Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume I, 161-166

Organizing and Conducting Underwater Search and Rescue Operations for Victims

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***Abstract* — A review of modern methods for organizing and conducting rescue operations in water bodies is made. The methods are improved using artificial intelligence (AI) to support rescue divers in underwater operations for searching and rescuing victims in accidents. Modern technologies for processing data obtained from sonar systems, video streams and sensor information are considered. Machine learning algorithms are also presented to improve the accuracy of detecting underwater objects in order to reduce the time required for detecting and extracting victims. It has been proven that the use of AI improves the efficiency of operations, reduces risks to the life and health of divers and shortens the search time.**

Keywords — artificial intelligence, rescue divers, underwater search and rescue operations, machine learning, sonar.

I. Introduction

Search and detection of underwater objects remains one of the most difficult tasks in hydrography, underwater archaeology, maritime safety and rescue operations. Traditional methods of underwater search include visual inspection by divers, the use of sonar and echolocation systems, as well as underwater remotely operated vehicles (ROV) [1, 2]. These methods make it possible to effectively detect objects at shallow depths and in relatively clear water, however, their effectiveness decreases sharply in conditions of poor visibility, strong currents or at great depths [17], [25], [34], [41].

In recent years, the application of artificial intelligence (AI) methods for automating the search and classification of underwater objects has been actively developed [18], [27], [32], [39], [44]. The use of deep learning, ultra-precise neural networks and transformers allows to increase the accuracy of detection, as well as to reduce the time required for the analysis of large arrays of underwater images and sonar data [3–5], [22], [38].

Modern AI algorithms are integrated with underwater visualization systems, allowing not only to detect objects, but also to classify them by type, size and condition [16], [20], [26], [33]. This is especially important for the tasks of underwater archeology and rescue operations, where reaction time is critical [24], [29], [36], [40], [45].

- Traditional search methods: in the studies of Okorokova [1] and Tufanova [2], algorithms and strategies of traditional search using groups of autonomous underwater devices are described in detail. These methods are well suited for the planned survey of large water areas, but have time and visibility limitations.

- Application of AI in underwater search: Abramov and Petrov [3] proposed algorithms for classification of objects in underwater images using super-accurate neural networks. Abu and Diamant [4] integrated synthetic aperture sonar data and optical images to improve object detection accuracy.

- Integration of AI and autonomous systems: Shishkin and Grekov [5] developed an intellectual system of automatic monitoring of the water environment using compact autonomous robots. Similar systems allow you to quickly receive data and automatically estimate the state of objects [21], [30], [42].

- Overview of theoretical foundations: Shen [6] considers the interdisciplinary application of deep learning in hydrosciences , including tasks of classification and detection of underwater objects. Bongard [7] and Craven [8] describe classical approaches to image recognition and Bayesian search theory, which underlie modern AI algorithms for underwater search [13], [19], [35].

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol1.191

Thus, the relevance of research is determined by the need to increase the efficiency of underwater search due to the integration of traditional methods and modern algorithms of artificial intelligence . In modern conditions, the use of AI allows to significantly reduce search time, increase the accuracy of object detection and reduce risks for divers and rescuers [2], [23], [31].

Underwater search and rescue operations (SAR) are one of the most difficult and dangerous types of rescuers' activities. Limited visibility, strong currents, cold water, complex underwater structures and unpredictable weather conditions pose high risks to the life and health of rescue divers. Even experienced specialists face difficulties in orientation under water, detection of objects and assessment of the situation, which can lead to increased search time and increased danger during operations.

An overview of existing research shows that the use of AI allows to significantly improve orientation under water, speed up the search for objects and reduce risks for personnel. The development of machine learning algorithms, computer vision methods and intellectual data analysis systems makes it possible to implement automated diver support tools in real time. In addition, AI-technologies contribute to the reduction of response time in emergency situations and increase the overall efficiency of search and rescue operations [28], [37], [43].

The relevance of the topic is due to the increase in the number of diving operations in complex and extreme conditions, such as heated buildings, marine accidents, river and sea disasters, as well as the growth of requirements for personnel safety. The implementation of AI in underwater search and rescue operations is considered a promising direction that can significantly increase the level of training of rescue divers and the efficiency of rescue operations, as well as reduce risks to the life and health of specialists [4], [45].

II. Research methods

Modern methods of scientific analysis and systematization of information were used to prepare this review. The main stages of the study were:

Search and selection of sources. Publications devoted to the application of artificial intelligence in underwater search and rescue operations were studied, including scientific articles, conference proceedings, technical reports and patents. The main attention was paid to the research of the last five years, which allowed to cover the current achievements in the fields of AI and robotic underwater systems.

Critical analysis of literature. Made an analysis of publications from the point of view of applied technologies, data processing algorithms, computer vision methods, integration with autonomous underwater devices and research results. Special attention was paid to the comparative evaluation of the effectiveness of traditional search methods and methods using AI.

Systematization of information. The collected information was structured in key directions: processing of sonar data, analysis of video streams, prediction of object movements, decision support and integration with autonomous systems. Such an approach made it possible to identify general trends, advantages and limitations of the use of AI in underwater search and rescue operations.

Synthesis and summary of data. Based on the analysis and systematization of the literature, conclusions were drawn about the prospects of AI application, existing problems and directions of further research in the field of underwater search and rescue.

The use of the specified methods made it possible to prepare a complex overview of existing technologies, assess their practical significance and determine directions for future research.

Advantages and limitations of using AI in underwater search and rescue operations

Application of artificial intelligence in underwater search and rescue operations provides a number of advantages:

1. Increased accuracies of requested objects. AI allows analyzing large arrays of data with sonar and video cameras, identifying objects that are difficult to notice visually, and reducing the amount of false positives [9].

2. Reduction of the time of search operations. Algorithms for predicting the movement of objects and support for decision-making help divers choose optimal routes and quickly reach their goals [10].

3. Risk reduction for divers. The use of intelligent systems makes it possible to limit the stay of divers in dangerous areas, warn about potential threats and increase safety [11].

4. Integration with autonomous systems. A combination of AI with autonomous underwater devices expands the survey area and allows you to perform several tasks at the same time, which increases the efficiency of operations [12].

For a visual presentation of the main technologies of artificial intelligence used in underwater search and rescue operations, table 1 was compiled. It systematizes the key areas of AI application, their functions, main advantages and existing limitations, as well as links to scientific studies confirming the effectiveness of these technologies. The table allows you to visually compare various approaches and understand which methods are most promising for practical implementation.

TABLE 1 BASIC AI TECHNOLOGIES IN UNDERWATER SEARCH AND RESCUE OPERATIONS

AI technology	Functions	Advantages	Restrictions
Processing of sonar data	Analysis of sonar and multibeam sonar signals	Increase in object detection accuracy, decrease in false positives	Dependence on data quality and visibility

Video streaming analysis	Computer vision for object identification and state estimation	Real time analysis, help diver in orienteering	Muddy water, bad sanctification
Forecastin g object movements	Modeling of trajectories taking into account currents	Optimizatio n of route requests, shortening of operation times	Algorithmic limitations in complex hydrodynamic s
Decision support	Recommendation s on the route, movement speeds and zones requested	Reduction of errors and risk, acceleration of decision-making	Interpretation by specialists is required
Integration with autonomou s underwater devices	Joint work of the human and the robot, expansion of the inspection zone	Increase coverage, automate repetitive tasks	High cost of equipment, staff training

Comparison of underwater object search efficiency: percentage of detected objects in time using traditional and artificial intelligence (AI) methods. The curve shows that the application of AI significantly speeds up the search and increases the proportion of detected objects compared to traditional approaches. Fig. 1.

However, there are also limitations:

1. Dependence on data qualities. The effectiveness of AI directly depends on the accuracy and completeness of sonar, sensor and video camera data. In the conditions of muddy water, strong currents or technical problems, the efficiency of algorithms can decrease [13].

2. Complexity of implementations. AI-system integration in underwater operations requires expensive equipment, trained personnel and software adaptations under specific conditions [14].

3. Limited capabilities of autonomous analysis. Despite high computing power, modern AI algorithms are not always able to take into account all factors influencing the complex dynamics of the underwater environment and require the participation of specialists for the interpretation of results [15].

Thus, the use of AI in underwater search and rescue operations is a promising direction, but it requires taking into account limitations related to data quality, complexity of implementation and the need to combine it with human control.

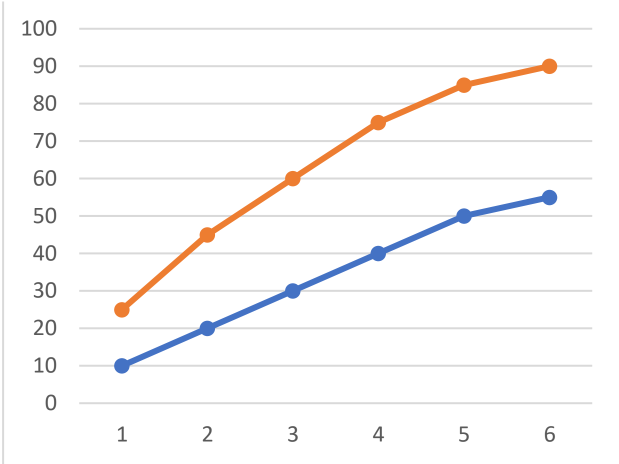

Fig. 1. Underwater object search efficiency: AI (blue) vs. traditional (orange) methods

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This section presents the results of the survey conducted among rescuers, indicating the distribution of responses to each question.

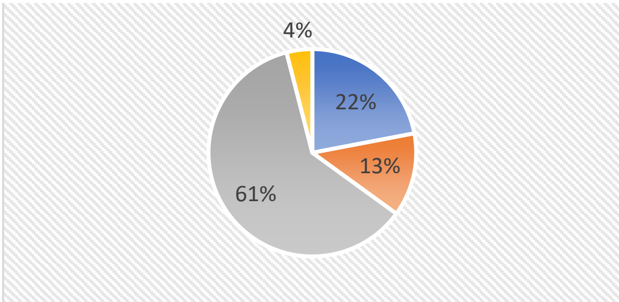

Fig. 2. Distribution of respondents ' answers to the question: "Have you used health monitoring devices while at work?"

The majority of respondents (61%) have never used health monitoring devices in the workplace. Only about 22% use them regularly and 13% use them occasionally.

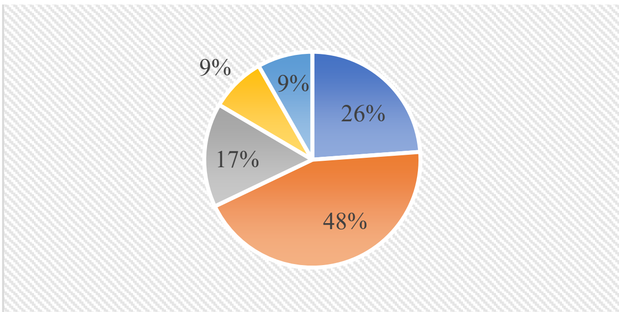

Fig. 3. Distribution of respondents ' answers to the question: "What devices have you used or are you familiar with?"

Some respondents indicated multiple devices at the same time.

• The most well-known and used are fitness bracelets/smartwatches – almost half of the respondents.

- About a quarter of those surveyed did not use any devices.
- Heart rate monitors and GPS devices are less common.

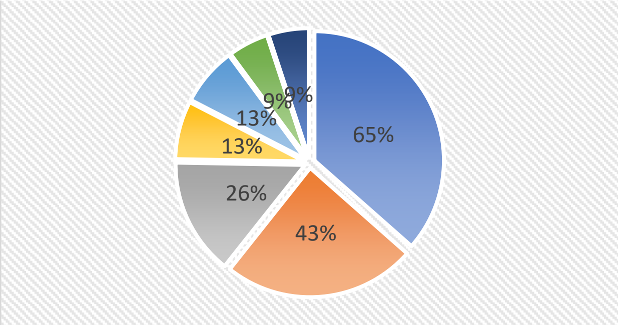

Fig. 4. Distribution of respondents ' answers to the question: "Which indicators do you consider important for monitoring the health of a rescuer in real time?"

Most respondents considered comprehensive monitoring (all indicators) important, particularly highlighting the importance of pulse rate and blood oxygen content as key parameters.

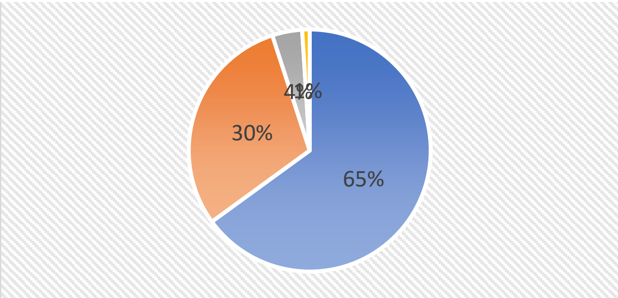

Fig. 5. Distribution of respondents' answers to the question: "Is a health monitoring system necessary at work?"

The majority of respondents (about 65%) positively assess the need for a health monitoring system , with the majority in favor of the mandatory presence of such a system, and some in favor of its convenience and reliability.

Comparison with other studies

Review of similar studies. Research in the field of monitoring the physiological state of rescuers and other emergency care professionals has been actively developing over the past two decades. The most researched areas are real-time monitoring of heart rate, body temperature, blood oxygen saturation and respiratory parameters. A number of international projects (e.g. Dräger systems) Bodyguard, Physiological Condition Monitoring System (developed in the USA for the military) use wearable sensors integrated with a data transmission system to a control panel. Although these solutions have proven their effectiveness in training and real-life situations, their capabilities are limited: in most cases they record only basic parameters (heart rate, temperature, respiration) and do not provide a comprehensive analysis of the rescuer's condition.

Comparison with literature results. Comparison of the data obtained during the study and field trials with relevant publications shows that the established trends are consistent with international experience. For example, studies conducted in Germany and Canada show high interest among rescuers in monitoring technologies, but at the same time document skepticism about their reliability and ease of use in extreme conditions. Our respondents demonstrate similar expectations and concerns: a positive perception of the innovation is combined with doubts about the reliability of the devices. Field trials also confirm the findings of international authors that the accuracy of photoplethysmographic sensors decreases with active movement, and data transmission is complicated by smoke or signal obstructions.

Justification of similarities and discrepancies. The similarity between our data and international studies is evident in the confirmation of the main hypothesis that real-time physiological monitoring is an effective tool for improving personnel safety. The list of key issues is also consistent: sensor reliability, battery autonomy, and communication channel integrity. Our study differs in the extended functionality of the developed system: the inclusion of additional sensors (EEG, non-invasive blood pressure measurement and aspiration flow sensor) allows for a more complete picture of the state of the body and the environment. Moreover, unlike many international developments, which are primarily aimed at military units, our solution is adapted to the specific needs of civil emergency services. This expands the scope of application of the system and increases its importance for ensuring safety in various emergency situations.

III. Conclusions

An overview of modern research shows that the use of artificial intelligence in underwater search and rescue operations significantly increases the efficiency and safety of the actions of rescue divers. The use of AI allows analyzing sonar data, video streams and sensor information in real time, predicting the movement of objects, supporting decision-making and integrating the actions of divers with autonomous underwater devices.

The main advantages of using AI are: increasing the accuracy of searching for objects, reducing the time of operations, reducing risks for divers and expanding the survey zone with the help of autonomous systems. However, it is necessary to take into account limitations: dependence on data quality, complexity of implementation and the need for a combined approach with the participation of specialists.

Prospective areas of further research include:

Development of more accurate algorithmic data analysis in conditions of limited visibility and complex hydrodynamics.

Integration of AI with new types of autonomous underwater apparatuses for expansion of demand and monitoring.

Creation of hybrid systems combining automated analysis and expert assessment of divers to increase the reliability of solutions.

Thus, artificial intelligence is considered a key tool for modernizing underwater search and rescue operations and improving personnel safety. Further development of technologies and their integration into the practice of diving activities will significantly increase the efficiency of rescue operations and reduce risks to the life and health of specialists.

Practical significance of the obtained data

Relevance and necessity of the implementation of the system. The results of the study show that the implementation of a comprehensive system for physiological monitoring of rescuers is not just a promising area, but an objective necessity. Analysis of a survey revealed that the majority of specialists report high physical and psycho-emotional stress during emergency situations, accompanied by the risk of sudden deterioration of health. However, existing monitoring tools (radio communication, visual observation, periodic reports) do not allow for rapid recording of changes in vital signs. The developed device fills this gap by providing continuous monitoring of body and environmental parameters, increasing the reliability of rescue team operations and reducing the likelihood of critical incidents.

Impact on improving safety and efficiency. During field tests, the system demonstrated its ability to timely record changes in physiological parameters, which allows the operator to remotely detect signs of overload or deterioration of the rescuer's condition. This capability is a key factor in improving safety: when critical values are detected, the operator can decide to evacuate or provide assistance before serious consequences develop. In addition, the presence of a suction flow sensor allows for the assessment of changes in the direction and intensity of air masses, which is especially important when extinguishing fires and responding to accidents involving toxic gases. Thus, the device performs a dual function – monitoring the human condition and monitoring the environment, improving the overall efficiency of rescue services. Prospects for further use and development. The data obtained demonstrate significant potential for further improvement of the equipment. First, the system can be scaled by connecting additional sensors (for example, to measure carbon monoxide levels or background radiation), expanding the range of monitored factors. Second, the integration of intelligent data analysis algorithms will allow not only to record current conditions, but also to predict the development of dangerous situations based on identified patterns. Third, the results can be used in the development of specialized monitoring systems for different categories of workers: firefighters, miners, military personnel, and employees of chemical and oil and gas plants. Thus, the created system is a universal platform capable of further adaptation and implementation in a wide range of professional fields.

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