SELECTION OF COMMUNICATION CHANNELS UNDER CONTROL BY MIXED GROUPS OF ROBOTIC COMPLEXES

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Abstract. The paper considers the choice of methods and control channels by robotic complexes of sea basing as a link of uniform management information space of various physical media. The reconfiguration of radio lines of different wave bands ensuring steady transportation of management teams to robotic complexes in both surface and underwater state is suggested. Possibilities of channels of space, optical (laser) and hydroacoustic communication are analysed alongside with comparative assessment of channels of decameter radio communication and superlong waves on communicating information to the robotic complex, being on global removal from the control centre. Possible methods of information exchange between submersibles are considered and an assessment of the maximum range at data exchange between the deep-sunk objects on the hydroacoustic channel is given. The arising difficulties in justification of distributed control systems by the mixed groups of robotic complexes, the ensuring necessary stability of control channels including impossibility and interaction in group on the boundaries of physical media, as well as small ranges to ensure hydroacoustic communication are revealed. Calculations of a rational number of robotic complexes operating in group are given. The conclusion is drawn that the essential increase in efficiency of actions of the mixed robotic group is reached along with the complex use of diverse control channels when finding robotic complexes in various environments, applying methods based on modern technologies of programmable radio with elements of cognitive radio systems, artificial intelligence when handling the accepted information during intensive information interaction on the basis of general databases of the distributed systems.

1. Introduction

A significant technological progress in the field of new superstrength materials, small-sized energy-intensive power sources, neurocomputers, basic elements of artificial intelligence currently provides for the creation of broad spectrum autonomous robotic complexes (RC) [1]. Besides, the tasks that the RC is supposed to accomplish are becoming ever more complicated each year. If at the rise of robotics the RC was mainly focused on the solution of a specific objective (operation) in an office, a workshop, a transport in close proximity to the operator, today the RC shall solve a variety of distributed missions at global distance from a controlled element. The relevance of the assigned missions often requires the designer to ensure universality of the RC functioning in various environments (inland, in air, under water and in space),
which is the most difficult task, or to develop a mixed robotic group interacting in a uniform information control space (field) (UICS) that is today quite achievable following the principles of the network-centric control [2].

Purpose: to choose and reconfigure the control channels of mixed robotic groups thus ensuring the increase in the range of interaction within a group in various operational environments.

2. Maritime RC as a SICS link of all physical media
The analysis of available reference sources in this subject domain shows that against the background of rapid development of unmanned spacecrafts (USC), unmanned aircraft vehicles (UAV) and unmanned ground vehicles and robots the application of the sea-based RC (SB RC) is the least studied [1-4]. At the same time the mixed robotic groups may be applied in the sea to show the situation in all environments (under water, above water, in air, in space and onshore) within a uniform information control field. But marine environment is characterized by variable parameters, which are yet not well studied and prevent the steady data exchange both at great depths and on the intersection of two environments [5].

The expansion of territorial zones and complication of tasks solved by the RC for the benefit of various industries posed the need to develop autonomous intellectual control systems of SB RC [6-8]. Thus, the work [7] presents the modeling results and experimental test of a network-centric control method of artificial intelligence in relation to the RC. This method made it possible for an autonomous device to bypass obstacles with subsequent return to the target route.

3. Efficiency improvement of the mission within the RC group
Further efficiency improvement of the SB RC may be reached due to their group use and interaction within a mixed group (in various operational environments: underwater, surface, air, space). For example, this will allow reducing time in case of rescue operations or search for sunk objects constituting chemical or radioactive danger to the environment, and in case of protection of extended perimeter of water boundary or search of a moving underwater object the application of the SB RC group becomes fully justified [6-9].

During single and group missions of the SB RC irrespective of rigid or intellectual operational program there is a need to ensure stable interaction of a complex with a base control station (BCS). During a group mission it is advisable to ensure inherent reliability of data exchange between the RC group. The lost opportunity to control the SB RC with UCP or failure to exchange information within the RC group, especially when performing special tasks, can at least lead to the loss of the RC and as a maximum to unpredictable effects.

Alongside with the comprehensive use of diverse control channels provided the RC is placed in various environments, a considerable increase in performance efficiency of this mixed robotic group is achieved through the application of CRS- and SDR-based methods with elements of artificial intelligence and neurobionics when the accepted information is processed during intensive information interaction on the basis of general databases and knowledge on distributed systems.

4. Reconfiguration of RC control channels in surface condition
At present, the interaction with the RC in surface conditions is generally ensured through the use of a satellite communication system, Wi-Fi and hydroacoustic communication, while within the RC it is ensured via the hydroacoustic channel (HAC). However, the task of ensuring a steady data exchange with the RC globally remote from the UCP is not yet fully solved [3]. Let us consider possible methods to increase probabilistic and time characteristics of information exchange with the SB RC in surface condition. This mode refers to autonomously controlled ships (boats) and to the RC in surface condition.

Satellite communication channel. In this case the data exchange satellite channel shall be considered the main type of communication. Currently, the Gonets-D1M multipurpose system of personal satellite communication (MSPSC) is being developed and deployed within the Federal Space Program of the Russian Federation up to 2015. The analysis of the main technical parameters of the user station of this system [10], particularly small weight-size parameters of Gonets-D1M MSPSC and low energy consumption, as well as its communications capabilities with subscribers located at global distances from UCP, makes it possible to draw a conclusion on its applicability as a part of the RC based on coast-sea-
coast radio lines (RL). Besides, in the conditions of severe sea disturbance (antenna washing-down) when the RC is under ice, as well as failure of elements within the satellite communication route, the efficiency of its application seems quite problematic.

Radio communication channels of decameter and superlong waves. Considering the possibility of the RC global movement (in 2009 the US experimental glider crossed the Atlantic Ocean in 7.5 months totally covering 11.7 thousand km [7]) it is advisable to use RL of decameter (DCM) and superlong waves (SLW) as a back-up communication, which ensures the possibility to communicate the information to the most distant sea and ocean zones. At the same time, besides parameters of antenna-feeder subsystems (AFSS) of a transmitter (and a receiver) and efficiency of signal-code sequence of transferred messages when choosing the RL it is necessary to consider both characteristics of WP environment and the impact of the atmospheric, as well as natural and artificial noises.

Fig. 1 shows the area graphically reflecting the external noise coefficients $F_a$ for SLW-DCM frequency band with the probability of $P>0.99$. Thus, the root mean square value of the noise field strength in decibels (in relation to $\mu$V/m) is defined by the expression [11]:

$$E_{\eta} = F_a + 20 \log f_o + 10 \log \Delta f_c - 95.5$$  \hspace{1cm} (1)

where $F_a = 10 \log \left( \frac{P_{\mu}^a}{\mu T_o} \right)$; $P_{\mu}^a$ – atmospheric noise power within a signal band (Watt); $\Delta f_c$ – band width of the accepted signal (Hz); $f_c$ – carrier signal frequency (MHz); $k$ – Boltzmann constant; $T_o$ – reference temperature ($290^\circ$ K).

Fig. 2 shows the dependence diagrams of the $E_{\eta}$ level for various $\Delta f_c$ and $f_c$ values calculated using formula (1) for the upper boundary of the external noise coefficient $F_a$ (see Fig. 1, dotted line).

The analysis of diagrams presented in Fig. 2 and the formula (1) confirms that to increase the reliability of communication under the natural noise there is a need to increase the message transmission power or to reduce the band of the emitted signal.

![Figure 1. External noise factors [11]](image-url)
Figure 2. Dependence of the noise field strength on the frequency reception band

The values of the required radiation power to ensure smooth reception along radio routes up to 1 thousand km long for the nearest sea zone may be assessed using diagrams presented in [12]. Fig. 3 shows the diagrams of field intensity for several frequency nominal values within SLW-DCM of a wave band characterizing a near sea zone (shaded areas correspond to the atmospheric noise field intensity levels expected with a probability of $P > 0.99$). Fig. 4 shows similar diagrams for routes more than 1 thousand km long (ionospheric wave propagation – WP).

Figure 3. Signal field intensity for a near sea zone
For the DCM range the calculation was carried out using semi-empirical Nevolin and Shchepotin’s formula received on the basis of the average median value of field intensity for sea routes at optimal frequencies [13]:

\[ E = \frac{122}{r_t} \sqrt{\frac{PD}{0.0021 \sin \theta}} \exp \left( -\frac{3.8 \cdot 10^{-2}}{\lambda^{0.2}} r_t \right) \]  \hspace{1cm} (2)

where \( P \) – signal radiation power (kW); \( D \) – antenna gain power; \( r_t \) – route range (th.km.); \( \theta \) – angular distance between receiving and transmitting points; \( \lambda \) – length of the radiated wave (m).

The frequency of SLW range was calculated following the modified Austin’s formula [12, 14]:

\[ E = 120 \sqrt{\frac{PD}{r_t \sin \theta \sin \theta}} \exp \left( -0.0457 f^{0.6} r_t \right) \]  \hspace{1cm} (3)

where \( f \) – signal radiation frequency in kHz.

It should be noted that the necessary radiation power of the required field intensity \( E_{tr} \) may be determined from the correlation \( P_{n=(E_d/E)^2} \), kW, where the \( E \) value corresponding to the specified path length is taken from diagrams shown in Fig. 3 (4) or is defined by formulas 2 (3) provided \( D=1 \) and \( R=1 \) kW.

The red dotted line in diagram on Fig. 4 represents the maximum expected value of atmospheric noise field intensity corresponding to \( \Delta f_c \approx 15 \) kHz \( \left( f_c = 10 \text{ MHz} \right) \), and dash-dotted black line – the minimum expected \( E_{tr} \) at the same values of \( \Delta f_c \) and \( f_c \).

The analysis of a diagram shows that high transmission rate may be achieved without random (deliberate) noises within the DCM range even on radio paths with global length. Thus, for the route \( r \approx 6 \) thousand km and the signal radiation power \( R_s \approx 1 \) kW, proceeding from the correlation [15], where \( V \) – transmission rate, \( N_o \) – spectral noise density:
\[ V = \log_2 \left( 1 + \frac{P_c}{\Delta f N_0} \right)^{\Delta f} \]  

(4)

Let us get the following path of possible transmission rates for the considered case: \( V_{\text{min/max}} \approx 10 \text{÷} 150 \text{ kbps} \) thus correcting the program of the RC mission in real time.

The efficiency of the RC control via the SLW channel is significantly lower. For example, even at the minimum expected static level (Fig. 4, black dotted line) the transmission rate for a reliable dissemination of instructions to the RC for \( r \approx 6 \text{ thousand km} \) and \( P_c \approx 10 \text{ kW} \) will make approximately \( V \approx 80 \text{÷} 90 \text{ bps} \). The analysis presented in [16] as well as the given formulas and diagrams show that the reliable communication of information to remote RC within the SLW range at the transmission rate of up to 10 bps (\( \Delta f_c \approx 10 \text{ Hz} \)) is only possible at \( P_c \geq 100 \text{ kW} \), and within the DCM even at \( V \approx 300 \text{÷} 500 \text{ bps} \) \( P_c > 500 \text{ W} \) will be required.

Thus, the DCM RL ensure the possibility of communicating the information to the remote RC at smaller radiation power than in case with the SLW radio lines thus ensuring higher transmission rate. However, the advantage of SLW RL is the relative stability of WP at ionospheric disturbance as well as significantly smaller propagation ratio at distribution in water environment, which makes it possible to receive the information in case of antenna washing-down, as well as in subglacial and underwater conditions (up to 15÷20 m) when plane ferrite active antennas are used. Hence, it is advisable to use data transmission along SLW and DCM radio lines as an alternate communication, especially in case of incomplete information on the RC coordinates and its technical condition.

5. Methods of information communication to deep-sunk objects

When the SB RC is underwater at a depth of more than 15-20 m there is no communication with it without a trailing antenna array or a repeater buoy even along SLW radio channel as was shown above. At the same time, the installation of such devices on the SB RC is problematic.

In order to solve the task of communicating the information to deep-sunk objects the experts suggest using different communication types and methods, including optical, hydroacoustic, parametrical, electromagnetic communication, as well as shadow methods of receiving hydroacoustic waves.

**Optical (laser) communication channels.** Optical band waves (blue-green range) have much smaller attenuation coefficient in water environment than SLW path radio waves, which allows using the laser communication (LC) in this interaction spectrum with underwater objects in case of using the USC group or UAVs repeaters, including the use of shadow devices [17, 18]. However, at present the use of the LC with globally moving RC is not technically and economically sufficient. This is explained by comparatively big dimensions of the optical receiver input module and the need for accurate alignment of its directional pattern (DP) towards the laser source. At the same time, autonomous small-sized navigation units aimed to determine the RC coordinates in course of its underwater movement do not provide for the reasonable positioning accuracy during a long-term mission, thus the submersible shall periodically determine the actual coordinates by emerging and interacting with the GLONASS (GPS) system.

It is obvious that in this case the data exchange with the base station may be organized through the main (satellite) channel without the optical communication channel. Besides, for the reliable LC using USC (UAV repeaters) when communicating the information to submersible RC there is a need to fulfill some conditions, such as low water turbidity, high transparency of ice, lack of extreme weather conditions (snowfall, dense fog, heavy rain), which is in fact impossible during a long-term RC mission.

**Hydroacoustic communication channels.** Data exchange with deep-sunk (up to 100 m and more) devices during their removal from surface (underwater) stationing site at a distance of up to 10 km is mainly ensured through hydroacoustic communication (HAC). Depending on salinity, water temperature and hydrology the hydroacoustic wave attenuation coefficient \( \alpha \) makes up to 10 dB/km and more for acoustic frequency in the range of \( f_z \approx 10 \text{÷} 50 \text{ kHz} \) (typical for HAC). Therefore, due to the limited power of hydroacoustic RC radiators when arranging the underwater HAC at considerable
distance from the UCP besides an optimal signal-code sequence of transmitted data it is necessary to ensure high sensitivity of the sonic signal sensor.

It should be noted that modern and advanced SB RC projects employ the HAC subsystem, which is embedded into the integrated control system (ICS) of a submersible to ensure its interaction with other submersibles (repeater buoys). This is caused by an extensive introduction of a digital signal processing technology, which made it possible to make hydroacoustic modems ensuring proper functioning on multipath distribution of acoustic signal and on exposure to external radiators.

Hydroacoustic receiving and transmitting antennas are supported by the system of digital synthesis of adaptive DP, and when the signal-code sequence of the transmitted message is formed the broadband signals and noise combating codes are thus used. This provides for a real-time high transmission rate and the required probability of communicating the information at considerable distances between objects interacting under water [19]. The size and weight of hydroacoustic modems of the previous generation (analog) is 2÷4 times bigger at the same radiation power at set distances of up to 1.5÷2 km and transmission rates of 200÷400 bps.

6. Mission control of a mixed RC at global distances

When assessing the probability of a mission requiring global RC removal from the basing site (i.e. a multi-day underwater cruise) it is necessary to consider the possible degradation of the RC basic elements, which is incompatible with successful completion of a mission, caused by reliability parameters of the RC elements, its accidental damage including due to collision with large objects or representatives of the sea fauna, icebergs, fishing nets, etc., not excepting intentional damage or destruction. Thus, the probability of a mission \( P_{\text{pm}} \) will decrease depending on the number of emersions for relocation and communication sessions with UCP. Hence, it may be concluded that there is a need for artificial intelligence embedded into the RC integrated control system thus ensuring the optimal movement route and its adjustment in case of unplanned (casual) obstacles or threats. Nevertheless, the specified factors confirm that when performing a single mission, especially confidential one, the \( P_{\text{pm}} \) may be unacceptably low. At the same time, when the RC is used as part of a group to achieve the required \( P_{\text{pm}} \) value it is sufficient to use the \( N \) number of devices defined from the inequality:

\[
N \geq \frac{\log\left(1 - P_{\text{pm}}\right)}{\log(1-P_1)},
\]

where \( P_1 \) – probability of a mission by one RC. In other words, even at approximately \( P_1 \approx 0.9 \) not more than three-four RCs identically equipped and having identical target function lead to \( P_{\text{pm}} \geq 0.999 \). At the same time, two options of their movement within a specified remote region of the World Ocean are possible: option I – independent travelling along the route by each RC; option II – group mission with further intellectual interaction of the RC in course of joint transition to the preset area, including in other environments.

Some works [2, 3, 7, 15] suggest creating the network of underwater integrated communication (NUIC) with a composite radio-hydroacoustic channel towards the control center – an underwater object to ensure survivability of underwater objects (RC, gliders, etc.). Thus, the Shitl Research Institute of Hydrocommunication proposes the NUIC on the basis of several independent ground communication lines, each of which consists of intermediate access points and end hydroacoustic modems united by fiber-optic communication lines.

The interaction of a communication network with UCP is ensured via a radio channel through incorporated autonomous hydroacoustic repeater buoy. At the same time, it might be difficult to install such NUIC in remote areas due to safety and cost of its deployment, as well as limited range of interaction with the RC. One of the solutions to the RC mission regarding the monitoring of remote regions of the World Ocean may be the international network of small-sized repeater buoys. However, this task is unlikely to be solved in the near future due to economic and military-political reasons. Thus, it is advisable to assign the functions of data exchange with UCP to the RC.

Hence, in case of the RC group mission following the option I the total number of interactions with UCP (number of emersions) during the mission will make \( M_I = N \cdot k \), where \( k \) – number of the given communication sessions with the RC, and following the option II – \( M_{II} = k < M_I \), which in some cases may determine its use. According to one of the possible algorithms of the RC mission as a part of \( N \) identical
devices, the RC Leader (RC-L) ensuring coordination of other RC is assigned at the initial stage. In this context, the programs of the current group actions are stored in parallel in databases of each RC and are periodically updated through the HAC channel.

In the need to interact with UCP or to relocate the group, the RC-L realizes the ‘assignment’ by radio-hydro-repeater buoy of one RC from the group upon schedule or according to their key parameters. To hold the next communication session, another RC can be determined by a repeater according to some indicators (similarly, the RC-L may be automatically reassigned according to some indicators in the course of a mission).

Depending on tasks assigned to the RC group, the back surface relief, external threat, etc. the RC-L may also ‘make’ a decision to ensure the maximum removal from the device performing the function of a repeater buoy; at the same time the maximum removal from it to the RC-L will make $L_{\text{max}} = (n-1) l_{\text{max}}$, where $l_{\text{max}}$ – maximum transmission range realized along the HAC channel. This means that to obtain the maximum $L_{\text{max}}$ value at the preset $N$ a bigger indicator for $l_{\text{max}}$ is required.

The stated maximum hydroacoustic transmission range for modern modems makes up to 30 km [19]. However, currently the HAC subsystem substantially defining the success of special tasks performed by the RC is imposed greater requirements in terms of the most achievable $l_{\text{max}}$ values.

7. Assessment of maximum remoteness during data exchange between RC

As a rule, to assess the effective range of a hydroacoustic system in its various modes (echolocation, noise direction-finding, telemetry) the general equation is used, which, when applied to HAC, may be presented as [19, 20]

$$
\frac{p_n^2 d_1^2 D_1^2(\phi)D_2^2(\phi)}{R^2} \cdot 10^{-0.1\beta R} \cdot A_o = h^2 p_o^2 \left(f_{wp}, \Delta f_o\right)
$$

where $p_n\left(f_{wp}, \Delta f_o\right)$ – noise pressure in a working band; $\Delta f_o$; $p_o$ – pressure developed by a transmitting antenna with radiated power $P_{\text{rad}}$ at conditional distance $r_o$; $D_1(\phi)$ and $D_2(\phi)$ – directional characteristics of transmitting and receiving antennas respectively; $p_o$ – pressure created by the radiation source at distance $r_o$; $h^2$ – relation of signal energy to noise spectral density; $R$ – distance between a hydroacoustic transmitter and a receiver; $f_{wp}$ – working frequency of a transmitted signal; $\beta$ – spatial attenuation factor of acoustic waves in water; $A_o=10\log\Phi$ – propagation anomaly factor considering focusing ($\Phi<1$) and defocusing ($\Phi>1$) of an acoustic field.

In [20] it is shown that taking into account the frequency dependences of the sea noise level and signal attenuation for the transcendental equation (5) there is an optimum value of working frequency $f_o$, for which the maximum transmission range is ensured at fixed parameters of hydroacoustic path (transmitting and receiving sets). Thus, for plane-type antennas at spectral noise density of $G(f) \sim f^n$, where $n=1\div2$, the optimum frequency will make: $f_{\text{opt}} \approx nR^{2/3}10^3$ kHz, where $n'=1.9\div3$, i.e. for $R=50\div100$ km the optimum frequency will be in the range of $f_{\text{opt}} \approx 0.9\div2.2$ kHz. Close $f_{\text{opt}}$ values are also obtained when using the linear antennas, which overall dimensions will make more than $1.5\div3$ m thus creating considerable constructional difficulties and in some cases the complete rejection from such hydroacoustic antennas on small and mid-size RC.

The transition to higher radiation frequencies due to downsizing of antenna elements will make it possible to install phased adaptive arrays (PAA) on the RC thus ensuring noise suppression from unauthorized radiators (reducing $p_{\text{pus}}$) and $D_2(\phi)$ increase towards a desired signal thus realizing the possibility of the transmission range increase.

Under the assumption that noises from unauthorized radiators are absent (suppressed) let us calculate the minimum (dotted line in Fig. 5) and the maximum values (dash-dotted line in Fig. 5) of the sea noise.
Figure 5. Spectral characteristics of a sea noise

Considering the numerical range of a formula (5), let us use the formula below for visualization of the corresponding calculations in a graph form:

$$\Phi = \phi + \beta \Phi + \Delta$$

Fig. 6 shows the calculation of $\lg h$ values according to formula (6) depending on distance between UUV for source data: $D_1(\theta)=1$, $A_\Phi=1$, $\beta = 0.036^{3/2}$ dB/km, $\Delta_\beta = 1$ Hz, $P_{\text{max}}=100$ W, $r_o=1$ m. $\rho_f(f_\nu,\Delta_f)$ is calculated according to diagrams presented in Fig. 5 under the assumption of using a four-element adaptive PAA operating on the basis of a cylindrical-type hydroacoustic receiving antenna, which suppresses noises from unauthorized radiators and forms the maximum DP in the direction of a desired signal.

Figure 6. Dependence of $\lg h$ values on the interaction range between the RC in a group
The analysis of diagrams shows that at frequencies over 10 kHz the stable transmission at \( R > 100 \) km is quite problematic since even by transmitting the considered narrow-band signal with a band of \( \Delta \nu = 1 \) Hz and \( \nu_0 = 10 \) kHz, under purely natural sea noises the signal/noise correlation will fall within \( h \approx 0.06 \div 5 \), i.e. the incoherent reception within a hydroacoustic modem might lead to satisfactory probability of communicating the information only under the minimum sea noisiness (dash-dotted line in Fig. 6).

Depending on the mission, the fields of repeater buoys and bottom stations (Fig. 7) may be applied for further increase in the RC instantaneous radius.

**Figure 7.** Topology of buoy field placement in course of the RC mission:
a) centralized network topology (for offshore drilling platforms);
b) multispans network topology (for narrow sea passages and on extended objects);
c) distributed network topology (for ports, bays, harbors)

8. Conclusions

At present, there are no reasonable options to create distributed control systems for mixed RC groups, which components, being distributed onboard of USC (UAV), as well as on surface and underwater RC, ensure information exchange thus providing the necessary control level over all components of the mixed RC. This is caused by difficulties of ensuring stability of control channels and interactions with a robotic group on the boundaries of physical media, as well as small ranges in ensuring HAC.

Though the given calculations were conducted for favorable communication conditions under the assumption of the minimum noise level and noise suppression from unauthorized radiators, as well as without potential occurrence of the accepting RC to the shadow region (or considerable reduction) of hydroacoustic wave typical for near-surface, underwater and shallow acoustic channels [20], nevertheless, the study only shows basic ways of ensuring the interaction of RC removed from each other at distances over 50 km, especially the RC with artificial intelligence allowing considering the hydrology of the mission region.

Further increase in data exchange ranges during the interaction of deep-sunk RC at remote distances of 50÷100 km is achieved by the HAC subsystem due to the reduction of the transmission rate to 1 bps and less taking into account noise suppression from unauthorized radiators and the Doppler shift. In this case, the increase in transmission rate may be achieved through parallel hydroacoustic modems. The global ranges and distributed nature of dynamics within the mixed RC group missions may be achieved by using the satellite communication channels as the main ones. In case of incomplete information on the RC coordinates and its technical condition, it is advisable to use data transmission along SLW and DCM radio lines based on distributed radio systems as an alternate communication [16].

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References

[1] Bocharov L 2009 Unmanned Underwater Vehicles. Their Status and General Development Trends. *Electronics: Science, Technology, Business* 7(97) 62-69
[2] Budko P, Chikhachev A, Barinov M, Vinogradenko A 2013 Principles of the organization and planning of strongly connected telecommunication environment of forces of a special purpose. *T-Comm: telecommunications and transport* 7(6) 8-12

[3] Belousov I 2013 Modern and promising unmanned underwater vehicles of the US Navy. *Foreign military review* 5 79-88

[4] Ageev M D, ed. 2005 Autonomous underwater robots. Systems and technologies (Nauka Publ.)

[5] Stoptsov N A, Boytsov V I, Shelemin V N 1990 *Communication under water.* (Leningrad, Sudostroenie Publ.)

[6] Inzartsev A V, Pavin A M, Bagnitckii A V 2013 Actions planning and execution in the inspection underwater robot on the basis of behavioral methods. *Underwater Investigations and Robotics* 1(15) 4-16

[7] Psikhopov V Kh, Chernukhin Yu V, Fedotov A A, Guzik V F, Medvedev M Yu, Gurenko B V, P’yavchenko A O, Saprykin R V, Pereverzev V A, Priemko A A 2014 Development of intelligent control system for autonomous underwater vehicle. *Izvestiya SFedU. Engineering sciences* 3(152) 87-101

[8] Martyanova L A, Mashoshin A I, Pashkevich I V, Sokolov A I 2015 Control system is the most complicated part of autonomous unmanned underwater vehicles. *Marine Radio-electronics* 4(54) 27-33

[9] Bychkov I V, Kenzin M Yu, Maksimkin N N, Kiselev L V 2014 Evolutionary approach to group routing of autonomous underwater vehicles in dynamic multiobjective monitoring missions. *Underwater Investigations and Robotics* 2(18) 4-13

[10] Bakanov D V, Moroz N V, Pukhov G G et al. 2014 The use of the multifunctional system of personal satellite communications "Gonets-D1M" to provide information interaction between remote subscribers 3(142) 63-67

[11] Recommendation ITU-R P.372-11 (09/2013). 2014 *Radio noise. Series P: Propagation of radio waves.* (ITU Publ.)

[12] Dolukhanov M P 1972 *Propagation of radio waves.* (Moscow, Svyaz' Publ.)

[13] Nevolin T N, Shchepotin V I 1977 *Organization and planning of radio communications in the marine fleet.* (Moscow, Transport Publ.)

[14] Akulov V S, Salyuk D V, Ugrik L N 2014 Accounting for the accuracy of predicting electromagnetic fields in the calculation of radio engineering systems. *Communication technology* 3(142) 53-56

[15] Fink L M 1970 *The theory of transfer of discrete messages.* (Moscow, Sov.radio Publ.)

[16] Nikolashin Yu L, Miroshnikov V I, Budko P A, Zhukov G A 2015 Cognitive connection system and influence of monitoring data usage on noise immunity of ultra-narrow decameter. *Marine Radio-electronics* 2(52) 16-22

[17] Aleshin O V, Katanovich A A 2016 The principles of making a computer-aided (automated) system of the satellite open optical connection with submarines. *Marine Radio-electronics* 1(55) 32-35

[18] Yakovlev V A, Zhurenkov A G, Shul’zhenko P K, Musin L F, Frolov A P 2012 Optoacoustic aiming device for an underwater wireless optical communication system. *Journal of Optical Technologyog* 79(10) 678-679

[19] Vershinin A S 2015 Comparative analysis of hydroacoustic modems. *Young scientist* 12(92) 156-161

[20] Sverdlin G M 1990 *Applied hydroacoustics.* (Leningrad, Sudostroenie Publ.)