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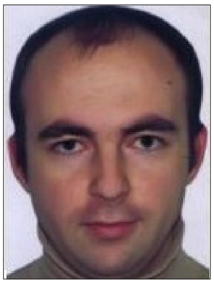

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EXPERIMENTAL STUDY OF GROUP CONTROL LAWS FOR AN AUTONOMOUS UNMANNED UNDERWATER VEHICLE AS A GROUP AGENT

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ЗАКОНІВ ГРУПОВОГО КЕРУВАННЯ АВТОНОМНИМ НЕНАСЕЛЕНИМ ПІДВОДНИМ АПАРАТОМ ЯК АГЕНТОМ ГРУПИ

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Abstract. Underwater works are effectively performed with the use of underwater vehicles. The use of groups of autonomous unmanned underwater vehicles for the monitoring of big volumes of underwater space is particularly effective. In this paper, modern approaches to group control of the motion of autonomous unmanned underwater vehicles are analyzed. The composition and configuration of the system of external environment sensors are proposed; the system allows an underwater vehicle to identify the presence of objects in close proximity and the direction of their motion. The structure of the automatic control system of a group of autonomous unmanned underwater vehicles in the mode of coordinated rectilinear motion is proposed. The system is based on the principle of subordinate control with the help of fuzzy logic controllers. The results of field trials of the system operation in the adhesion and cohesion modes of two underwater vehicles confirm the operability of the proposed approach.

Keywords: autonomous unmanned underwater vehicle; automatic control system; fuzzy controller; field trials.

Анотація. В даній роботі запропоновано структуру системи автоматичного керування групою автономних ненаселених підводних апаратів в режимі узгодженого прямолінійного руху. Запропоновану систему організовано з використанням принципу підпорядкованого керування на базі нечітких регуляторів. Результати натурних випробувань функціонування системи в режимах адгезії та когезії двох підводних апаратів підтверджують працездатність запропонованого підходу.

Ключові слова: автономний ненаселений підводних апарат; система автоматичного керування; нечіткий регулятор; натурні випробування.

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Problem statement. Joint performance of tasks by a group of autonomous unmanned underwater vehicles (AUUV) improves the efficiency of underwater operations, taking advantage of the parallel data capture and processing. Particularly effective is the application of the group control principle for AUUVs when solving complex problems, for example, in the process of rescue operations, in the search for sunken objects, search and inspection works, etc.

To ensure the effectiveness of the mission, a group of vehicles must have the property of self-organization, which would protect neighboring vehicles of the group from collision (adhesion mode) and prevent dispersion of the vehicles in the underwater environment (cohesion mode).

Synthesis of the control laws for the AUUV group is a complex problem, which is associated with the development and tuning of appropriate controllers. Computer modeling is an effective way of studying the operability and accuracy of control laws and systems both for single AUUVs and for those constituting a group.

In model tests under laboratory conditions, it is impossible to achieve complete hydrodynamic similarity between the model and the actual vehicle [11, 18], since the behavior of the vehicle is not controlled under water at the stage of synthesis and verification of the automatic control system (ACS). Therefore, full-scale tests (or field trials) are conducted for a final verification of calculation results and model experiments.

Setting of field experiments and processing of their results are very often difficult to implement, therefore, techniques and setups are being developed that allow research to be carried out under the conditions close to full-scale. An example of experimental setups is the work on creation of a simulation complex with the appearance of the first working-class underwater robots that tackle practical problems [5].

Besides, a full-scale field experiment intended to prove the operability of the ACS for the AUUV motion within the group entails substantial time and money expenditure. In addition, there is a risk of losing either one or a number of AUUVs participating in the experiment in the event of a non-routine or emergency situation. Therefore, it is expedient to carry out the field experiment using two mock-ups with the functions sufficient to provide for the mode of their coordinated movement. The results obtained during such an experiment can then be generalized for a group of vehicles of an arbitrary size, and the components of such a group can have different hardware and software configurations.

Latest research and publications analysis. The development of approaches to the design of AUUVs and automation of their control began in the 1960s. However, the AUUVs developed back then were intended for solving a number of specific problems. Currently, there is a wide range of issues on the topic of joint control of the motion of underwater vehicles, both from the theoretical and from the practical point of view [14].

The use of a group of interacting AUUVs was first considered in the 1980s. One of the first operations was the sea test of the GREX project. It involved a fleet of two AUUVs performing a simple coordination task based on acoustic communication between the vehicles [7] with a common architecture for the purpose of joint control of marine vehicles during modeling.

There were also considered theoretical and practical issues of developing promising systems for the control of motion of groups of autonomous marine vehicles with coordination of heterogeneous autonomous systems under uncertainty [16]. The main difficulty in the development of such systems is the unstable connection between the elements of the group due to the impact of noise and interference on the information exchange process. These features were taken into account in the project with the communication package GREX BOX, which can be integrated into any AUUV.

Paper [15] describes sea trials conducted during the development of a hydroacoustic communication system for the group control and navigation of the AUUVs and autonomous surface vehicles in an uncertain environment. The processes employed a fuzzy logic controller and a genetic algorithm [7]. An onboard sonar installed on the AUUVs provided detection and prevention of collision with obstacles [13]. It should be noted that the accuracy of determining the location of the AUUV using long-range sonar navigation systems significantly depends on the degree of correspondence between the measured and actual distances between the navigation objects [6].

In 2016, there was presented a method for collective control of a heterogeneous group of vehicles with a given motion trajectory. It took into account the speeds of the vehicles, special features of the information exchange channel, and the accuracy of the navigation component of the system [10]. The efficiency of the proposed approach was confirmed by the results of field trials.

Publication [11] proposes an ACS for the group of AUUVs which takes into account the limitations of communication in an underwater environment. The peculiarity of this system is the possibility of joint use of the computing resources of the group by all its vehicles.

The MORPH project offers the concept of an underwater robotic system created through integration of various mobile robotic modules with additional resources [9, 12]. Each node of the building blocks (a set of small and cheap robotic marine vehicles) of the MORPH is an AUUV is capable of performing particular tasks.

One of the main tasks of group control of a robot swarm is to provide a mode of coordinated movement of the vehicles along a specified path or route. It is important to keep the robots close to their group and avoid merging separate groups, that is, to maintain cohesion and segregation modes [17].

It is worth noting that scientific literary sources extensively cover the issues of automatic group control. This work deals with experimental study of the operability of the automatic control system for the AUUV as a group agent.

THE ARTICLE AIM is experimental verification of the correctness of operation of the ACS for the coordinated movement of AUUVs as group agents, in particular, implementation of adhesion and cohesion algorithms.

To achieve this aim, the following problems were formulated and solved:

– there has been developed a generalized diagram of the marine field experiment on the coordinated motion of two AUUVs along a common route. A remotely operated vehicle in the mode of flat subsurface motion was used as the AUUV under study (AUUV-1), while a radio-operated boat (ROB) was used as a neighboring underwater vehicle of the group (AUUV-2);

– there has been developed an automatic system for the control of the AUUV’s stabilized plane motion [18], which reacts to the AUUV-2 with the help of surface sensors installed on its mast and operates in the cohesion and adhesion modes.

Basic material. The ACS for AUUVs includes a module for simulation of the external navigation environment and a unit identifying navigation threats. The task of synthesis of the navigation environment simulation module as an element of the underwater vehicle’s control system is a relevant applied scientific task.

AUUVs are used in two basic modes: single navigation and group navigation. The task of modeling of the external navigational situation is relevant for both modes, but it is most difficult to solve for the case of group control, since the neighboring vehicles may create threats that are changing very rapidly and need to be detected and eliminated automatically in due time.

Let us assume that the vehicles are controlled only in the horizontal plane, and there is no vertical maneuver (or it is implemented in the case of emergency, when horizontal maneuvers are not sufficient for the safe movement of the AUUV, or when it is a forced movement to avoid collisions with neighboring vehicles).

Since the uncertainty in automation tasks usually increases with the increase in the functional hierarchical level, the possibilities of fuzzy logic approaches are also expanded. Fuzzy control at the base level can be attractive for the processes in which only qualitative knowledge is available and there are highly nonlinear properties.

It is necessary for each AUUV to maintain a safe distance from neighboring vehicles in a given range of distances. The minimum distance between them should not create the threat of an accidental collision (adhesion mode)ю Meanwhile, the maximum distance should guarantee the safety of the group and should not promote the movement of individual vehicles beyond the range of the sensors of other members of the group (cohesion mode) [1, 3].

Fig. 1 shows how the AUUVs making various moves will maneuver relative to the AUUV1. The AUUV2 is in the Danger Zone, so it moves away from the AUUV1 (adhesion mode). The AUUV3 and the AUUV5 are in the Attraction Zone and therefore must operate in the cohesion mode, that is, approach the AUUV1. The AUUV4 is in the Track Zone and therefore must move along the same route as the AUUV1. If the AUUV1 is beyond the range of the distance sensors installed in the AUUVs, it must move along a predetermined course.

The distance between two AUUVs is identified by means of external environment sensors (EES); it is proposed to use ultrasonic range finders for this purpose. The operating principle of the ultrasonic sensors is based on measuring the time of passage of direct and reflected waves.

One of the main characteristics of such sensors is the direction pattern, a graphic representation of the area within which the object can be detected by the sensor. Using an experimental setup (Fig. 2), the direction patterns were constructed for four ultrasonic range finders (model MB1003-EZ0 produced by MaxBotix).

The direction pattern is constructed according to the scheme shown in Fig. 3.

The AUUV model is installed at the h distance from the sensor in such a way that its diametric plane is perpendicular to the straight line drawn through the center of the sensor and the center of the AUUV buoyancy. Afterwards, the vehicle is shifted along the longitudinal axis to the left until the sensor readings change abruptly = to the value corresponding to the maximum distance. The l_- distance is then measured between the initial and current locations of the AUUV; the latter is shifted towards the initial location until the sensor readings are same as in the beginning.

In the same way, the l_+ distance is measured with the vehicle being shifted to the right. The measurement

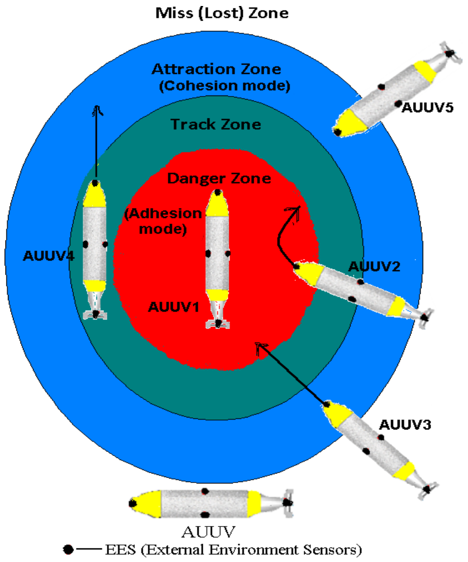


Fig. 1. Operation of a group of vehicles in the adhesion and cohesion modes

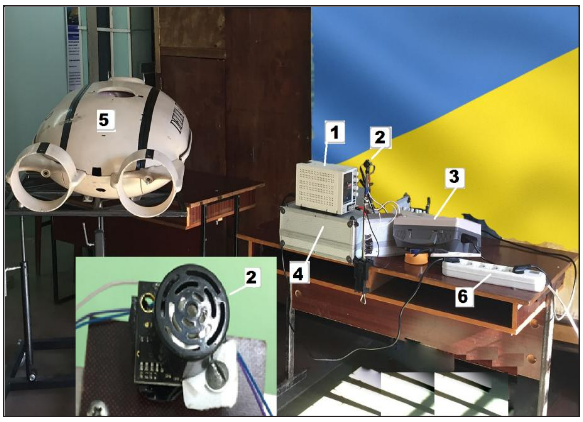


Fig. 2. Exterior of the setup for the construction of the direction pattern of ultrasonic range finders: *1* — power supply; *2* — ultrasonic range finder; *3* — oscilloscope; *4* — auxiliary equipment; *5* — AUUV mockup; *6* — extension cord

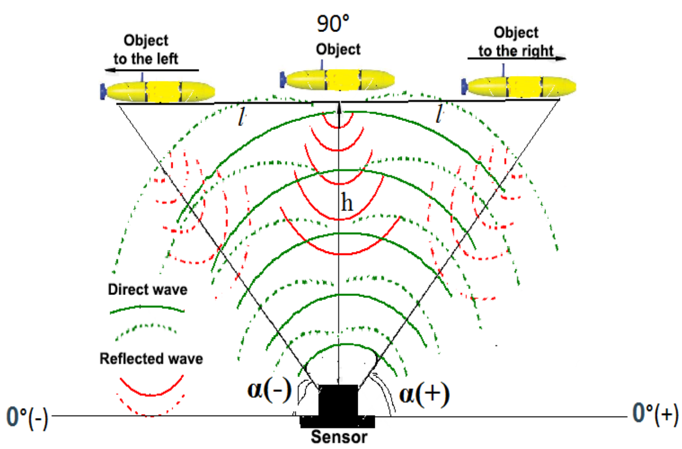


Fig. 3. Scheme of the experiment for the construction of the direction pattern of an ultrasonic range finder

is repeated for the range h = [1.0; 3.0] m with the increment of 0.5 m. For the distances obtained, the maximum angles of the target deviation from the center of the sensor are calculated:

$$\alpha_{\pm} = \arctan(l_{\pm}/h).$$

The experiment results are presented in Table 1.

Table 1. Results of the experiment on direction pattern of sensors

h, m	Sensor no.							
	1		2		3		4	
	l_-, m	l_+, m	l_-, m	l_+, m	l_-, m	l_+, m	l_-, m	l_+, m
3	–0.48	0.57	–0.56	0.59	–0.55	0.64	–0.56	0.56
2.5	–0.57	0.57	–0.55	0.63	–0.52	0.61	–0.66	0.77
2	–0.51	0.55	–0.57	0.67	–0.69	0.63	–0.84	0.58
1.5	–0.81	0.80	–0.65	0.75	–1	0.71	–0.76	0.98
1	–0.96	1.01	–0.93	1.07	–1.1	0.91	–1.08	0.93

In the automatic control problems, the integration of readings from several sensors enhances the quality of control processes in transient and steady-state conditions (as compared to feedback control of one sensor). If several identical sensors are used, combining the observations will improve the estimation of the position and speed of the target. The statistical advantage is achieved by adding *N* independent observations (for example, estimation of the target's location or speed is improved proportional to $N^{1/2}$), provided that the data are combined in an optimal way. The same result can be obtained by combining *N* observations from a single sensor.

The direction patterns obtained from the data of Table 1 were combined in such a way as to achieve the maximum possible diagram width without substantially reducing the maximum object recognition distance (Fig. 4). For the sensors under consideration, this effect can be achieved by arranging them so that the straight lines passing through their centers are at an angle of no more than 10° to each other. In this case, the direction pattern width made up 2.5...3 m in the near zone (h = 0.3...2 m) and 4 m in the far zone (h = 2...3 m).

The field trials of the ACS for AUUVs are performed to check the operability of cohesion and adhesion modes. The scheme of the field trials on coordinated movement of two AUUVs is presented in Fig. 5.

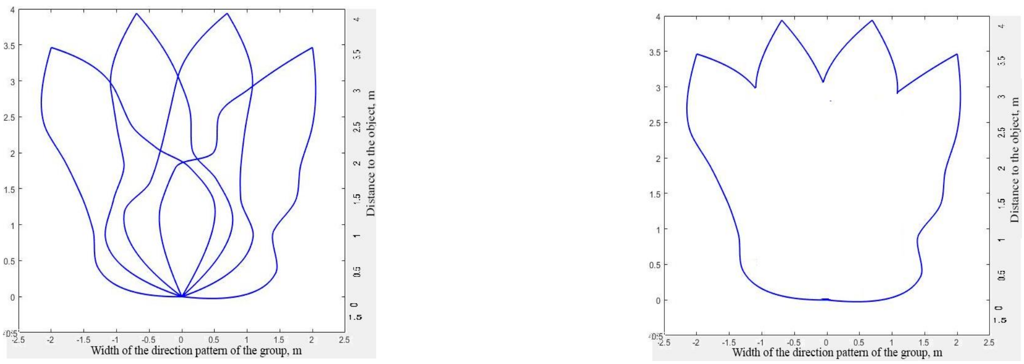
A remotely operated unmanned underwater vehicle controlled via the software of the power and control post (PCP) is employed as the AUUV-1. This solution allows recording and analyzing the experimental data in real time. The AUUV-1 is connected to the PCP with the help of a communication cable. The impact of the cable on the controlled movement of the AUUV is nondeterministic; it can significantly affect the quality of control processes. Therefore, the process of cable removal/collection is automated using a cable winch (CW).

The AUUV-1 is driven by a propulsion and steering unit based on AC motors; their control signals are generated by the ACS for the AUUV-1 movement. This system (see Fig. 5) employs the external environment sensors (Fig. 6) and the navigation system sensors (NSS) as feedback links. They provide data on the spatial orientation of the AUUV-1.

A radio-operated boat (ROB) is used as the AUUV-2; the operator controls it manually with the use of the control panel (ROB CP). The ROB PSU provides the rectilinear motion and flat circulation modes, which is sufficient for the field trials of the ACS for the AUUV-1.

The field trials consist of a series of experiments, each making it possible to test the operability of a particular mode of the ACS for the AUUV-1 under various environmental conditions (position, speed and spatial orientation of the AUUV-2, perturbations caused by water waves and the AUUV-1 cable, etc.).

The block diagram of the generalized algorithm of the experiment is given in Fig. 7.



a) *b)*

Fig. 4. Direction pattern of four range finders: *a* — arrangement of sensors; *b* — total direction pattern

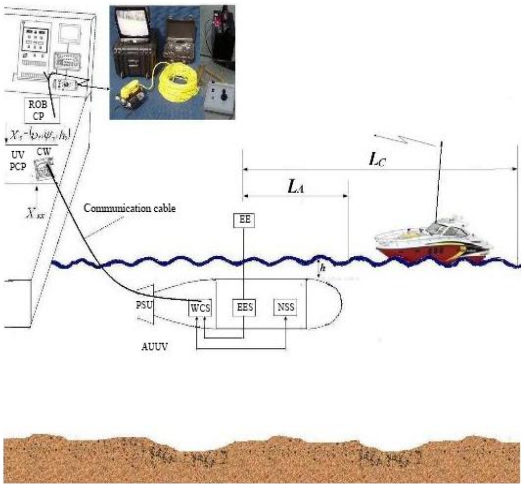


Fig. 5. Scheme of the field trial on coordinated movement of two AUUVs

Fig. 6. Exterior of the EES system and its arrangement on the AUUV-1

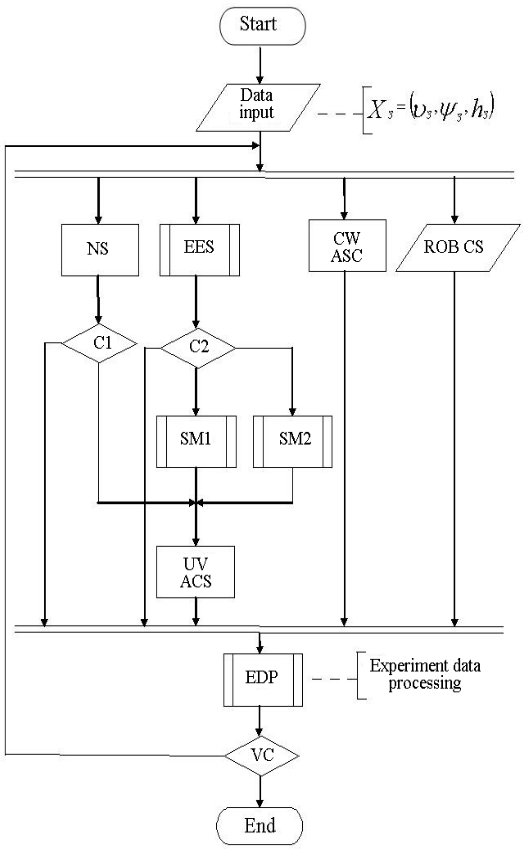


Fig. 7. Experiment algorithm

The experiment begins with the operator entering the desired speed of rectilinear motion of the AUUV-1, the course and depth of its immersion. Then four processes take place simultaneously. If no objects are detected within the range of the AUUV-1 EES (condition C1), the vehicle moves rectilinearly, maintaining the motion parameters specified by the operator.

If there is a foreign object within the range of the EES, the ACS for the AUUV-1 performs one of the following actions (condition C2):

– if the object is detected in the Track Zone, the AUUV-1 will resume its rectilinear movement along the specified course;

– if the object is detected in the Danger Zone, the ACS for the AUUV-1 will implement the adhesion mode (the set of rules SM1), that is, the control actions generated by the ACS will be aimed at increasing the distance to the object;

– if the object is detected in the Attraction Zone, the vehicle's ACS will function in the cohesion mode (the set of rules SM2), that is, the control actions generated by the ACS will be aimed at reducing the distance to the object.

The ACS of the CW minimizes external disturbances generated by the communication cable through controlling the process of cable removal/collection during the movement of the AUUV-1. In addition, during the experiment, the AUUV-2 operator controls the movement of the ROB with the help of a special CP.

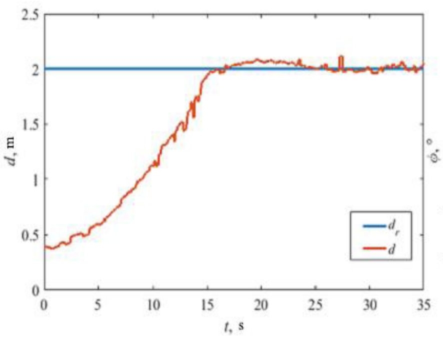
At the end of the experiment, the experimental data are processed (the function EDP). The described processes are repeated cyclically until the quality indicators of the control processes achieve the desired values.

Field trials of the ACS for the coordinated movement of AUUVs were carried out in accordance with the "Program and Methods of Marine Research Tests of the ACS for AUUVs" and GOST 24.026-80 in the marine laboratory "Delta" of the NUOS, which is located on board of the research vessel "Delta". The trials took place in the Bug Estuary (Mykolaiv, Ukraine) in 2017 (Fig. 8).

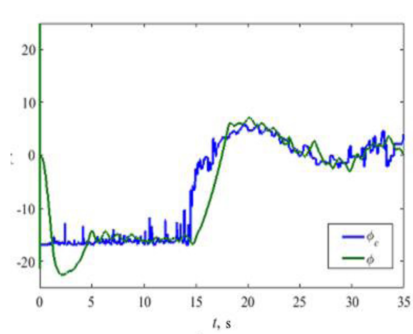
Experimental study of the distance controller should be started with the testing of the adhesion mode. Before the beginning of the experiment, the AUUV was withdrawn to the distance of 0.5 m from the neighboring vehicle; the board with the EES was located parallel to the neighboring vehicle. The graphs showing the transient process are provided in Fig. 9.

At the amplitude of the input step being equal to 1.5 m, the transient process has an aperiodic character with the overshoot of 6.7%. The transient process lasts for 25 s. The AUUV follows a specified course but for the end of the transient (time interval of 1...20 s). In this case, the PSU of the vehicle cannot develop the specified rate of the course change, which leads to the overshoot.

Fig. 8. Mutual arrangement of the AUUV-1 and the AUUV-2 during the experiment testing the operability of the adhesion mode



a)



b)

Fig. 9. Graphs of the transient process in the adhesion mode: *a* — distance; *b* — control action

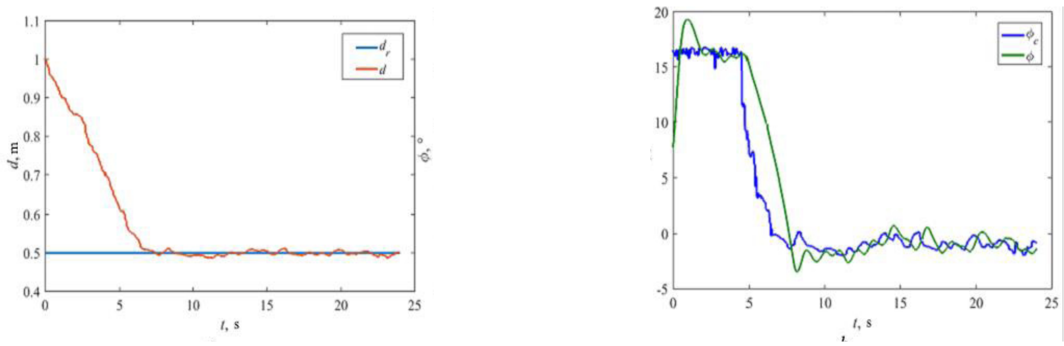
Next, let us study the operability of the ACS of the AUUV in the cohesion mode. The graphs of the transient process are shown in Fig. 10.

The transition process also has an aperiodic character. The overshoot is 2%, and the duration of the transient process is 10 s.

Next, let us confirm the operability of the ACS of the AUUV when its body is exposed to external disturbances. The graphs of transient processes for this mode are given in Fig. 11. At the beginning of the experiment, the device was withdrawn to the distance of 1.5 m from the board of the neighboring vehicle. At the end of the transient process, a disturbing action with the amplitude of 0.8 m was generated by removing the AUUV-2 away from the AUUV-1. The effect of this action was eliminated in 15 seconds after the end of its application.

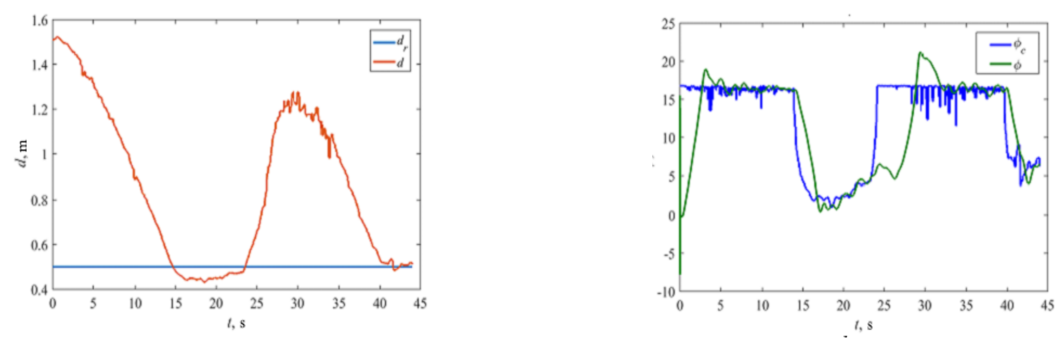
Let us study the dynamic properties of the ACS for the AUUV by setting the control signal which varies according to the sinusoidal law (Fig. 12). The control signal has the following parameters: displacement of 1.5 m, amplitude of 0.5 m, frequency of 0.2 rad/s. The transient process is completed 5 s after the start of the experiment.

The vehicle follows a sinusoidal trajectory with a two-second delay relative to the control signal. Based on



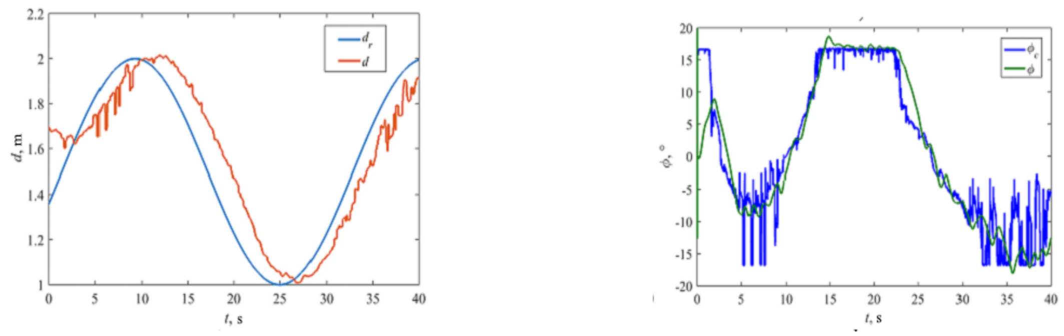
a) *b)*

Fig. 10. Graphs of the transient processes in the cohesion mode: *a* — distance; *b* — control action



a) *b)*

Fig. 11. Graphs of the transient processes under the impact of external disturbances: *a* — distance; *b* — control action



a) *b)*

Fig. 12. Graphs of the transient processes at the harmonic control signal: *a* — distance; *b* — control action

the results of the field trials (see Fig. 11–12), we can conclude that the proposed approach is acceptable for the application of group control laws to the AUUV movement. Improvements in the quality of control processes can be achieved by employing a more advanced component base (distance sensors, navigation system) and optimizing the parameters of the course controller as a component of the ACS for the coordinated movement of AUUVs.

CONCLUSIONS. 1. There has been proposed a block diagram of the automatic control system for the motion of an autonomous unmanned underwater vehicle as a group agent. The automatic control system provides stabilization of the speed of the rectilinear motion of the vehicle, the course and depth of its immersion, and implements the adhesion and cohesion algorithms to ensure the coordinated movement of two underwater vehicles.

2. An algorithm has been developed and field trials were conducted for the automatic control system for the coordinated movement of two autonomous unmanned underwater vehicles. The overshoot occurring in the transient modes does not exceed 7 %, which is within the engineering error. There is no static error. Such results allow concluding that the proposed system is operable and effective.

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