

TECHNICAL CHARACTERISTICS, OPERATIONAL CAPABILITIES OF UNDERWATER VEHICLES (ROVS)

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ABSTRACT

Remotely operated vehicles (ROVs) play a key role in civil, industrial, and military maritime operations. This article presents the current technical characteristics and operational capabilities of ROVs, with a clear distinction between ROVs (remotely operated vehicles) and AUVs (autonomous vehicles). It discusses design classes, drive and sensor architecture, modern manipulators, 3D vision systems, and operator interfaces (HMI) with VR/AR elements. The application section indicates scenarios for use in offshore, infrastructure inspections, SAR operations, and military tasks. Directions for development are outlined: automation of operator support functions, use of AI algorithms for data analysis and motion stabilization, and standardization of operator training (including in Poland). Our own research was conducted among practitioners – unmanned aerial vehicle (UAV) operators with experience in carrying out inspection and observation missions. Their opinions were used to assess the validity and potential of integrating ROV systems with UAV platforms in the context of increasing the effectiveness of observation and inspection activities.

Keywords: ROV, remotely operated vehicles, AUV, 3D vision systems, underwater manipulators, HMI operator interface, operator training.

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INTRODUCTION

Unmanned underwater vehicles, referred to as UUVs, are becoming increasingly important in modern maritime operations, both in the civilian and military sectors. Remotely Operated Vehicles (ROVs) play a special role, maintaining a connection with a control unit on the surface via a communication and power cable (umbilical) [1,2]. ROVs are used wherever precise operations are required in difficult and dangerous underwater environments – from scientific research to military operations and commercial infrastructure inspections. Alongside them, there are also autonomous underwater vehicles (AUVs), capable of independently performing programmed tasks without direct operator supervision. AUVs are used, among other things, in reconnaissance, seabed mapping, and the detection of underwater hazards, including mines [1–5]. However, the literature increasingly emphasizes that the line between ROVs and AUVs is gradually blurring due to the automation of selected control functions. These solutions do not mean full autonomy, but are a transitional stage to so-called hybrid platforms, combining the features of both classes. [4–12].

In research and technical practice, it is difficult to clearly assign specific ROV designs to strictly defined categories. As Jakus and Olejnik [3] note, various classification approaches are used – from weight-based and task-based to open classifications based on functionality. In Poland, weight-based classification in accordance with the NO-07-A118:2015 *Unmanned underwater vehicles – classification and technical requirements* standard is still widely used, which divides ROVs into classes: mini, small, medium, and large. This standard defines basic parameters such as weight range, operating depths, and operational safety criteria. However, with rapid technological advances, especially in the field of electronics and automation, the adopted criteria are increasingly proving insufficient to describe modern units [3,11].

The weight classification of ROVs and their corresponding depth ranges and applications are listed in Table 1.

Tab.1

Classification of ROVs according to weight, operating depth, and function criteria. Based on [1–3] and standard NO-07-A118:2015. Unmanned underwater vehicles – classification and technical requirements.

ROV Class	Typical application	Operating depth	Weight (kg)	Number of drives	Example features
Micro/Mini ROV	Visual inspections, scientific research	Up to 300 m	< 50	3 – 4	HD camera, LED lighting, sonar
Observation ROV	Monitoring, image recording, observations	300– 1000 m	50 – 200	4 – 6	Cameras, side sonar, GPS integration
Work-Class ROV	Technical work, interventions, repairs	1000– 3000 m	500 – 3000	6 – 8	Manipulators, hydraulic tools
Heavy-Duty ROV	Construction operations, deep-sea work	> 3000 m	> 3000	8 – 10	Cutting and welding systems, AI modules

For the purposes of this study, the classification of ROVs proposed by Christ and Wernlie [1] was adopted, in which membership is determined by operational capabilities and equipment.

The smallest micro- and mini-ROVs are used for visual inspections and simple research tasks. Observation-class vehicles are used for monitoring and real-time image recording. The smallest micro- and mini-ROVs are used for visual inspections and simple research tasks. Observation-class vehicles are used for real-time monitoring and image recording, which often supports rescue and maintenance operations. Work-Class ROVs are technologically advanced units equipped with manipulators, hydraulic tools, and extensive sensor systems, enabling complex operations such as cutting, welding, or assembling underwater structures. The largest Heavy-Duty vehicles are used for construction tasks at considerable depths and in difficult environmental conditions [1,2].

The history of the development of remotely operated underwater vehicles goes back more than half a century, and its beginnings are described in the literature

in various ways, covering the first designs dating back to the 1950s [1,6]. In the following decades, this technology was adopted by the offshore industry, where traditional diving methods were too risky and costly. The greatest development took place in the 1980s and 1990s, when vehicles began to be mass-produced and used in an increasingly wide range of applications. Advances in hydrodynamics, electronics, image processing, and automation have made modern ROVs highly precise, mobile, and capable of operating at depths exceeding 3,000 meters [1–4].

In Poland, the first scientific work on remotely operated underwater vehicles (ROVs) was conducted in the 1980s by Prof. Piegat at the Szczecin University of Technology, who developed the design of the “AITS” vehicle. The first ROV systems were delivered to the Polish Navy in the early 1990s (Benthos and Achille, followed by the Polish ROV Ukwiąg), confirming more than 30 years of tradition in the use of this technology in the country. It is worth noting that the first patent in Europe for an autonomous underwater vehicle was filed in Poland – it

was developed in 1979 by Prof. Wiliński from Prof. Wojnowski's team as a submarine imitator. It was only in subsequent years, as part of technical modernization, that AUV systems were also introduced into service [13,14]. Systems such as the Gavia AUV are designed to detect and neutralize underwater threats, including sea mines, and their implementation is part of the process of rebuilding maritime capabilities and adapting to NATO standards. In recent years, there has also been growing interest in ROVs for civilian applications, particularly in the inspection and maintenance of energy infrastructure such as pipelines, drilling platforms, and offshore wind farms [4,5].

ROVs are also widely used in environmental research and underwater archaeology, allowing for the safe documentation of shipwrecks and observation of deep-sea ecosystems. From the point of view of underwater operation safety, the use of ROVs brings measurable benefits. Eliminating direct human contact with the harsh marine environment allows complex tasks to be carried out without endangering the lives of operators. ROVs offer high measurement precision and immediate data transfer to the operations center, which increases efficiency and reduces response times in emergency situations, such as infrastructure failures, oil spills, or shipwrecks [2–6]. Practical examples of the use of this type of technology were presented by M. Dawidziuk and A. Olejnik, who analyzed the operation of the Falcon ROV during work on the wreck of the WŁA-127 vessel. The authors emphasized the stability of the vehicle's positioning and the high quality of the recorded image in conditions of limited visibility and poor lighting [15].

TECHNICAL CHARACTERISTICS OF ROV VEHICLES

Remotely Operated Vehicles (ROVs) are specialized technical devices designed to operate in demanding marine environments. Their effectiveness and range of possible applications depend primarily on their design, class, and onboard technologies. Depending on their intended use, ROVs vary in size, weight, equipment, and operating parameters, but the basic architecture of these systems remains similar [7,8].

From a design point of view, each ROV consists of several basic modules. The hull serves a protective function, shielding sensitive components from seawater and high pressure at great depths. Corrosion- and compression-resistant materials are used in its construction, mainly aluminum alloys, titanium, and polymer composites. Inside the hull are electronic, power supply, and communication systems responsible for control and real-time data transmission [7].

A key component of every ROV is its propulsion system, which allows the vehicle to maneuver in six degrees of freedom. A typical ROV is equipped with four to eight electric traction motors (thrusters) that enable maneuvering in six degrees of freedom, while hydraulic systems are used exclusively to power high-power tools and manipulators.

Modern designs use integrated stabilization systems that utilize inertial sensors and current compensation algorithms to maintain position in a dynamic marine environment [8,9].

The vehicle is usually powered by an umbilical cable connecting the floating unit to the ROV. Smaller

experimental and research systems also use internal lithium-ion batteries, but this limits the mission time.

Advanced units use separate power and data transmission channels, which allows for the simultaneous transmission of power, images, and high-bandwidth telemetry data [9].

The control system consists of an operating unit on the surface (usually on a ship or platform) and on-board controllers and processors. The operator controls the vehicle using a console with joysticks and HMI (Human-Machine Interface) interfaces that display visual, sonar, and navigation data. Modern systems increasingly support the operator with semi-autonomous algorithms that assist in stabilization, course maintenance,

and depth control. The integration of inertial navigation (INS) with USBL or LBL positioning systems allows for precise positioning even in environments without GPS signal [9,10].

Modern HMI interfaces use haptic solutions with force feedback, allowing the operator to feel the resistance of the manipulator and interact with the object. This increases the precision of the grip and the safety of technical operations, especially in assembly and intervention tasks.

Particularly important are the sensory systems responsible for observing and analyzing the environment in ROV operations. Standard kits include HD or 4K cameras with pan and zoom functions, LED spotlights, and environmental parameter sensors (depth, temperature, salinity, flow). Work-Class vehicles also use side and multi-beam sonars, 3D imaging systems, and laser scanners to create spatial models of the seabed. These solutions are used in both scientific research and industrial inspections [10].

The technical parameters of ROVs vary greatly and depend heavily on the class of the vehicle. *Work-class* vehicles typically reach operating depths of 1,000 to 3,000 meters, although designs capable of operating at depths of up to 6,000 meters are available. The length of the umbilical cable ranges from several hundred meters to 10 kilometers, and the operating speed is between 1 and 3 knots, with the most advanced units reaching 5 knots. Maneuvering efficiency depends on the number of thrusters and their placement, which is crucial during technical and inspection operations [7–9].

ROVs are equipped with various working tools and specialized sensors. HD and 4K cameras with image stabilization systems enable accurate documentation of the underwater environment. Hydraulic and electric manipulators allow for precise operations such as grabbing objects, cutting, drilling, and sampling. In scientific applications, water samplers, bottom sediment samplers, and biological and chemical sensors are used. In military missions, vehicles can be equipped with magnetic sensors or underwater radars to aid in threat detection [9–11].

In summary, the technical complexity of ROVs makes them extremely versatile tools for underwater operations. Their modular design, diverse propulsion systems, precise sensor systems, and integration with modern tools and analytical software allow them to be adapted to almost any type of mission, from simple inspections to complex technical operations and scientific research. Advances in automation, artificial intelligence, and computer vision indicate that in the coming years, ROVs will gradually gain greater autonomy, while the

operator will continue to play a key role in the decision-making process [10,12].

The general layout of the system and its integration with an unmanned aerial vehicle (UAV), which acts as a retransmission platform, is shown in Fig. 1. In the presented model, the UAV acts as an intermediary node in the transmission of signals between the surface vessel and the command post, without affecting the physical limitations resulting from the ROV cable connection.

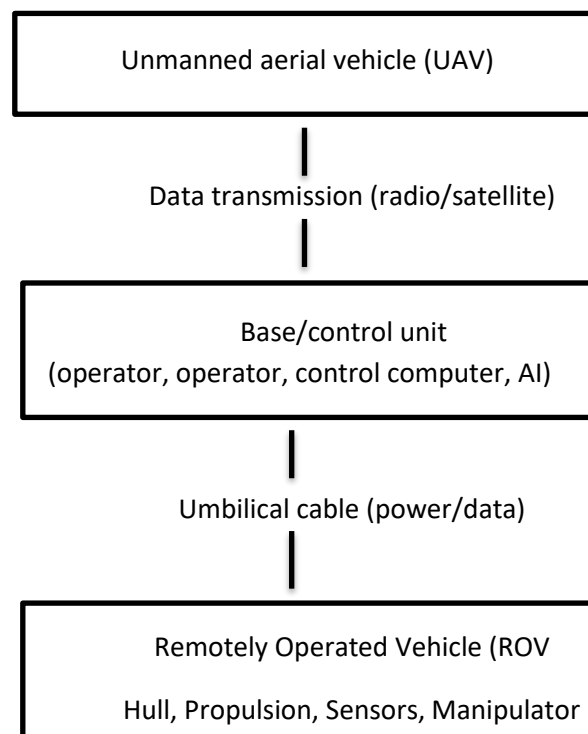


Fig. 1 Sketch 1. Block diagram of the ROV system with the possibility of integration with UAV.

The diagram shows the basic components of an unmanned underwater vehicle (ROV) and how it can be integrated with an unmanned aerial vehicle (UAV). The ROV is connected to the base unit by an umbilical cable, which provides power and transmits data and images. Integration with the UAV extends the operational communication range between the base unit and the command post; it does not affect the physical length of the umbilical cable connecting the ROV to the surface unit.

The use of UAVs as a retransmission platform extends the operational communication range between the base unit and the command post, allowing missions to be conducted at greater distances from the shore or in areas with limited access to communication infrastructure. The integration of the ROV system with the UAV enables simultaneous observation of the environment above and below the water surface and rapid exchange of information in real time.

OPERATIONAL CAPABILITIES AND APPLICATIONS OF ROVS

Remotely Operated Vehicles (ROVs) play a key role in modern maritime operations, both civil and military. Their specific design, high maneuvering precision, and ability to operate in extreme environmental conditions make them widely used in tasks related to the exploitation, protection, and exploration of the underwater environment. In accordance with IMCA and OPITO guidelines, ROVs are currently considered a basic element of operational infrastructure in inspection, intervention, and research missions [8,10].

ROVs are used for a variety of missions, from scientific research and technical inspections to military and rescue operations. In oceanography, they enable long-term monitoring of deep-sea ecosystems, sampling of sediments and microorganisms, and recording images and mapping the seabed [10]. Their accuracy and ability to operate at great depths make them an indispensable tool for geologists, marine biologists, and climatologists. In recent years, vehicles of this class have increasingly been working with autonomous AUVs, which conduct preliminary reconnaissance, while ROVs perform precise technical work in selected locations.

In the industrial and engineering sectors, ROVs are commonly used to inspect underwater infrastructure such as pipelines, fiber optic cables, drilling platforms, and offshore wind farm foundations. Compared to technical diving, the use of ROVs allows work to be carried out more safely, quickly, and with less risk to personnel [8]. Thanks to multibeam sonars, high-resolution cameras, and image analysis supported by artificial intelligence algorithms, it is possible to detect microdamage, leaks, and material corrosion, which significantly increases operational safety and reduces downtime costs [9,10].

ROVs play an irreplaceable role in search and rescue operations, enabling quick and precise searches of the seabed after shipwrecks, plane crashes, or maritime accidents. Equipped with sonar and manipulators, these vehicles can locate, recover, or secure underwater objects. Well-known examples of the use of this technology include the search for the wreckage of Air France Flight 447 in 2009 and the rescue operation following the sinking of the *Sewol* ferry in 2014 [9]. In such operations, the ability of ROVs to operate in conditions of limited visibility and at great depths, where direct human involvement would be impossible, is of key importance.

In military applications, ROVs perform both tactical and strategic tasks. They are used to detect and neutralize sea mines, conduct hydrographic reconnaissance, map the seabed, and protect critical infrastructure such as ports, cables, and undersea sensors [11]. Modern ROV systems can be integrated with unmanned surface vehicles (USVs) or aerial vehicles (UAVs), which serve as communication and observation support units. This approach increases mission effectiveness while reducing risk to personnel.

It should be emphasized that the presented concept of integrating ROV-USV-BSP systems is a model and theoretical proposal for a solution, rather than a finished technical design. Under current operating conditions, the implementation of such an architecture would require overcoming a number of barriers, including those related to communication system compatibility, electromagnetic interference resistance, navigation synchronization, and procedural restrictions resulting from military and civil regulations.

The operational effectiveness of ROVs is largely dependent on environmental conditions. Open seas and oceans, due to strong currents, waves, and considerable depths, require the use of dynamic stabilization and assisted navigation systems. In enclosed waters, such as lakes or bays, limited visibility and high concentrations of suspended solids necessitate the use of 3D sonars and high-intensity cameras [8,12]. Despite these limitations, the right technical configuration and a trained team of operators allow for effective operations in most aquatic environments.

Compared to manned vehicles, ROVs offer significant operational advantages – they eliminate the risk to human life, are cheaper to maintain, and are quicker to deploy. Thanks to the development of vision technologies, manipulators, and control systems, the difference between the capabilities of ROVs and manned vehicles is steadily decreasing [10,11]. Supported by simulators and VR/AR training environments, modern operating systems enable increasingly intuitive vehicle operation, which translates into mission precision and safety.

However, technical and organizational limitations cannot be ignored. The umbilical cable limits the range and maneuverability of the vehicle, especially in

environments with numerous obstacles. Appropriate surface infrastructure, specialized support units, and highly qualified personnel are also required. Environmental factors are an additional challenge – strong currents or extreme weather conditions can prevent operations from being carried out. The maintenance and modernization of more advanced vehicles also represent a significant financial burden [8,12].

Legal and organizational issues are also important. ROV operations must comply with international regulations governing underwater work, environmental protection, and maritime safety. In the case of military missions, additional procedures apply regarding data protection, information classification, and operational security [11].

In summary, the operational capabilities of ROVs are impressive and continue to expand as technology advances. Their versatility, safety, and potential for integration with autonomous systems make them a key tool for modern maritime operations. Further developments in automation, artificial intelligence, navigation systems, and operator interfaces will determine their growth in autonomy, precision, and resistance to external factors in the coming years.

ROV OPERATOR TRAINING SYSTEMS

The dynamic development of unmanned underwater vehicle (ROV) technology and its growing importance in maritime operations necessitate the training of highly qualified operating personnel. Operating such vehicles requires not only technical knowledge, but also responsibility, analytical skills, and knowledge of safety procedures and rules for working in a maritime environment. For this reason, ROV operator training systems are strictly regulated by international standards aimed at ensuring the safety, efficiency, and reliability of operations [8,10].

In the Polish ROV operator training system, the regulations of the Ministry of National Defense apply, in particular the qualification procedures approved by the Diver Qualification Commission at the General Command of the Armed Forces of the Republic of Poland. Training for ROV operators at the Naval Academy has been conducted continuously since 2008, initially in the form of advanced courses for Ministry of National Defense personnel. In 2017, the academy expanded its curriculum by introducing a specialization in “underwater work” as part of the mechatronics program, which includes a course on “Marine Robot Operation.” The program includes both theoretical modules and practical training on deep-sea equipment. These solutions form the basis of the national ROV operator training system and remain consistent with the applicable guidelines of the Ministry of National Defense.

The military ROV operator training system operates within the framework of regulations governing underwater work in the Polish Armed Forces. The implementing acts of the Minister of National Defense are of key importance in the ROV operator qualification system in the Polish Armed Forces, in particular:

- Regulation of June 21, 2012, on safety conditions for underwater work (Journal of Laws 2021, item 1377),
- Regulation of April 25, 2019 (Journal of Laws 2019, item 954), clarifying the provisions of the

Regulation of 2005 (Journal of Laws 2005, No. 185, item 1547).

Chapter 2 §19 of the 2005 regulation specifies who can obtain military qualifications as an ROV operator, which forms the basis for the activities of the Qualification Commission for Divers of the DG RSZ RP.

The scope of competence required of ROV operators depends on the class of vehicle and the type of tasks performed. It includes knowledge of mechanics, electronics, hydrodynamics, control systems, and the basics of automation. The operator must be able to interpret sonar and visual data, respond to emergency situations, and cooperate with the surface vessel crew and technical personnel [1]. Knowledge of issues related to maritime safety, environmental protection, and technical rescue is also increasingly required, especially during operations in protected areas.

In response to the increase in the number and complexity of missions using ROVs, international training and competency standards have been developed. The most widely used model is the IMCA (*International Marine Contractors Association*) qualification system, which defines the following training levels: Trainee Pilot Technician, Pilot Technician Grade II, and Pilot Technician Grade I [8]. Each level covers a detailed range of theoretical knowledge, practical skills, and documentation of experience gained in actual operations. IMCA certification is currently the global industry standard, and obtaining it is a prerequisite for working in most offshore companies.

The training process usually consists of three stages: theoretical, simulation, and practical. In the theoretical phase, participants acquire knowledge about vehicle construction, control principles, emergency procedures, and the basics of hydrography and underwater navigation. They then move on to the simulation stage, which has become a key element of modern training thanks to the development of digital technologies and visual simulators.

Modern ROV simulators reproduce realistic underwater conditions, taking into account variable visibility, water currents, system failures, and interactions with objects. The use of 3D simulation, as well as VR (Virtual Reality) and AR (Augmented Reality) technologies, allows operators to improve their response in emergency situations without the risk of damaging equipment [9]. This makes training more effective and minimizes the number of errors in real missions.

Simulators used in training centers, compliant with IMCA, OPITO, or DNV GL standards, enable realistic reproduction of the operation of various classes of vehicles and specific scenarios – from simple inspections to complex construction works [8,10]. In recent years, remote training using e-learning platforms and network simulators has also been increasingly introduced, which increases the availability of courses and enables joint international exercises.

In the Polish context, ROV operator training is additionally regulated by ministry guidelines and military center practices. Simulation solutions developed in cooperation with domestic universities (including the Military University of Technology) are used, which allows programs to be adapted to the specific nature of reconnaissance, rescue, and engineering tasks¹.

The final stage of training consists of practical operational exercises carried out on actual equipment. These are conducted on vessels or in test pools equipped with ROV systems. Operators learn how to start the vehicle, manage the umbilical cable, operate manipulators,

sonars, cameras, and how to deal with hydraulic or electrical failures [1–10]. The training ends with a practical exam and the awarding of a certificate confirming the acquisition of professional competence.

At military and academic centers, such as the Military University of Technology, training also covers elements of the tactical use of ROVs in reconnaissance, rescue, and engineering operations. The integration of ROVs with navigation bridge simulators and unmanned surface vehicles (USVs) enables comprehensive training scenarios that replicate real operating conditions.

Due to rapid technological advances, ROV operators must systematically update their qualifications. Regular refresher courses and specialized supplementary training cover topics such as geophysics, hydraulic repairs, operation of new control interfaces (HMI), and safety in contaminated environments [8,9].

In summary, ROV operator training is a key element in ensuring the safety and effectiveness of underwater operations. A high level of standardization, the development of simulation technologies, and the integration of VR and HMI systems make it possible to prepare specialists capable of carrying out complex missions in all conditions. With the further development of automation and artificial intelligence, operator training methods will increasingly focus on improving human-machine cooperation and semi-autonomous system supervision skills.

OWN RESEARCH

The research conducted was pilot and exploratory in nature, which means that its purpose was to preliminarily identify the opinions of UAV operators on the possibility of implementing and using ROV systems. Due to the small, unrepresentative sample ($N = 4$), the results should be treated as supporting material, indicating trends and directions for further analysis, rather than as a basis for formulating generalized conclusions. In order to obtain expert opinions on the operational potential of unmanned underwater vehicles (ROVs) in the context of their integration with unmanned aerial vehicles (UAVs) and to assess the validity of their application in various areas of maritime activity, qualitative research was conducted. Due to the preliminary nature of the research, expert interviews and participant observation were used, which enabled an in-depth analysis of the opinions and experiences of practitioners.

The research was conducted among four pilots within visual line of sight (VLOS) and beyond visual line of sight (BVLOS). The selection of respondents was purposeful and included individuals with professional experience in remote operations, both civil and military².

The expert interviews covered questions concerning:

- the applicability of ROVs in the civil and military sectors,
- the potential for integrating ROVs with UAVs and other autonomous systems,
- as well as identifying the advantages and limitations of using ROVs in operational activities.

The results of the study confirmed that, according to respondents, ROVs have high application potential in the civil sector, especially in the inspection of underwater infrastructure – hydrotechnical structures, bridges, pipelines, ports, and energy installations. The study

participants emphasized that these vehicles can effectively support research and exploration activities, as well as the inspection of vessels and structures that are difficult to access.

With regard to military applications, the operators surveyed indicated that ROVs can play an important role in reconnaissance, mine detection and neutralization, critical infrastructure protection, and anti-sabotage operations. According to experts, the integration of ROVs with aerial (UAV) and surface (USV) systems could be a breakthrough in observation and inspection activities. Integrated operations would provide a more complete picture of the situation both above and below the water surface, which is particularly important for the protection of port facilities, offshore installations, and maritime borders.

Respondents indicated that stable real-time data transmission and the development of common operational and navigation procedures enabling mutual location and automatic coordination of activities are key to the effective use of integrated ROV-UAV systems. Such solutions increase mission effectiveness, reduce response times, and reduce the risk of human error.

The limitations identified include, above all, the limited operational range of the ROV, resulting from the need to use a power and communication cable (umbilical), as well as high operating and maintenance costs. On the other hand, the most important advantages mentioned were the ability to work in environments that are dangerous to humans, the precision of inspections, and the multiple uses of the system in various types of tasks - both civilian and military.

All the experts surveyed unanimously emphasized that ROVs are an important element of the future of underwater operations. They pointed to the need for further improvement of these systems in terms of increasing operational autonomy, reducing weight and size, improving imaging quality, and developing navigation and communication systems. In their opinion, the development of common training standards for air and underwater system operators will also be of key importance, as it will enable integrated multi-domain operations.

In summary, the expert interviews conducted allowed us to identify the main directions for the development and implementation of ROV systems in the context of cooperation with UAVs. Despite the limited size of the research sample, the results obtained provide valuable practical conclusions and may serve as a starting point for further in-depth quantitative research on the integration of unmanned aerial and underwater systems.

DIRECTIONS FOR FURTHER TECHNOLOGICAL AND TRAINING DEVELOPMENT OF ROVs

The ongoing technological development of unmanned ROV underwater vehicles and their growing use in the civil, industrial, and military sectors are driving a constant search for solutions to increase efficiency, autonomy, and operational safety. Contemporary research focuses on implementing technologies such as artificial intelligence (AI), machine learning (ML), and automation, as well as developing modern training methods. Current research focuses on the implementation of technologies such as artificial intelligence (AI), machine learning (ML),

and automation, as well as the development of modern training methods using virtual reality (VR) and augmented reality (AR).

The integration of artificial intelligence and machine learning with ROV onboard systems opens up new possibilities for the analysis of sonar, optical, and navigation data. AI algorithms enable real-time detection of patterns and anomalies, which translates into faster identification of damage to underwater infrastructure and classification of objects encountered during inspection missions [1,4]. Machine learning also supports the process of improving navigation algorithms, enabling route optimization and automatic obstacle avoidance in variable hydrodynamic conditions.

The implementation of AI algorithms contributes to the increased autonomy of underwater vehicles. While traditional ROVs require constant operator supervision, modern hybrid platforms are capable of maintaining their position independently, following programmed routes, and even performing emergency ascent maneuvers in the event of loss of communication with the base unit [4,5]. Modern ROVs are increasingly equipped with integrated environmental perception systems that combine data from cameras, sonars, and inertial sensors, bringing them closer in functionality to fully autonomous AUVs. Polish researchers emphasize the need to develop hybrid technologies that combine the advantages of ROVs and AUVs, pointing to their potential to increase operational flexibility and reduce the costs of underwater missions [11].

The dynamic development of information technology is also changing the way ROV operators are trained. Systems using VR and AR are becoming increasingly widespread, allowing for the simulation of realistic marine environments and the practice of complex operational scenarios without the risk of damaging equipment.

Training in a VR environment allows for full immersion in a simulated environment and practice of emergency, inspection, and navigation procedures, significantly reducing the time needed to achieve operational readiness [1,7].

AR technology is mainly used in technical and service training. By superimposing virtual information - technical diagrams, diagnostic tips, or system parameters - onto the actual image of the vehicle, operators can diagnose and repair faults more quickly. Polish studies, including those by the staff of the Naval Academy, highlight the importance of simulation environments integrated with real mission databases and AI modules, which enable the personalization of the training process to suit the operator's level of experience [11,12].

As part of the concept of further development of unmanned systems, solutions combining air, surface, and underwater platforms into integrated observation and research systems are becoming increasingly important.

The use of a retransmission element - in the form of an aerostat or an unmanned platform

with an increased operating ceiling - allows for a significant increase in operational communication range and data transmission continuity.

This type of integration is an important direction for the development of ROV systems in maritime and rescue operations.

A diagram of the general concept of cooperation between an ROV underwater vehicle, an unmanned aerial

vehicle (UAV), and a retransmission element is shown in Sketch 2.

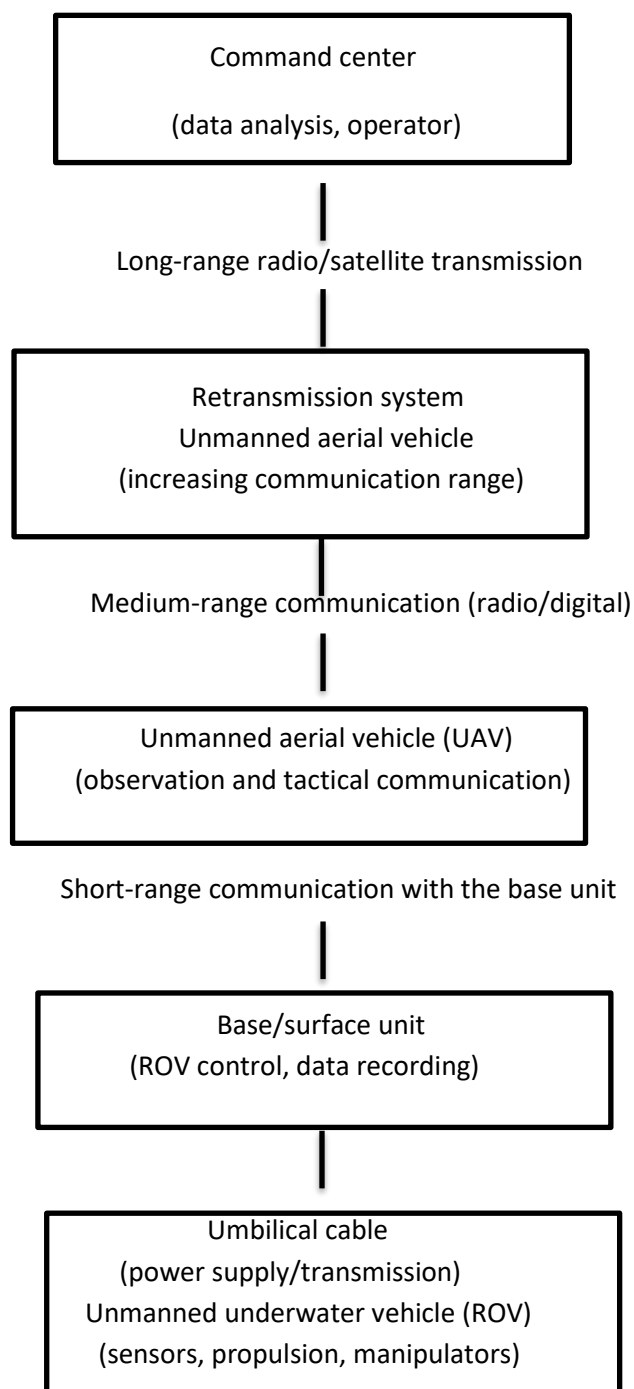


Fig. 2 Schematic diagram of the concept of integrating the ROV-BSP system with the retransmission platform. The diagram shows the concept of unmanned platforms cooperating in a marine environment, including an underwater vehicle (ROV), an unmanned aerial vehicle (UAV), and a signal retransmission element (e.g., an aerostat or a UAV with an increased operating ceiling).

The system enables the extension of operational communication range between the base unit and the command center, ensuring continuity of data and image transmission in real time. Such a solution can be used in reconnaissance, research, and rescue operations, especially in areas without network infrastructure or at great distances from the shore.

In view of the growing importance of ROV technology for the security sector, offshore industry, environmental research, and undersea logistics, further research and design initiatives are crucial. These solutions are forward-looking and also include concepts for the cooperation of hybrid platforms and AUVs, not just classic ROVs. Recommended areas for development include:

- Integration of AI with ROV sonar and navigation systems, increasing their autonomy in complex underwater environments.
- Development of multi-vehicle formations (swarm robotics) enabling cooperation between multiple ROVs in exploration and research tasks (prospective solutions, also including AUV and hybrid platforms).
- Design of universal VR/AR training interfaces integrated with operational data.
- The creation of a national ROV operational database for analytical, training, and research purposes.
- The development of dual technical education programs combining knowledge in the fields of mechatronics, computer science, and hydronautics.

The implementation of these directions requires close cooperation between technical universities, industry, military units, and research institutes. An example of good practice is the activity of the Naval Academy in Gdynia, which conducts research in the field of underwater robotics, designs prototypes of unmanned systems, and develops training standards and methodologies in line with international norms [11,12].

It is worth noting that the development of autonomous functions in ROVs is intended to support the operator's work and does not mean that the system is fully independent. Full autonomy remains the domain of AUVs, while in ROVs we are talking about the automation of selected tasks (position maintenance, route, emergency procedures) while maintaining the operator's decision-making role.

In summary, current trends in ROV technology and training development focus on increasing autonomy, efficiency, and operational safety. The use of artificial intelligence, automation, and VR/AR environments allows for the optimization of activities and preparation for future challenges, such as deep-sea exploration, offshore infrastructure development, and strengthening maritime defense capabilities. In this context, the importance of national research centers, such as the Naval Academy and the Military University of Technology, remains crucial for building national capabilities in the field of underwater robotics and unmanned technologies. Both literature analysis and pilot studies indicate the growing importance of ROV systems in civil and military operations, but a full assessment of their operational potential requires further research involving broader, representative user groups and real-world testing.

REFERENCES

1. Christ R. D., Wernli R.L. The ROV Manual: A User Guide for Remotely Operated Vehicles. Butterworth-Heinemann; 2014.
2. Griffiths G. Technology and Applications of Autonomous Underwater Vehicles. Taylor & Francis; 2002.
3. Jakus B., Olejnik A. The Analysis of Drive Systems in Unmanned Underwater Vehicles Towards Identifying the Method of Drive Transmission. *Pol Hyperbar Res.* 2017;60(3):7–16.
4. Bibuli M., Caccia M., Lapierre L., Bruzzone G. Guidance of Unmanned Underwater Vehicles. *IFAC Proc Volumes.* 2012;45(5):313–324.
5. Yoerger D.R., Jakuba M., Bradley A.M., Bingham B. Techniques for Deep Sea Near Bottom Survey Using an Autonomous Underwater Vehicle. *Int J Robot Res.* 2007;26(1):41–54.
6. Manley J.E., Unmanned Surface Vehicles, 15 Years of Development. *OCEANS 2008 IEEE*; 2008.
7. Bingham B., Foley B., Singh H., Camilli R., Mindell D. Archaeological and Deep Sea Applications of Autonomous Underwater Vehicles. *J Field Robot.* 2010;27(6):702–717.
8. IMCA. Competence and Training Guidelines for ROV Personnel. International Marine Contractors Association; 2017.
9. Barlow C. Simulator-based training for ROV pilots. *J Mar Technol.* 2015;49(3):211–219.
10. OPITO. ROV Personnel Training Standard. Offshore Petroleum Industry Training Organization; 2020.
11. Martynowicz A, Czaplewski K. Zastosowanie systemów autonomicznych i półautonomicznych w działaniach morskich. *Zeszyt Nauk AMW.* 2021;224(1):56–68.
12. Rdzanek D, Kołakowski P. Wirtualne środowiska szkoleniowe dla operatorów pojazdów podwodnych. *Przegląd Sił Zbrojnych RP.* 2020;3(43):78–85.
13. Dura M., *Pierwsze pojazdy podwodne trafiły do Marynarki Wojennej.* Dostęp 10.04.2025 dostępne w: [<https://defence24.pl/sily-zbrojne/pierwsze-pojazdy-podwodne-trafily-do-marynarki-wojennej>]
14. Zalesiński Ł. *Drony na fali.* Dostęp: 12.04.2025, dostępne w: [<https://www.polska-zbrojna.pl/home/ArticleShow/36189>]
15. Dawidziuk M., Olejnik A., *Wspomaganie prac podwodnych za pomocą bezzałogowych pojazdów głębinowych na przykładzie prac przy wraku jednostki WŁA-127*, *Polish Hyperbaric Research* 1(58) 2017, *Journal of Polish Hyperbaric Medicine and Technology Society*.

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¹ see Ministry of Defense guidelines on training technical specialists; AMW practices in the field of training simulators,

² Expert interviews and observations were conducted among four UAV pilots. Two pilots are professionally involved in infrastructure inspections using drones (including towers, masts, and photovoltaic installations). The interviews focused on three main issues: (1) the use of ROVs in the civil and military sectors, (2) the integration of ROVs with UAVs or other autonomous robots, and (3) the advantages and disadvantages of ROV operation,