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IMPROVEMENT OF TECHNICAL SUPPLY OF PROJECTS OF ROBOTIZED MONITORING OF UNDERWATER CONDITIONS IN SHALLOW WATER AREAS

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Abstract

The intensification of industrial activity in shallow water areas and the growing requirements for the safety of their use determine the urgency of developing new technologies for monitoring their underwater environment. The monitoring tasks include mapping of the bottom surface, inspection of hydraulic structures, search for sunken objects, control of unauthorized access to protected areas, etc.

A promising direction for improving the efficiency of monitoring projects for such water areas is the use of uninhabited autonomous and remote-controlled underwater robots. However, the use of traditional types of such equipment has low efficiency because of the impossibility of the operational management of the missions of autonomous vehicles in real time and the complexity and high cost of using remote-controlled vehicles.

As an alternative to the robotic support of underwater monitoring projects in shallow water areas, it is proposed to use autonomous underwater vehicles with a radio beacon, since they make it possible to survey large areas, perform high-quality and comprehensive search and mapping work, while providing operators with real-world underwater conditions of time.

A generalized structure and composition of the equipment for an autonomous underwater vehicle with a radio beacon is described, its main underwater missions and types of underwater operations are described.

In order to assess the resources for the execution time of projects for the robotized monitoring of shallow water areas, dependencies are proposed for calculating the time costs for different trajectories of the movement of the underwater vehicle-robot. Using this methodology, time expenses were calculated and the number of underwater vehicle operation cycles for the main ports of Ukraine was estimated during the examination of the mooring walls with video equipment of the underwater vehicle and examination of the shallow water area by its sonar.

The obtained results are a preliminary assessment of the time spent on the study of shallow-water offshore and port water areas, and also form the theoretical basis for the formation of a technical assignment for the creation of modern robotic support for monitoring projects in such water areas.

Keywords: monitoring project management, shallow water area, autonomous underwater vehicle with a radio beacon, time resource.

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1. Introduction

The shallow waters are coastal sea and river waterways, the waters of ports and their external raids and anchorages, the waters of lakes and reservoirs. They have depths of up to 50–60 m and are actively used for transport and passenger transportation, for the extraction of energy carriers and building materials [1, 2].

The intensification of industrial activity in shallow water areas and the growing requirements for the safety of their use stimulate the development of new technologies for their monitoring.

Such technologies are of additional relevance for the tasks of protecting objects of critical maritime infrastructure – ports, naval bases, nuclear and hydroelectric power plants, offshore stationary gas production platforms on the shallow water shelf, etc. [3, 4].

Traditionally, projects monitoring the surface situation in shallow water areas are implemented using optical and radar surveillance systems [5].

Underwater monitoring projects are more complex because they require the use of special instruments and tools for underwater robotics. Currently, the greatest use received:

– automatic radiohydroacoustic buoys [9];
– stationary hydroacoustic instruments and systems installed on the seabed [6, 10, 11];
– magnetometric systems [7];
– autonomous underwater vehicles (AUV) [8, 12];
– remotely-operated vehicles (ROV) [5, 13, 14].

Automatic radiohydroacoustic buoys are installed at controlled points of the water areas and are combined into a single information support system via a satellite communication channel. Thus, the buoy of the MIOOS project, developed by scientists from two universities in Malaysia [9], is equipped with a number of sensors for acoustic information, oceanographic and meteorological sensors, and a video camera for recording audio and visual environmental data. Buoys of this type provide for the collection and transmission of data in real time, but do not have the ability to move under water for operational monitoring of large volumes of the aquatic environment.

Hydroacoustic systems are described in [6], using groups to monitor underwater space on large areas of marine waters. However, they are not intended to display fast underwater processes that require prompt response from personnel.

Hydroacoustic stations described in [10, 11], specifically designed to monitor the fleeting processes, in particular, to identify small mobile objects under water (divers, underwater vehicles, etc.). However, such stations do not provide high-quality identification of these objects and their prompt examination.

The main direction of improving the technical support of underwater monitoring projects is the use of autonomous and tethered (telecontrolled) underwater robots.

The first type of such equipment, AUV, is distinguished by high productivity of underwater operations, but does not provide real-time monitoring of the underwater situation [12].

The second type of underwater robotics, ROV, provides such an opportunity, but requires for its use special vessels as carriers of underwater robots and complex ship equipment for their operation (control and power supply stations, trip equipment, etc.) [13].

The intermediate position between these two types of robotics is occupied by underwater robots, built according to a hybrid scheme [14]. Such devices have two main modes – tethered mode, when they are controlled and video communication with the ship's control station is performed using a thin fiber optic cable, and autonomous mode, when the device turns off the cable and completes the underwater mission in a critical underwater situation. However, for monitoring tasks in shallow water areas, such an underwater vehicle also requires the involvement of a carrier vessel, and increases the operating costs of their use.

In connection with the above, the actual task is including in the technical support projects for monitoring shallow-water and, in particular, port, water areas of new and more productive means of underwater robotics, combining the advantages of AUV and ROV.

The object of research in the article is the robotic support of these projects, which ensures the implementation of underwater work in real time and with high performance.

The aim of research is improving the existing robotic support projects for monitoring underwater conditions in shallow water areas by organizing two-way information exchange between the underwater robot and the control post in real time using a towed radio beacon, as well as developing a methodology for evaluating its performance when inspecting the bottom surface and underwater part of the mooring designs.

2. The main underwater missions that are performed during robotic monitoring of shallow waters

The main (basic) underwater missions performed when monitoring shallow waters are [15]:

– engineering surveys and documentation of the underwater part of hydraulic structures – moorings of ports, locks, dams, hydroelectric dams, underwater pipelines, underwater components of the infrastructure of nuclear power plants, pumping stations of irrigation systems and the like;

– environmental surveys of marine coastal waters, rivers, lakes, reservoirs;

– survey and mapping of the bottom area of ports, fairways, recommended coastal waterways, water areas of recreational zones, other coastal waters;

– control of unauthorized access of intruders from the sea to objects of critical marine infrastructure (cargo and passenger ports, naval bases, offshore stationary gas production platforms on the shallow shelf, etc.);

– control of unauthorized access of intruders to critical coastal infrastructure facilities with access to water areas (automobile and railway bridges, nuclear, thermal and hydroelectric power plants);

– search and inspection of emergency sunken objects in the water area.

By the nature of the survey, robotic monitoring of the underwater situation in shallow water areas can be:

– one-time (examination and documentation of objects in the event of an emergency situation in the water area);

– periodic (survey and documentation of the technical condition of hydraulic structures and the bottom surface of the water area);

– permanent (protection from unauthorized entry into the water area with the documentation of the process and the results of the mission).

When performing these missions, it is possible to identify the main types of work that should be performed by the underwater vehicle-robot:

– survey and mapping of the bottom surface of shallow sea areas and inland waters (rivers, reservoirs, estuaries, etc.);

– survey and documentation of extended objects that lie on the soil of a given water area (underwater pipelines, communication cables, etc.);

– survey and documentation of point objects (underwater part of navigation structures, sunken objects, etc.);

– identification, inspection and documentation of vertical objects (hydraulic structures, mooring walls, walls of a sunken ship, etc.);

– mapping of the bottom surface of shallow sea areas and inland waters (rivers, reservoirs, estuaries, etc.);

– survey of the water column and bottom surface to identify the facts of unauthorized penetration of feathers and small-sized underwater vehicles in the water area.

3. Autonomous underwater vehicle with a radio beacon as a means of improving the performance of underwater monitoring projects in shallow waters

A promising way to improve the technical support of operational monitoring projects in shallow-water and, in particular, port waters is the use of the AUV with a radio beacon (AUV-RB) [15, 16]. This type of underwater robotics has the properties of the classic AUV (use without a carrier ship, automatic modes of movement), and at the same time – the ROV properties (radio and/or mobile communication with the onshore or ship control post in real time, the ability to manually control complex underwater missions), **Fig. 1**.

The advantages of this type of underwater vehicle-robot compared with the use of "classic" ROV and AUV are much less dependent on flexible communication (beacon cable-tug) due to the shallow depth, complete independence from the carrier ship and, most importantly, operational two-way radio communication with onshore or ship control post of underwater mission.

A preliminary analysis shows that, for carrying out basic underwater missions, AUV-RB can have the following technical characteristics:

– maximum working depth, m 50
– overall AUV dimensions, mm 850×420×350;
– marching speed, knots 1;
– cable length, m up to 75;
– vehicle weight, kg 50;
– RB overall dimensions, mm:
  – length 350;
  – diameter 80;
– autonomy, hours 3;
– number of operators 2.

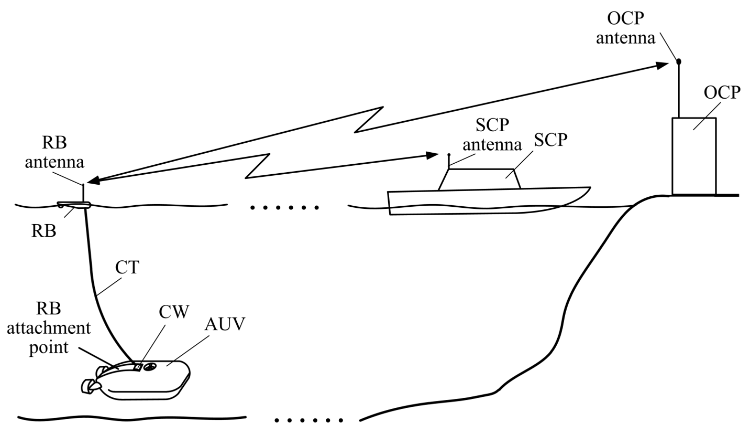

Fig. 1. AUV-RB application technology

This type of underwater vehicle is equipped with a moving complex consisting of two main engines for controlled movement in the horizontal plane and one engine for vertical movement. The vehicle also has a small-sized towing winch to change the length of the RB cable-tug in accordance with the depth and speed of the AUV.

As a basic search equipment must have an underwater video complex and circular sonar.

The control of the AUV-RB can be provided by both the operator over the radio channel and the automatic control system. In the nominal mode of operation, the underwater vehicle is controlled by the automatic control system, and for complex maneuvers or unpredictable control operation modes, it is transferred to the manual mode.

Appearance of such AUV is shown in **Fig. 2**.

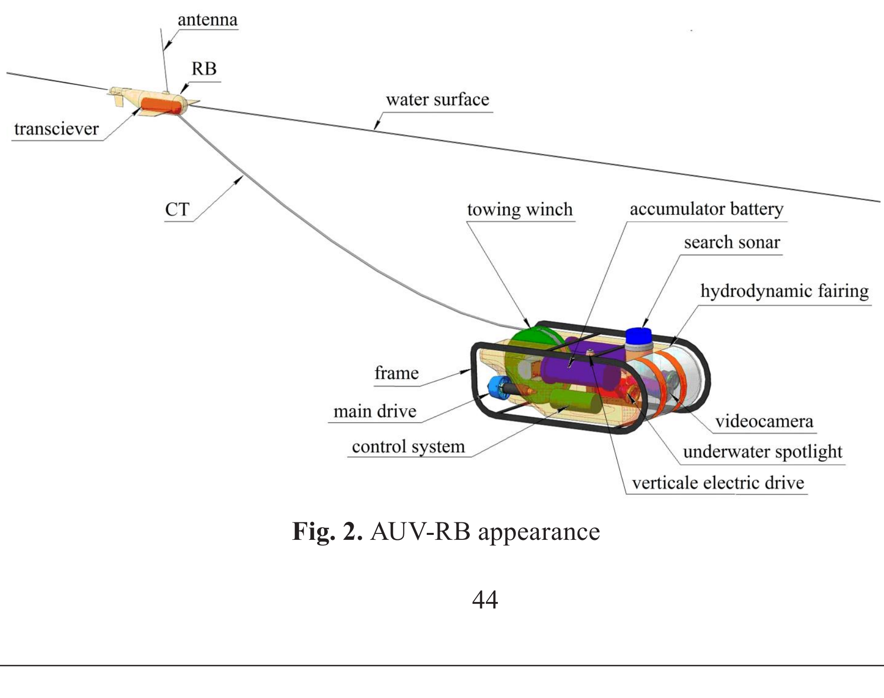

Fig. 2. AUV-RB appearance

The proposed architectural-constructive type of AUV includes towed radio beacon (RB) as an external attachment, which move the surface of the sea in tow mode to provide two-way communication with the coast or ship control station. A controlled change in the length of the design bureau for these modes is provided by a small-sized automatic towing winch, which is located on the AUV.

A features of the use of such a device are:

– possibility of prompt transmission of underwater information to the control post;

– elimination of the routine work of a person in the monitoring process by automating the process of controlling underwater movement, due to the small length of the cable-tug, significantly reduces the likelihood of its entanglement;

– possibility of re-detailed examination of the identified objects in manual and automated modes.

4. Estimation of time spent on monitoring of port areas

Sea and river ports belong to the objects of critical infrastructure. Their technical condition should guarantee a safe event, parking and exit of ships for various purposes, as well as safety for passengers and cargo [4]. The time spent by the AUV-RB on monitoring, in general, depends on the mission that the underwater vehicle performs and on the method of movement of the device. The most common types of AUV-RB equipment are video and sonar devices (underwater video cameras with lamps and sonars). In some cases, magnetometers, profilographs, manipulators are used.

The most common method of movement of the device when monitoring the underwater situation is longitudinal tacks. To determine the time of work in this mode, it is first necessary to determine the length of the covered path (L) of the AUV-RB. To monitor the port area of a complex shape, let's imagine that it is limited to two curvilinear functions $F_1(x)$ and $F_2(x)$ (**Fig. 3, *a***).

The distance between the tacks dx is determined by the width of the video camera capture (with the required overlap of the survey and documentation strip), and the number of tacks *n* is determined by the formula:

$$n = \frac{La}{dx} - 1. \tag{1}$$

Thus, dividing the entire water area into separate parts, the total length of the path that the apparatus needs to go through can be determined by the formula:

$$L = \sum_{i=0}^{n}\left(F_1(x)_i - F_2(x)_i\right) + \sum_{i=0}^{n-1}\begin{cases}\sqrt{dx^2 + (F_2(x)_i - F_2(x)_{i+1})^2} & \text{at } i \in 0, 2, 4, 6...,\\ \sqrt{dx^2 + (F_1(x)_i - F_1(x)_{i+1})^2} & \text{at } i \in 1, 3, 5, 7...,\end{cases} \tag{2}$$

where i – the number of the current tack; $F_1(x)_i$ and $F_2(x)_i$ – the extreme points of the longitudinal tack (along the x axis) along the y axis on the given tack i.

For open water areas, the formula (2) will be:

$$L = \sum_{i=0}^{n} F_1(x)_i + \sum_{i=0}^{n-1}\begin{cases} dx & \text{at } i \in 0, 2, 4, 6...\\ \sqrt{dx^2 + (F_1(x)_i - F_1(x)_{i+1})^2} & \text{at } i \in 1, 3, 5, 7...\end{cases} \tag{3}$$

For the underwater part of the rectangular mooring structures, let's simplify the formula (2) as follows: $F_1(x)$=const=H – the depth at the mooring; $F_2(x)$ =0. Thus, let's obtain the dependence:

$$L = n(H + dx) - dx. \tag{4}$$

The advantages of this method of illuminating the underwater situation are the ease of control of the AUV-RB.

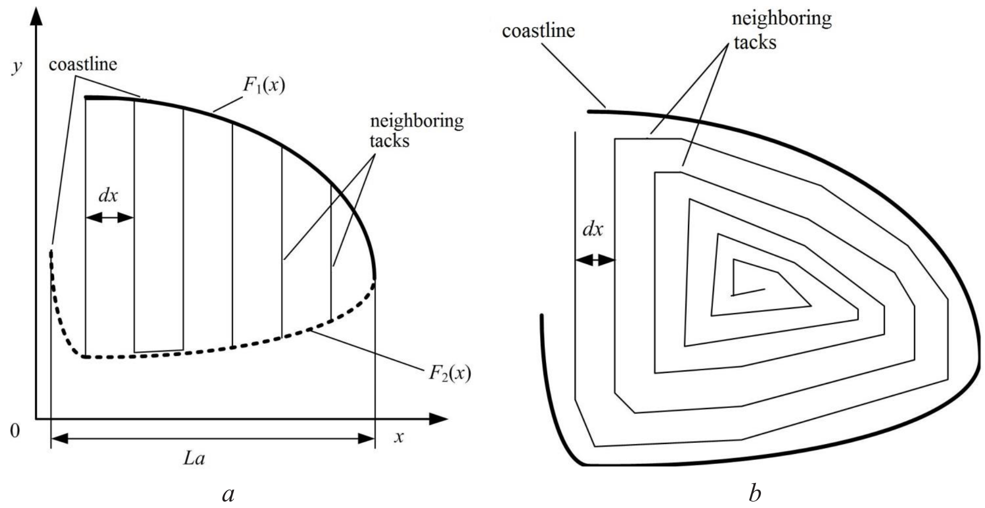

Fig. 3. Methods of movement for the survey area:
a – the passage of the longitudinal tacks; *b* – using a concentric grid

The next method of movement of the device when monitoring the underwater situation is the method of concentric grid (**Fig. 3, *b***), when the vehicle moves along the contour of a given water area with a decrease in radius. The distance between adjacent spiral tacks corresponds to the capture width of the video camera dx (with a given overlap).

Since in this case the same part of the area is not scanned, the distance can be measured based only on the total area *S* of the water area. Thus, the total length of the route traveled by the vehicle will be:

$$L = \frac{S}{dx}. \quad (5)$$

To determine the total time of the survey, the AUV route must be divided into m parts, in which the device moves with equal speed. Thus, the dependency to determine the total cost of time T will be:

$$T = \sum_{j=0}^{m} \frac{v_j}{l_j}, \quad (6)$$

where l_j – the length of the path for constant speed; v_j – speed on a given part of the path.

Let's analyze the AUV-RB effectiveness for the seaports of Ukraine [17], given the following characteristics:

– AUV-RB speed – 1 m/s;

– water transparency – 1 m (d);

– angle of capture of a video camera 60° (α);

– battery life 3 hours;

– review of the mooring walls will be carried out by the method of longitudinal vertical tacks, and monitoring of the water area by the method of concentric grid;

– overlap zone of the camera, 0.3 m (Δ).

Based on these characteristics, the width of the video capture will be:

$$dx = 2\frac{d}{tg(\alpha)} - \Delta = 2\frac{1}{tg(60)} - 0,3 = 0,85 \text{ m}. \quad (7)$$

Thus, the previous analysis of the AUV-RB, which is provided with video cameras for the technical maintenance of the mooring, is written to the **Table 1.**

Table 1
Efficiency of AUV-RB use of for inspection of the underwater part of the mooring structures of the seaports of Ukraine

No.	Port	Total mooring length, m	Average mooring depth, m	Total inspection time, h	Number of AUV operation cycles
1	Bilhorod-Dniester sea trade port	1275	5.5	2.7	1
2	Berdiansk commercial sea port	1511	7.9	4.4	2
3	Dnipro-Buh sea port	810	9.4	2.8	1
4	Sea commercial port "Chornomorsk"	962	13.5	4.6	2
5	Mariupol sea trade port	3693	9.3	12.3	5
6	Mykolaiv sea port	2940	10.3	10.8	4
7	Odesa commercial sea port	6664	9.65	22.9	8
8	Ochakiv sea port	726	4.1	1.2	1
9	Skadovsky sea port	792	5.5	1.7	1
10	Kherson commercial sea port	1262	6.2	3	1
11	"Yuzhne" sea trade port	2196	14	10.7	4

An overview of the seaports water area is proposed to be carried out using a concentric grid. Thus, the calculation will be conducted relative to the area of the water area. The monitoring of the water area will be carried out by means of hydroacoustics with the capture of the bottom area with the width of the capture dx=50 m and the overlap area Δ=10 m. The calculation results are given to the **Table 2.**

Table 2
Analysis of the effectiveness of the AUV-RB use in hydroacoustic examination of the bottom surface of the waters of the seaports of Ukraine

No.	Port	Total water area, m^2	Total inspection time, h	The path traveled by the vehicle,	Number of AUV operation cycles
1	Bilhorod-Dniester sea trade port	590400	4.1	14760	2
2	Berdiansk commercial sea port	414550	2.9	10363.8	1
3	Dnipro-Buh sea port	980000	6.9	24500	3
4	Mykolaiv sea port	693000	4.9	17325	2
5	Odesa commercial sea port	1410000	9.8	35250	4
6	Ochakiv sea port	122000	0.9	3050	1

As can be seen from the calculations, the AUV-RB use provides maximum performance of underwater missions, which is limited mainly by the speed of movement of the underwater vehicle in the survey mode.

A further increase in the efficiency of surveying these waters can be achieved by using several underwater vehicles simultaneously. This technology can be used in two ways:

– division of responsibility between several AUV-RBs, which will reduce the survey area for each device;

– use of several AUVA-RBs in master-slave mode, with overlapping visibility, which will increase the capture zone dx.

6. Discussions of research results

As a result of the analysis of the technical support of the monitoring projects in shallow water areas, the following disadvantages were identified, which reduce the effectiveness of such projects:

– when using stationary hydroacoustics and magnetometry systems – the impossibility of identifying the detected underwater objects and the inability to change their structure in space in the event of operational necessity;

– when using AUV – the inability to perform information exchange with the control center in real time, which reduces the effectiveness of the monitoring system in cases when it is necessary to respond promptly to a change in the underwater environment (for example, if unauthorized underwater penetration into the controlled area is detected;

– in the ROV application – the complexity and high cost of application, since for their effective use it is necessary to attract the appropriate carrier vessels and limit navigation in the controlled area.

It is proposed to combine the advantages of AUV (high performance of underwater operations) and the ROV (transmission of information about the underwater environment in real time and the possibility of operational manual control of complex underwater missions) by building a special AUV with a towed radio beacon.

The structure and composition of the basic equipment of the AUV with a beacon as the basis for the construction and field tests of a prototype of this type of underwater robotics is proposed.

A method is proposed for calculating the time spent on surveying the bottom surface and the underwater part of the mooring facilities of the ports of Ukraine at various trajectories of the AUV traffic from a radio beacon, which allows to effectively control time in projects of robotized monitoring of the underwater conditions of port and other shallow waters.

7. Conclusions

Coastal sea areas and water areas of inland waterways are shallow and are characterized by the intensification of their use in the conduct of industrial activities, the transport of passengers and cargo. Monitoring the underwater conditions of these areas ensures their safe operation.

Modern approaches to the management of shallow-water monitoring projects should be based on the widespread use of underwater robotics. This will provide a qualitative and timely determination of the technical condition of waterways and their navigation support, hydraulic structures and facilities of critical marine infrastructure.

The technical support of projects to monitor such water areas with traditional robotics – autonomous and tethered underwater vehicles – does not allow performing underwater work with high efficiency because of the impossibility of real-time control of autonomous vehicles missions in real time and the complexity and high cost of using tethered devices.

The paper proposes an alternative version of the robotic support of underwater monitoring projects in shallow water areas through the use of autonomous underwater vehicles with a radio beacon. They provide the ability to survey large areas of water, quality and comprehensive implementation of search and cartographic underwater missions, providing operators with information about the underwater situation in real time.

A technique is proposed for estimating the resources of the execution time of projects of a robotic sonar and video monitoring of shallow water areas at different trajectories of motion of an autonomous underwater vehicle-robot with a radio beacon. With the help of the developed methodology, time expenses for monitoring the main ports of Ukraine were calculated.

The disadvantages of the use of AUV with radio beacon should include minor restrictions on navigation in the studied areas associated with towing a beacon. This disadvantage can be further eliminated by equipping the AUV with a system of automatic deepening of a beacon when a floating device is detected on the surface, which is approaching.

The obtained results form the theoretical basis for the formation of technical specifications for the creation of modern robotic support projects for monitoring shallow waters.

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