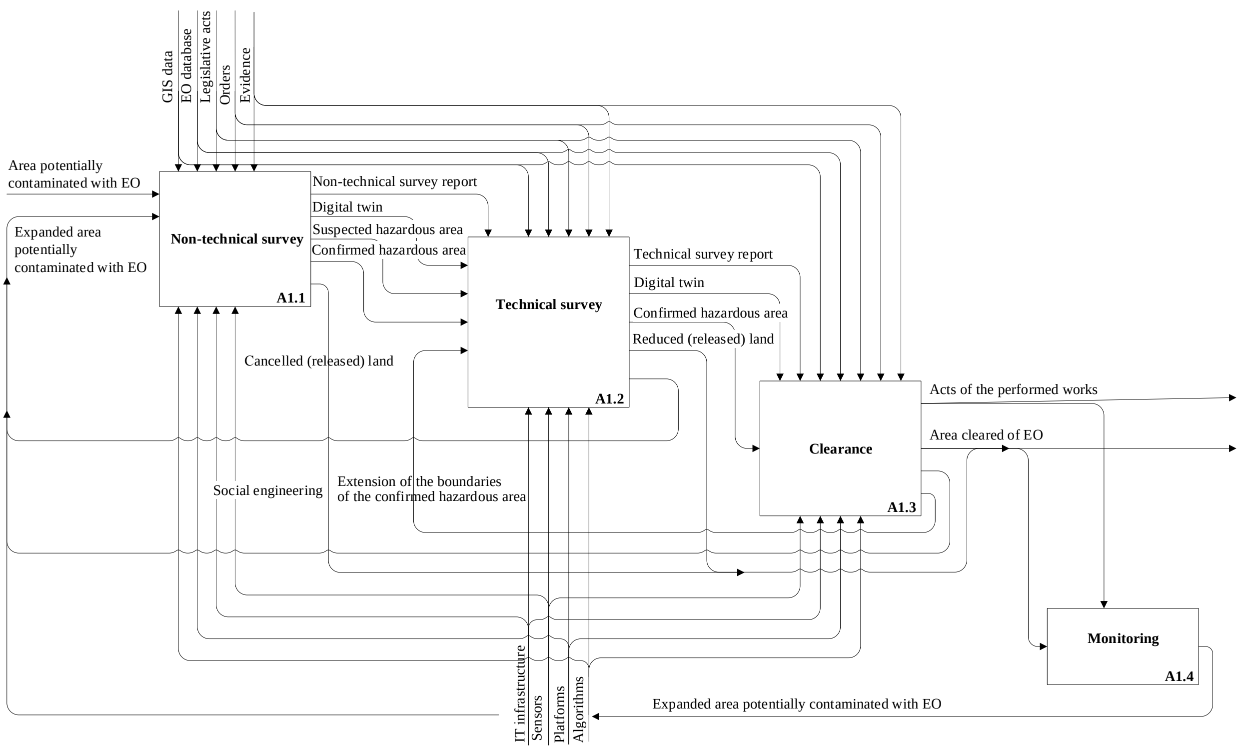

Fig. 6. Context diagram A1

The purpose of a Non-technical survey (NTS) is to collect and analyse data about the presence, type, distribution, and surrounding environment of EO contamination, without the use of technical interventions, in order to better define where EO contamination is present and where it is not, and to support land release prioritization and decision-making processes through the provision of evidence. The main results of NTS are:

- Non-technical survey report based on the results of the NTS and proposals for land release operations;

- Digital twin – a model of the survey site in 3D format with data on the classification of the territory according to the status of hazard, establishment, and marking of the boundary of the hazardous area;

- data on the level of hazard:

a) if, during the NTS, no evidence of EO contamination is found in the area, such area (part of the area) is classified as a Celled (released) land;

b) in the presence of only indirect evidence, the area is classified as a Suspected hazardous area;

c) in the event that at least one direct evidence was received, such an area is classified as a Confirmed hazardous area.

The purpose of the Technical (TS) is to collect and analyse data, using appropriate technical interventions, about the presence, type, distribution, and surrounding environment of EO contamination to better define where EO contamination is present and where it is not, and to support land release prioritization and decision-making processes through the provision of evidence. TS results are:

- Technical survey report, which includes:

a) establishment of the border for further cleaning (demining);

b) confirmation (clarification) of the classification of the area according to the status of the hazard;

c) confirmation of evidence regarding EO contamination, determination of further cleaning (demining), necessary forces and means, as well as material and technical resources;

- Digital twin, which is a supplement to the model of the survey site in 3D format regarding the classification of the area according to the status of the hazard and the marking of the border of the d hazardous area, as well as the plotting of coordinates and the probable type of EO.

Based on the results of the TS, a decision can be made to determine:

a) Confirmed hazardous area that requires cleaning (demining);

b) Reduced (released) land if the area previously classified according to the status of hazard does not contain EO and can be released without cleaning (demining);

c) Expanded area potentially contaminated with EO in the case of an increase in the limit of the dangerous area based on the discovery of new direct evidence of EO contamination, which requires the NTS and TS procedure to be repeated.

The purpose of the Clearance (demining) procedure is to search for and identify munitions using technical means, remove the detected ammunition, and create conditions for the safe use of the cleared (demined) area by the beneficiaries. This procedure includes: the search and detection of EO, their extraction, transportation, and disposal (destruction) in designated places (or, if necessary, at the place of detection), quality control of work on cleaning (demining) territories from EO and transfer to the beneficiary of the Territory cleared of EO.

The result of performing works according to the clearance (demining) procedure is the Area cleared of EO, which is confirmed by Acts of the performed works.

In the case of the discovery of new artefacts at the demining stage or the appearance of other reasons that do not allow performing cleaning work in a safe manner, the area is classified as an extension of the boundaries of the confirmed hazardous area or an Expanded area potentially contaminated with EO and is returned to the appropriate stage (NTS and TS)

Upon completion of demining (cleaning) of the areas, all areas that have undergone the Non-technical survey report, Technical survey report, and Clearance (demining) procedures are subject to constant monitoring for the presence of EO omissions and deviations of the quality of the work performed from technical requirements.

6. Case-study. The project IDEM

The methodological principles, models, and structures of RBS, which are described in Sections 2-4, are the development of solutions proposed during the preparation and ongoing implementation of the scientific project “Methods and means of explosive objects detection using multifunctional intelligent UAV systems” (IDEM, No. 0123U101992) by order of the Ministry of Education and Science in 2023-2024.

The aim of the project is to increase the productivity and reliability of the detection and identification of EO by developing and implementing a software and hardware platform for EO detection using unmanned intelligent systems (UIS), as well as means of supporting decision-making regarding the planning and management of the use of a multifunctional fleet (MFF) of UAVs.

The main tasks of this project are:

1) analysis of the experience of using and perfection of the existing methods, software, technical and operational means of EO detection using artificial intelligence systems (AISs) and options to use the MFF

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

of UAVs for the detection and disposal of EO;

2) formalization of the initial data for training the AIS models for EO identification by systematizing them, determining features for further identification, and developing methods and means of artificial intelligence for EO identification;

3) development of a multi-level distributed software-hardware platform architecture based on some information and measurement tools, tools for flying edge computing, and a private secure cloud system;

4) development and profiling of AIS quality models for the MFF of UAVs, methods, algorithms, and software tools for evaluating and visualizing compliance of AISs with requirements for trustworthiness, resiliency, reliability, safety, etc., and adjusting design decisions based on the evaluation results;

5) development of methods, algorithms and software tools for planning the composition of the MFFs of UAVs and the sequence of their use for EO detection in view of various options and conditions of utilizing these fleets as well as tactical and technical characteristics of UAVs;

6) development of a layout of UIS software and hardware for the tasks to detect and identify EO.

These tasks and expected results significantly correspond to the ideas of this study and are the basis for their further implementation. Separate software and hardware solutions developed in works [34-37] and related to reliability models and algorithms for substantiating the composition of the MFF of UAVs, algorithms for covering the monitoring space (EO detection), the use of flying edge sensors and networks, and so on, confirm the feasibility and effectiveness of the formulated concepts and structures.

7. Discussion

While the use of UAVs, robots, and animals for demining purposes holds great potential, there are several challenges that need to be addressed.

Here are some of the key challenges associated with using UAVs and robots for demining.

1) As operations often occur in challenging and unpredictable environments such as rough terrains, dense vegetation, and contaminated areas, UAVs and robots need to be capable of navigating and operating effectively in these complex and varied conditions without getting stuck or damaged.

2) UAVs and robots rely on sensors to detect and identify explosive devices. However, current sensor technologies may have limitations in terms of detection range, accuracy, and the ability to discriminate between different types of mines and non-explosive objects.

3) The wide variety of mine types, including different sizes, shapes, and activation mechanisms, requires UAVs and robots to be versatile and adaptable.

4) To use UAVs and robots in harsh conditions for a long time, they need to be robust and reliable, with the ability to withstand impacts, vibrations, extreme temperatures, and exposure to hazardous materials.

5) The use of UAVs and robots in demining must prioritize the protection of human life and adhere to humanitarian principles.

6) The research and development of sophisticated fleets of UAVs and robotic systems, as well as the associated training, maintenance, and logistical requirements, can present financial challenges for demining organizations, particularly in resource-constrained regions.

7) Establishing clear guidelines and protocols for the use of demining UAVs and robots is essential to ensure their proper and responsible deployment in terms of international conventions and national laws.

8) It is essential to ensure the necessary level of dependability (reliability, maintainability, safety, cybersecurity) and resilience of the UAVs and RBS-D&I as a whole, considering not only component failures but also possible cyber attacks on digital infrastructure in conditions when demining is carried out in an aggressive environment during hostilities.

Now let's consider some of the key challenges associated with using animals for demining.

1) Training animals for demining tasks is a specialized and time-consuming process requiring skilled trainers and handlers who understand both animal behavior and the intricacies of demining.

2) Animals used for demining may have limitations in terms of the types of explosives they can detect, making them less versatile in certain demining scenarios.

3) While animals can be trained to detect explosives, there is always a risk that animals may trigger an explosive device if not properly trained, or they may encounter hidden hazards during the search process.

4) Animals have physical limitations in terms of speed, endurance, and ability to cover large areas efficiently. They may require rest and breaks during demining operations, which can impact the overall productivity and duration of clearance efforts.

5) It is essential to ensure animals' well-being and minimize any potential harm or stress they may experience during the demining process.

6) Maintaining and caring for animals involved in demining operations requires resources, including veterinary care, food, shelter, and transportation. The logistics involved in deploying and supporting animals in different demining areas can be complex and costly.

7) It is important to consider the possibility of placing sensors and micro video cameras on animals (taking into account safety-related and humanitarian constraints) that could interact with UAVs and ground

robots via the instructor or directly with the digital infrastructure as a whole.

While these challenges exist, ongoing advancements in robotics/sensor technologies and animal training techniques, coupled with collaborative efforts among researchers, demining organizations, and humanitarian agencies, hold promise for overcoming these obstacles and improving the effectiveness and safety of demining operations.

Conclusions

In this article, the elements of the methodology of building and using robotic-biological systems for demining tasks were suggested. The main contribution is the following:

- first, the definition of the RBD-D&I conceptual model as a complex coordinated system of interacting robotic (flying and ground), biological (animals controlled by instructors), and informational subsystems that form the digital infrastructure of the entire system;

- second, the development of structural, automatic, and hierarchical models for EO detection supplemented with a model of the operational cycle of preparation and execution of demining tasks using RBS-D&I.

The proposed concept and RBS-D&I solutions can provide high-performance and guaranteed EO detection in designated areas by the implementation of an intelligent platform and tools for planning the use of MFFs of UAVs and other RBS-D&I subsystems.

Taking into account the large areas contaminated by EO and their further growth, the presented results meet the needs of Ukraine and the world, as they will allow to increase the safety of demining and the quality of D&I due to a multi-level distributed architecture using edge computing.

Future research directions can be related to:

- detailing of RBS-D&I digital infrastructure according to improving the role of the robotic subsystems and their interaction with biological subsystems;
- investigating RBS-D&I dependability and resilience considering component reliability and the influence of environment;
- development of EO detection and identification methods based on the hierarchical model.

Acknowledgements. This article was prepared with the support of the project “Methods and means of explosive objects detection using multifunctional intelligent UAV systems” which is financed by the Ministry of Education and Science of Ukraine, No. 0123U101992. The authors of the article express their gratitude to colleagues from the Department of Computer Systems, Networks and Cyber Security of the National Aerospace University “Kharkiv Aviation Institute”, as well as to the participants of the scientific and technical seminar “Critical Computer Technologies and Systems” for participating in the discussion of task statements and research results. Special thanks to the representatives of the Interdepartmental Research Center on Problems of Combating Organized Crime at the National Security and Defense Council of Ukraine for their cooperation in the preparation of proposals for the creation and future use of RBS-D&I.

Contributions of authors: conceptualization, methodology – **Gennadiy Fedorenko**, **Herman Fesenko**, **Vyacheslav Kharchenko**; formulation of tasks, analysis – **Ihor Kliushnikov**, **Ihor Tolkunov**; development of models – **Gennadiy Fedorenko**, **Herman Fesenko**, **Vyacheslav Kharchenko**; verification – **Ihor Tolkunov**, **Ihor Kliushnikov**; analysis of results, visualization – **Gennadiy Fedorenko**, **Ihor Kliushnikov**; writing – all authors; original draft preparation – **Herman Fesenko**, **Ihor Kliushnikov**, review and editing – **Vyacheslav Kharchenko**.

All the authors have read and agreed to the published version of the manuscript.

References

1. *The UNMAS Annual Report 2022*. Available at: https://www.unmas.org/sites/default/files/unmas_ar_2022.pdf (accessed 08.02.2023).

2. *Landmine Monitor 2022*. Available at: http://www.the-monitor.org/en-gb/reports/2022/ landmine-monitor-2022.aspx (accessed 08.02.2023).

3. Fedorenko, G., Fesenko, H. & Kharchenko, V. Analysis of methods and development of the concept of guaranteed detection and recognition of explosive objects. *Innovative Technologies and Scientific Solutions for Industries*, 2022, vol. 4, iss. 22, pp. 20–31. DOI:10.30837/itssi.2022.22.020.

4. Bajić, M., Jr. & Potočnik, B. UAV Thermal Imaging for Unexploded Ordnance Detection by Using Deep Learning. *Remote Sensing*, 2023, vol. 15, article id: 967. DOI: 10.3390/rs15040967.

5. Petrişor, S.M., Simion, M., Bârsan, G. & Hancu, O. Humanitarian Demining Serial-Tracked Robot: Design and Dynamic Modeling. *Machines*, 2023, vol. 11, article no. 548. DOI: 10.3390/machines11050548.

6. Fang, W. Design of Obstacle Avoidance Control System for Mobile Robot Based on Vision. *Lecture Notes on Data Engineering and Communications Technologies*, 2022, vol. 125, pp. 1005–1011. DOI: 10.1007/978-3-030-97874-7_146.

7. *Unmanned underwater vehicles are being developed in Ukraine*. Available at: https://mil.in.ua/en/news/unmanned-underwater-vehicles-are-being-developed-in-ukraine/ (accessed 08.02.2023).

8. Schoon, A., Heiman, M., Bach, H., Berntsen, T. G. & Fast, C. D. Validation of technical survey dogs in Cambodian mine fields. *Applied Animal Behaviour*

Science, 2022, vol. 251, article no. 105638. DOI: 10.1016/j.applanim.2022.105638.

9. Jones, B. M. Applied behavior analysis is ideal for the development of a land mine detection technology using animals. *The Behavior Analyst*, 2017, vol. 34, iss. 1, pp. 55–73. DOI: 10.1007/BF03392235.

10. Edwards, T. L., Cox, C., Weetjens, B., Tewelde, T. & Poling, A. Giant African pouched rats (Cricetomys gambianus) that work on tilled soil accurately detect land mines. *Journal of Applied Behavior Analysis*, 2015, vol. 48, iss. 3, pp. 696–700. DOI:10.1002/jaba.214.

11. *IMAS 05.10: 2019 Information management for mine action*. Available at: https://www.mineactionstandards.org/standards/05-10/ (accessed 08.02.2023).

12. *IMAS 07.10: 2018 Guidelines and requirements for the management of land release and residual contamination operations.* Available at: https://www.mineactionstandards.org/standards/07-10/ (accessed 08.02.2023).

13. *IMAS 08.10: 2019 Non-technical survey.* Available at: https://www.mineactionstandards.org/standards/08-10/ (accessed 08.02.2023).

14. *IMAS 08.20: 2019 Technical survey.* Available at: https://www.mineactionstandards.org/standards/08-20/ (accessed 08.02.2023).

15. *IMAS 09.10: 2020 Clearance requirements.* Available at: https://www.mineactionstandards.org/standards/09-10/ (accessed 08.02.2023).

16. *IMAS 09.30: 2022 Explosive ordnance disposal.* Available at: https://www.mineaction-standards.org/standards/09-30/ (accessed 08.02.2023).

17. *IMAS 09.40: 2020 Animal Detection Systems - Principles, Requirements and Guidelines.* Available at: https://www.mineactionstandards.org/standards/09-40/ (accessed 08.02.2023).

18. *IMAS 09.41: 2020 Operational procedures for Animal Detection Systems.* Available at: https://www.mineactionstandards.org/standards/09-41/ (accessed 08.02.2023).

19. *A Study of Mechanical Application in Demining.* Available at: https://www.gichd.org/fileadmin/GICHD-resources/recdocuments/Mechanical_study_complete.pdf (accessed 08.02.2023).

20. *The MW370 is a powerful mine and route clearance platform used for the effective clearance of landmines across large areas.* Available at: https://www.pearson-eng.com/product/mw370/ (accessed 08.02.2023).

21. Van Verre, W., Podd, F. J., Daniels, D. J. & Peyton, A. J. A Review of Passive and Active Ultra-Wideband Baluns for Use in Ground Penetrating Radar. *Remote Sensing*, 2021, vol. 13, iss. 10. DOI: 10.3390/rs13101899.

22. Bouchette, G., Gagnon, S., Church, P., Luu, T. & McFee, J. Electrical impedance tomography for underwater detection of buried mines. *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIII*, 2008, vol. 6953, article id. 69530O. DOI: 10.1117/12.775546.

23. Song, X., Liu, T., Xiang, D. & Su, Y. GPR Antipersonnel Mine Detection Based on Tensor Robust Principal Analysis. *Remote Sensing*, 2019, vol. 11, iss. 8. DOI: 10.3390/rs11080984.

24. *Schweitzer, K. M., Davis, B. M., Pettijohn, B. A., Clark, R. D., Davison, A. D. & Staszewski, J. J. Optimization of Army- Navy/Portable Special Search (AN/PSS)-14 Operator Training. ARL-TR-3970.* Available at: https://apps.dtic.mil/sti/pdfs/ADA457012.pdf (accessed 08.02.2023).

25. Johnson, J. T., Kim, H., Wiggins, D. R. & Cheon, Y. Microwave radiometry for humanitarian demining: experimental results. *Detection and Remediation Technologies for Mines and Minelike Targets VII*, 2002, vol. 4742, pp. 303–313. DOI: 10.1117/12.479101.

26. Shemer, B., Palevsky, N., Yagur-Kroll, S. & Belkin, S. Genetically engineered microorganisms for the detection of explosives residues. *Frontiers in Microbiology*, 2015, vol. 6. DOI: 10.3389/fmicb.2015.01175.

27. *U.S. Navy Demos MCM Equipment Prototype On MQ-8C.* Available at: https://www.navalnews.com/naval-news/2022/07/u-s-navy-demos-mcm-equipment-prototype-on-mq-8c (accessed 08.02.2023).

28. Otagaki, Y., Barras, J. & Kosmas, P. Improving Detection of a Portable NQR System for Humanitarian Demining Using Machine Learning. *IEEE Transactions on Geoscience and Remote Sensing*, 2022, vol. 60, pp. 1–11. DOI: 10.1109/TGRS.2021.3101226.

29. Dorn, A. W. Eliminating Hidden Killers: How Can Technology Help Humanitarian Demining? *Stability*, 2019, vol. 8, iss. 1, pp. 1–17. DOI: 10.5334/sta.743.

30. *Field trials of the smart system and technical survey dogs in Cambodia: Final report 2021.* Available at: https://www.gichd.org/fileadmin/GICHD-resources/recdocuments/SMART_Cambodia_v13__1__01.pdf (accessed 08.02.2023).

31. *Efficiency and Effectiveness Study using MDR capability.* Available at: https://apopo.org/who-we-are/publications/2016/efficiency-and-effectiveness-study-using-mdr-capability/?v=3943d8795e03 (accessed 08.02.2023).

32. *Mine detection dog programs.* Available at: https://www.marshall-legacy.org/mine-detection-dog-programs (accessed 08.02.2023).

33. *Explosive Ordnance Guide for Ukraine – Second Edition.* Available at: https://www.gichd.org/publications-resources/publica-tions/explosive-ordnance-guide-for-ukraine-second-edition/ (accessed 08.02.2023).

34. Fesenko, H., Illiashenko, O., Kharchenko, V., Kliushnikov, I., Morozova, O., Sachenko, A. & Skorobohatko, S. Flying Sensor and Edge Network-Based Advanced Air Mobility Systems: Reliability Analysis and Applications for Urban Monitoring. *Drones*, 2023, vol. 7, article no. 409. DOI: 10.3390/drones7070409.

35. Kharchenko, V., Fesenko, H. & Illiashenko, O. Basic model of non-functional characteristics for assessment of artificial intelligence quality. *Radioelectronic and Computer Systems*, 2022, no. 2, pp. 131–144. DOI: 10.32620/reks.2022.2.11.

36. Moskalenko, V. & Moskalenko, A. Neural network based image classifier resilient to destructive perturbation influences - Architecture and training method. *Radioelectronic and Computer Systems*, 2022, no. 3, pp. 95–109. DOI: 10.32620/reks.2022.3.07.

37. Moskalenko, V., Kharchenko, V., Moskalenko, A. & Kuzikov, B. Resilience and Resilient Systems of Artificial Intelligence: Taxonomy, Models and Methods. *Algorithms*, 2023, vol. 16, article no. 165. DOI: 10.3390/a16030165.

Received 17.03.2022, Accepted 20.05.2023

РОБОТОБІОЛОГІЧНІ СИСТЕМИ ДЛЯ ВИЯВЛЕННЯ ТА ІДЕНТИФІКАЦІЯ ВИБУХОНЕБЕЗПЕЧНИХ ПРЕДМЕТІВ: КОНЦЕПЦІЯ, ЗАГАЛЬНА СТРУКТУРА ТА МОДЕЛІ

Геннадій Федоренко, Герман Фесенко, Вячеслав Харченко, Ігор Клюшніков, Ігор Толкунов

Предметом дослідження є системи виявлення та ідентифікації (ВІ) вибухонебезпечних предметів (ВНП). **Метою** дослідження є розробка концепції, загальної структури та моделей роботобіологічної системи для ВІ ВНП (РБС-ВІ). **Завдання**: 1) класифікувати мобільні системи для ВІ ВНП та запропонувати концепцію РБС-ВІ; 2) розробити загальну структуру РБС-ВІ, що складається з робототехнічної (літаючої та наземної) та біологічної підсистем; 3) розробити моделі РБС-ВІ, включаючи автоматні, ієрархічні та операційні; 4) описати завдання та заплановані результати наукового проекту, пов'язаного зі статтею; 5) обговорити результати дослідження. Були отримані наступні **результати**. 1) Загальна структура РБС-ВІ. Структура складається з наступних рівнів: центри управління та обробки (мобільний наземний центр управління та обробки (МНЦУО) та віртуальний центр управління та обробки); сили виявлення та ідентифікації (флот безпілотних літальних апаратів (ФБПЛА), біологічна інформаційна підсистема виявлення (БІПС), роботизована інформаційна підсистема виявлення (РІПС)); завади; натуральний покрив і підстилка; цільові об'єкти (усі боєприпаси, що містять вибухові речовини, матеріали ядерного поділу або термоядерного синтезу, а також біологічні та хімічні агенти). 2) Концепція РБС-ВІ. Концепція базується на описі, аналізі, розробленні та експлуатації РБС-ВІ як інтегрованої комплексної кіберфізичної та кібербіологічної системи, що працює в мінливих фізичних та інформаційних середовищах. 3) Модель автоматів РБС-ВІ. Модель описує роботу РБС-ВІ у двох режимах. У режимі 1 ФБПЛА та БІПС працюють окремо та взаємодіють лише через МНЦУО. У режимі 2, в залежності від специфіки виконуваних завдань, ФБПЛА та БІПС можуть безпосередньо взаємодіяти між собою або через МНЦУО. 4) Ієрархічна модель. Модель має два набори вершин: виявлення ВНП та платформи, оснащені необхідними датчиками. 5) Модель операційного циклу. Модель описує операції із розблокування земель за допомогою методології функціонального моделювання та графічного опису процесів IDEF0. **Висновки**. Запропонована концепція та рішення РБС-ВІ можуть забезпечити високоефективне та гарантоване виявлення ВНП у визначених зонах шляхом впровадження інтелектуальної платформи та інструментів для планування використання багатофункційних флотів БПЛА та інших підсистем РБС-ВІ.

Ключові слова: роботобіологічна система; виявлення та ідентифікація; вибухонебезпечні предмети; технічне обстеження; нетехнічне обстеження; очищення; розмінування; небезпечна зона.

Федоренко Геннадій Леонідович – канд. техн. наук, докторант каф. комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Фесенко Герман Вікторович – д-р техн. наук, проф., проф. каф. комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Харченко Вячеслав Сергійович – д-р техн. наук, проф., зав. каф. комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Клюшніков Ігор Миколайович – канд. техн. наук, с.н.с., доц. каф. комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Толкунов Ігор Олександрович – канд. техн. наук, доц., доц. каф. піротехнічної та спеціальної підготовки, Національний університет цивільного захисту України, Харків, Україна.

Gennadiy Fedorenko – PhD, Doctoral candidate of Computer Systems, Networks and Cybersecurity Department of National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail:g.fedorenko@csn.khai.edu; ORCID: 0000-0003-0162-7422.

Herman Fesenko – Doctor of Technical Science, Associate Professor, Associate Professor at the Department of Computer Systems, Networks and Cybersecurity, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: h.fesenko@csn.khai.edu, ORCID: 0000-0002-4084-2101, Scopus Author ID: 57190123735.

Vyacheslav Kharchenko – Doctor of Technical Science, Professor, Head of the Department of Computer Systems, Networks and Cybersecurity, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: v.kharchenko@csn.khai.edu, ORCID: 0000-0001-5352-077X, Scopus Author ID: 22034616000.

Ihor Kliushnikov – PhD, Senior Researcher, Associate Professor at the Department of Computer Systems, Networks and Cybersecurity, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: i.kliushnikov@csn.khai.edu, ORCID: 0000-0001-9419-7825, Scopus Author ID: 57218092653.

Ihor Tolkunov – PhD, Associate Professor, Associate Professor at the Department of Pyrotechnics and Special Training, National University of Civil Defence of Ukraine, Kharkiv, Ukraine,
e-mail: tolkunov_ia@ukr.net, ORCID: 0000-0001-5129-3120, Scopus Author ID: 57190441930.