Research article
DOI: https://doi.org/10.18721/JCSTCS.16103
UDC 62.5

REQUIREMENTS FOR COMMUNICATION AND POSITIONING SYSTEMS FOR GROUP OPERATION OF AUTONOMOUS UNMANNED UNDERWATER VEHICLES

N.N. Semenov[1], V.G. Mikhlin[2], D.B. Akhmetov[3] ✉

[1,2] St. Petersburg State Marine Technical University, St. Petersburg, Russian Federation;

[3] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

✉ akhmetov@spbstu.ru

Abstract. When gathering a group of AUVs in a limited area, both the safety of their work and the possibility of participation are necessary. In a group, AUV should be out of the way of the other devices in the very least, but ideally should contribute to completion of the common task. This paper discusses issues related to the parameters of communication systems and positioning of AUVs working in a group to solve a single common task. The paper presents the numerical calculation results of the dependence of the AUV efficiency on the size of the subgroup. An assessment of the delays in data transmission and restructuring of the synchronization method in the group is also given, as well as the possibility to simplify group management in the case under study.

Keywords: robotics, underwater robotics, group application, AUV, communication systems, positioning

Citation: Semenov N.N., Mikhlin V.G., Akhmetov D.B. Requirements for communication and positioning systems for group operation of autonomous unmanned underwater vehicles. Computing, Telecommunications and Control, 2023, Vol. 16, No. 1, Pp. 35–45. DOI: 10.18721/JCSTCS.16103

Научная статья
DOI: https://doi.org/10.18721/JCSTCS.16103
УДК 62.5

ТРЕБОВАНИЯ К СИСТЕМАМ СВЯЗИ И ПОЗИЦИОНИРОВАНИЯ ДЛЯ ГРУППОВОЙ РАБОТЫ АВТОНОМНЫХ НЕОБИТАЕМЫХ ПОДВОДНЫХ АППАРАТОВ

Н.Н. Семенов[1], В.Г. Михлин[2], Д.Б. Ахметов[3] ✉

[1,2] Санкт-Петербургский морской технический университет, Санкт-Петербург, Российская Федерация;

[2] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация

✉ akhmetov@spbstu.ru

Аннотация. При использовании группы АНПА на ограниченной территории необходимо обеспечить как безопасность их работы, так и возможность взаимодействия. АНПА в группе не должны мешать работать другим аппаратам, их цель – помогать решению общей для всей группы задачи. В статье рассмотрены вопросы необходимых параметров систем связи и позиционирования АНПА, работающих в группе для решения единой для всей группы задачи. Показаны результаты численного моделирования зависимости эффективности группы АНПА от размера подгруппы. Также дана оценка влияния задержек передачи данных и перестроения на синхронизацию в группе и показан способ упрощения управления группой в данном случае.

Ключевые слова: робототехника, подводная робототехника, групповое применение, АНПА, системы связи, позиционирование

Для цитирования: Semenov N.N., Mikhlin V.G., Akhmetov D.B. Requirements for communication and positioning systems for group operation of autonomous unmanned underwater vehicles // Computing, Telecommunications and Control. 2023. Т. 16, № 1. С. 35–45. DOI: 10.18721/JCSTCS.16103

Introduction

Autonomous unmanned underwater vehicles (AUVs), "mobilis in mobili", move in a complex mobile environment, which is rather muddy, therefore the optical methods of observation and detection work only at short distances and do not pass radio waves. This complicates communication and positioning, while acoustic communication, though allows information transmission for long distances, is significantly limited by communication speed and range. These limitations are particularly severe when using groups of AUVs – information transmission between two AUVs becomes interference for other AUVs, preventing them from exchanging information. Therefore, communication and positioning issues for AUV group operation are still unsolved, being urgent and important.

Positioning

Satellite positioning systems used for land, surface and air navigation (GPS, GLONASS, Galileo, ...) cannot work under water, since water is a conductor and electromagnetic waves quickly attenuate. Even 10 cm of the water layer do not allow to use them [1].

Creating a global system of underwater acoustic navigation proves technically difficult, although the communication ranges may be sufficient for this, since the acoustic signal propagation is affected by the layered structure of the propagation medium (changes in the speed of sound in water depending on pressure, salinity and temperature) and reflection from boundaries (bottom and surface) [2]. Therefore, the construction of such systems is not even considered at present.

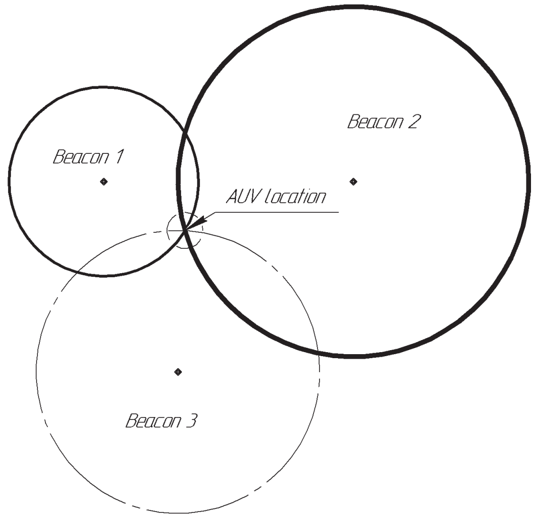

Fig. 1. Example of trilateration for three beacons

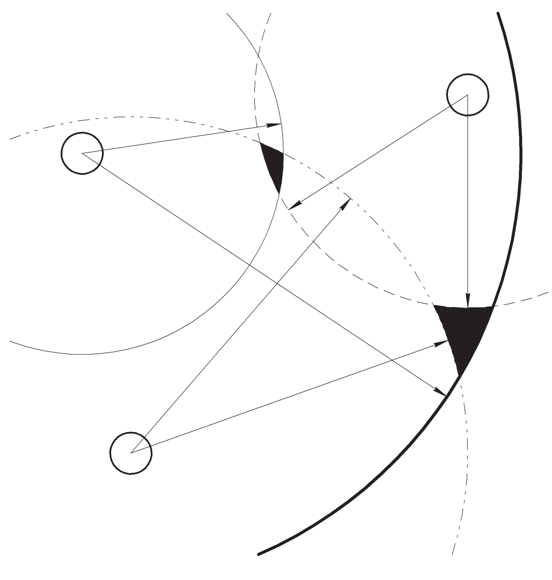

Fig. 2. Example of the beacon positioning errors structure

There are local positioning systems, which can be divided into three main directions: positioning with long base (LBL – Long Base Location), positioning with short base (SBL – Short Base Location) and positioning with ultra-short base (USBL – Ultra-Short Base Location) [3–6].

LBL is a system consisting of a set of hydroacoustic beacon responders located at the boundaries of the work area and moving AUVs. Upon request from the AUV, the beacons send a response signal with a known delay. The AUV calculates its own position by trilateration based on the response signal delays and knowledge of the exact position of the beacons, as shown in Fig. 1. The accuracy of positioning in such a system is determined by the accuracy of signal arrival delays, nonlinear signal propagation, position relative to the beacons, and the positioning inaccuracies of the beacons themselves, which may have an overhead part that receives GPS coordinates [7]. It is the most exact method for the whole area of works (accuracy of tens of centimeters when the distance from beacons is not more than 2000 m and when being inside the zone limited by beacons), but it is also the most time-consuming method for water area preparation – beacons must be placed and their coordinates adjusted beforehand. The structure of position-dependent coordinate errors is shown in Fig. 2, which shows that while the vehicle is inside the area bounded by beacons, the errors are symmetrical relative to the true position of the vehicle, and they can be reduced by repeated measurements. But when the vehicle leaves this area, the errors become asymmetrical, and the positioning accuracy drops dramatically.

The accuracy of the LBL, as seen in Fig. 2, is determined by the accuracy of distance, and as practice shows, due to the nonlinear propagation of acoustic signals is up to 5 % of the distance [8, 9]. Consequently, the further from the center of the area bounded by beacons, the greater the positioning error. Since the error is static, it cannot be removed by repeating measurements. If errors of defining distance E are expressed as vectors Δr_i, which direction coincides with the direction on the beacon, and the length is equal to the error standard deviation, the quantity of beacons N, the positioning error E can be expressed through product of these vectors:

$$E = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\overrightarrow{\Delta r_i}\,\overrightarrow{\Delta r_j}.$$

SBL is a system that has multiple hydroacoustic response beacons, located within the working area, and moving AUVs. The beacons can be positioned on the sides of the support vessel (Fig. 3), which limits the distance between the beacons. This reduces water area preparation time, but increases AUV positioning error – it depends on the distance from the beacons. The errors structure is similar to the long base location, when the device is outside the zone limited by beacons.

The ultrashort base location assumes that the receiving antennas on AUV contain several receivers, the arrival direction is determined by the phase difference, and the distance is determined by the delay. Thus, it is possible to determine the location of all AUVs in a group by one beacon, as well as to determine the mutual location of AUVs relative to other AUVs (Fig. 4).

The accuracy of determining the coordinates in the system with ultra-short base depends not only on the accuracy of distance (it depends on the distance similar to other methods and is up to 5 % of the distance, denoted as Δr, m), but also on the accuracy of angles ($\Delta\alpha$, radians), is about 1° which when using small antennas [10, 11]. Then the accuracy will be as follows:

$$E = \Delta r \Delta\alpha.$$

Inertial positioning systems are based on Newton's laws of mechanics for inertial reference systems. Such systems are divided into angle measuring systems (gyroscopes), which allow to keep a given direction for a long time, and linear acceleration sensors (accelerometers), data from which can be converted into the current AUV coordinates by double integration method. Double reintegration of acceleration in time leads to the fact that such systems quickly enough accumulate error [12], and therefore can be used only for tasks lasting units to tens of minutes.

Optical positioning systems are often used to control a large number (up to several thousands) of flying vehicles or ground robots [13]. To do this, the signal from video cameras (usually several to suppress collisions when one vehicle is behind another) is fed to a pattern recognition system, objects are selected, identified, and by analyzing their position and motion parameters, control commands are formed. But such systems cannot work in water, as water is quite muddy and refracts optical beams. There are optical communication systems, when an amplitude-modulated optical signal propagates in water for hundreds of meters and allows a high speed of information transmission. According to the propagation delays of such a signal, it is possible to measure the distance between two devices under water [14]. The advantages are high accuracy, possibility of simultaneous operation of several AUVs, the disadvantage is limited range.

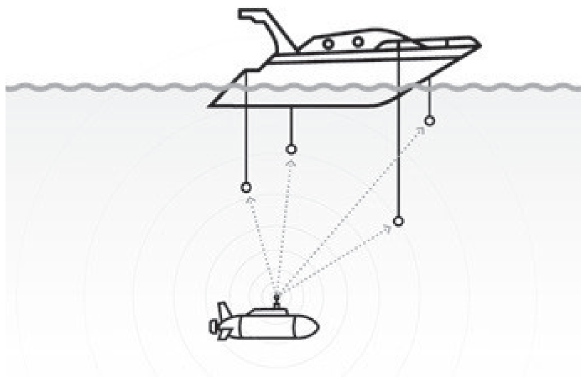

Fig. 3. Example of SBL

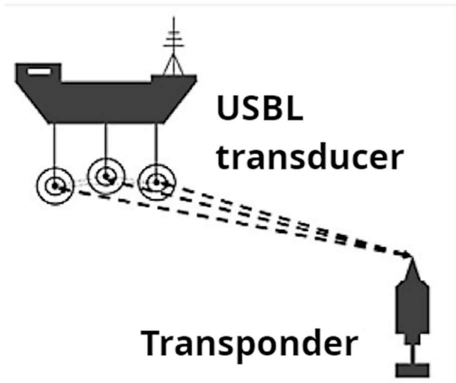

Fig. 4. Example of USBL

Thus, for a group of AUVs, the optimal solution for positioning is a system with ultra-short base location on each of the devices, supplemented with inertial systems for Kalman filtering of current coordinates. The current accuracy is no worse than 0.1° by angle, no worse than 10 cm by distance in the range of 0...4000 m in a homogeneous medium, or no more than 1.5 % of the distance when taking into account the nonlinear propagation of acoustic waves [8]. Frequency range is 25–50 kHz, the size of the antenna is 150 × 150 × 100 mm.

Collecting and transmitting information

After launching the AUV starts execution of the set program, it moves in muddy water, and thus the visual control of the state is impossible. Therefore, a communication channel is required to monitor the current state of each AUV. When the task changes, a new command should be communicated to each AUV. If it is impossible to transmit a message from one AUV to the control center (control service of the whole AUV network, located on the support vessel or on shore), it is necessary to provide retransmission of the message through other AUVs.

When working in a group the following takes place: distribution of tasks between AUVs, control of neighbors' status, joint maneuvering and avoiding obstacles. This requires a communication channel between ANPAs in the group.

Existing hydroacoustic modems have a range up to 4000–5000 m, but are severely limited by the speed of information transfer. Therefore, it is preferable to use faster modems with lower transmission speed to exchange information in a group, and a modem with maximum range, though with low transmission speed to transfer information to the control center. Thus, if each AUV in a group of AUVs is equipped with a high-speed modem with a range sufficient for information exchange within the group, and several AUVs in this group are additionally equipped with modems with a long transmission range, the whole group will be equipped with everything necessary for information exchange both between themselves and with the control center.

Hydroacoustic modems at distances up to 300 m can transmit up to 60 kbit/s and more, while at distances up to 1000 m – only up to 30 kbit/s, and the speed drops to 12–13 kbit/s at distances up to 3500 m, and to tens of bits per second at distances over 4000 m [15]. This is due to the peculiarities of signal propagation in water, the high level of natural and artificial noises as well as the restrictions on the size of the antennas on the AUV. The Shannon-Hartley theorem [15] describes the relationship of information transmission rate as a function of signal-to-interference ratio and bandwidth as follows:

$$C = B\log_2\left(1+\frac{S}{N}\right),$$

where C is the channel bandwidth, bits/s; B is the bandwidth of the communication channel, Hz; S/N is the ratio of signal power to noise.

And the signal-to-noise ratio S/N (SNR) is determined from the basic equation of hydroacoustics [16]:

$$SNR = RL - IL - PL + AD,$$

where RL is the radiation level; IL – the interference level; PL – the propagation loss; AD – the antenna directivity parameter. All values are in dB.

The radiation level is limited by the area of the antenna and is a design parameter, like the directivity parameter. Interference level is determined by the bandwidth of the receiver tuned to the signal bandwidth, making signal bandwidth expansion an unaffected factor in the S/N ratio. The propagation loss is determined by the widening of the signal wave front and the absorption of the wave by the aqueous medium:

$$RL = \beta r + 20\log(r),$$

where r is the distance, m; β is the spatial attenuation coefficient, dB/m.

Thus, the range and speed of communication are design parameters of hydroacoustic modem and cannot be better than theoretical limit.

If AUVs move in a sufficiently compact group, it is possible to use optoacoustic communication between AUVs – an acoustic modem for long-range communication and an optical modem with a range up to 200–300 m for communication of AUVs inside the group. Both suspended particles and dissolved organic matter (DOM) (fatty acids and amino acids, amino sugars, chlorine pigments, hydrocarbonates, phenols, etc.) affect absorption of light radiation. Due to differences in the DOM composition, there are differences in the estimates of the attenuation coefficient α. It was established by means of experimental studies [8] that the absorption index of dissolved organic matter changes according to the following law:

$$\alpha(\lambda) = \alpha_i e^{-\mu_i(\lambda-\lambda_0)},$$

where μ depends on concentration and on wavelength λ; α_0 – the absorption at wavelength λ_0. The blue-green light with λ_0 = 520–530 nm has the minimum absorption coefficient in seawater.

The following scattering coefficient is used for monochromatic green LED, which has a wide directionality:

$$b = \frac{d^2}{4\left(d + rtg(\alpha)\right)^2},$$

where b is the fraction of light after scattering; d – the diameter of the emitter; r – the distance; α – the given angle of illumination.

Thus, the maximum amount of light energy that will reach the receiver at a distance of 200 m will be about 1 %, but the light absorption coefficient can reach the value of 0.4 in coastal waters, then the transmission factor will be 10–89 for a distance of 200 m, which technically does not allow to transmit signals at such a distance. The maximum communication distance in muddy water will be 9.4 m with a receiver sensitivity of 10^{-6} of the transmitter power.

Increasing the transmitter power will allow us to transmit at distances of over 200 m (theoretically up to 500 m) in clear sea water, but such distances are unattainable in coastal waters because of active light scattering on suspended particles.

Such modems have high speed of information transmission, small delay, allow several messages to be transmitted simultaneously, but are limited in range.

The recommended hydroacoustic modem is a USBL modem with a broadband antenna, able to operate both in the high frequency range for high-speed exchange with other AUVs and positioning, and in the low frequency range for message transmission over long distances, combined with an optical communication system. This system allows significant expansion of high-speed data transmission between network agents.

Message relaying protocols are well considered for peer-to-peer (mesh) communication networks [9], and will not be considered in this paper.

Automatic network reconfiguration

The following abnormal situations may occur during the operation of the AUV group:

1. Failure of one or more AUVs;
2. Addition of one or more AUVs to the group;
3. Obstacles in the group's way;
4. Change of task for the group.

A group of AUVs moves in formation along a given route. We do not consider interaction protocols for route selection yet. It is necessary to control the group state and bring the changed information to all AUVs in the group taking into account peculiarities of underwater communication and positioning.

It is necessary to maintain formation in moving environment, i.e. to position each AUV relative to neighbors and relative to the bottom, to move in formation. The frequency of mutual position request depends on the speed of the vehicles and the distance between them, as well as on the accuracy of keeping the position in formation. For example, it is enough to make a request at least once every 3 s, at speed of 3 m/s, 30 m distance between units, and position accuracy of 3 m. Each packet transmits its state (serviceable / faulty / battery loaded) and the calculated coordinate.

If one of the AUVs does not respond at the next request cycle, that AUV is requested again, confirming that it is out of order, and then the group begins to realign. If one request cycle begins to rearrange only one AUV, it will take a lot of time to rearrange the whole group, which will lead to decrease of group efficiency, therefore it is necessary to inform all devices that need to be rearranged in minimum time.

When new AUVs are added to the group (or contact is restored with old ones leaving the group), the new AUVs start the group realignment procedure so that the group is lined up in a given formation in minimal time with minimal loss of resources. The optimization procedure is a mathematically solved "consensus problem" for multiagent systems.

Bypassing obstacles and changing the group's task triggers a new rearrangement with recounting of participants, after which the group moves in an organized formation.

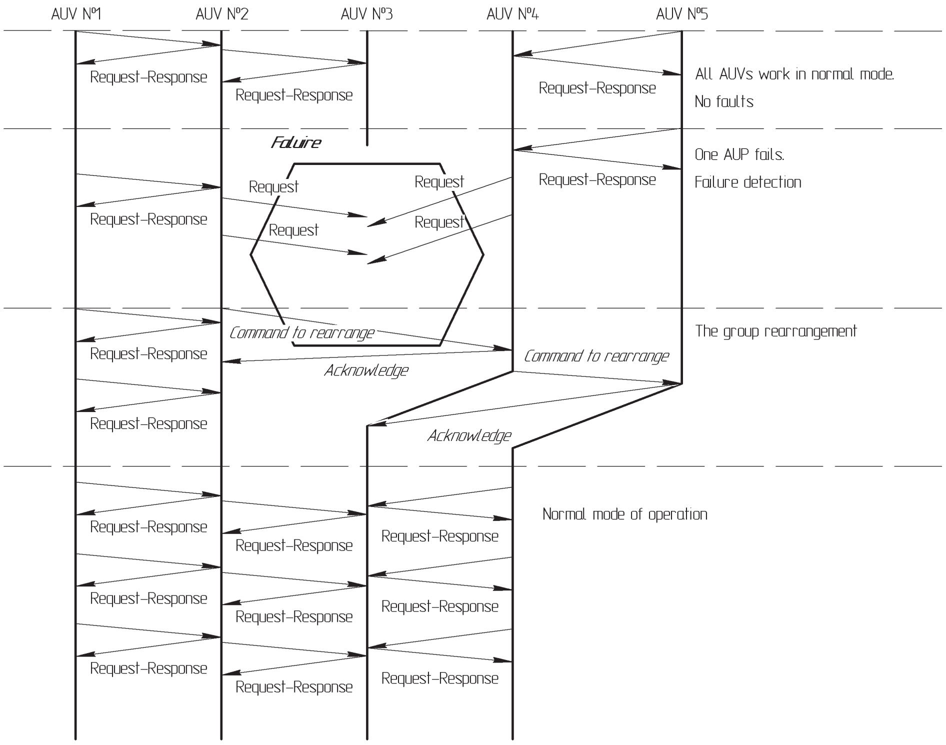

Fig. 5. Temporal diagram of exchange between AUVs when one AUV fails

The time to make a decision depends on the number of vehicles, the range and speed of communication, and also the communication protocol (how many messages to send and who to) [17].

Numerical modeling of AUV group behavior to select communication and navigation system requirements

Let us consider the necessary information exchange for movement of a group of 100 AUVs moving at a speed of 4 m/s in a line to inspect the territory of the bottom 20 × 20 km for detection of sunken objects. The distance between the AUVs in the line is 50 m. Range of communication and positioning within the group is 300 m, communication speed is 50 kbit/s. Positioning based on USBL modems. All the AUVs are the same, there are no dedicated "commanders" in the group. The example of exchange between 5 AUVs in case of failure of AUV 3 is shown in Fig. 5.

The described protocol of accident exchange and detection followed by rearrangement works well when the number of AUVs in a group does not exceed 15–20. In large groups, it is suggested to divide the groups into subgroups of up to 15–20 AUVs, monitor the state of the whole subgroup within this subgroup, and inform other subgroups only when an accident has occurred or rearrangement is required. In this case the accident of one AUV is detected within a subgroup, this subgroup receives a command to rearrange within it, and in parallel informs the other subgroups where to rearrange. Having received the command to realign, the other subgroups disseminate the information within the subgroup and further to the remaining subgroups, after which the entire subgroup realigns.

Let us perform numerical simulation of behavior of a large group of AUVs (300 units) with different number of subgroups. Let us derive group efficiency (as a ratio of probability of object detection on the bottom to time of group operation $E = P/t$), consider the probability density of failures in time constant, equal for all AUVs and chosen so that during the whole mission 5 % of AUV failures occurred as a comparison criterion. All the AUVs are in good working order at the start of the mission.

The signal processing time is not taken into account, only the time for signal propagation between AUVs is:

$$t_{ij} = \frac{r_{ij}}{c},$$

where r_{ij} is the distance between units i and j; c is the speed of sound in water.

When the AUV fails due to delays in neighbor requesting and signal propagation in the course of the mission, there are areas not surveyed by either AUV, so the resulting probability of detection P_{res} is expressed as follows:

$$P_{res} = P_d \left(1 - \frac{\sum_{i=1}^{M} S_{i,unsurv}}{S_{\Sigma}} \right),$$

where P_d is the probability of detection during site survey; S_{Σ} – the total survey area; $S_{i,unsurv}$ is the area of the section where the AUV failed and which was left unsurveyed (so as not to stop the whole group); M is the number of unsurveyed sections.

The results of the simulation are shown in Table 1 and in Fig. 6.

Table 1

Results of modeling group efficiency as a function of subgroup size

Test number	Subgroup size	Operation time, mins	Efficiency, %	Comment
1	No failures	500	1/500 = 100 %	Reference efficiency
2	0-No MAC	1827	27	Several inspections
3	1	936	53	–
4	3	895	56	–
5	10	677	74	Optimal size
6	20	706	71	–
7	50	798	62	–
8	100	863	57	–
9	300	936	53	–

As it can be seen in Table 1 and Fig. 6, the efficiency is minimal without use of MAC (group size 0). When any AUV fails, it is necessary to repeat inspection of the territory which was to be inspected by the failed AUV, which greatly increases total inspection time and decreases efficiency. When subgroup size is equal to one AUV or 300 (all AUVs in one subgroup), the efficiency is determined by the speed of message transmission between all AUVs through the chain, acknowledgement of reception, and sequential rearrangement. As the size of a subgroup increases, it is possible to divide and parallelize the procedure of requesting the AUV serviceability in each subgroup; when a failure occurs, not individual AUVs but subgroups are rearranged, which significantly increases the efficiency of the whole group. But with further increase in the number of AUVs in a subgroup, the time of the requesting AUV serviceability increases again, and efficiency decreases.

Conclusion

Based on the review of possible positioning and communication systems, the authors propose using a broadband acoustic modem with a mutual positioning system on ultra-short distances and optical commu-

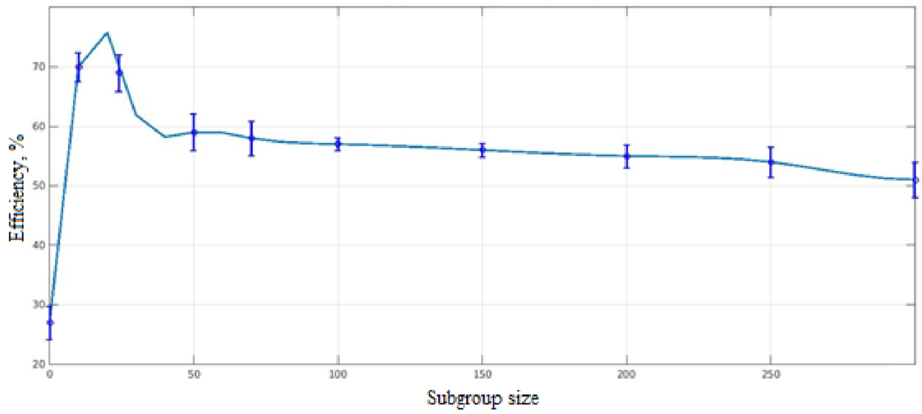

Fig. 6. Dependence of efficiency on subgroup size

nication system on short distances for each AUV. Such a solution makes it possible to transmit information both for long distances (for communication with the control center) and exchange information between a large number of AUVs in a group with small dimensions of the modem and optical system.

Since information exchange and subsequent realignments are delayed, synchronization of actions for large groups of AUVs is quite time consuming. However, controlling a large group is much easier and faster if large groups are divided into subgroups, and each subgroup is provided with state control, positioning and joint rearrangements.

The dependence of AUV group efficiency on the size of a subgroup became clear as a result of a numerical simulation: there is a number of AUVs in the group optimal for the chosen parameters and performed tasks. There are 10...20 units in the example above. Such a number of vehicles allows controlling the number and condition of all vehicles in the group, to transmit commands and to monitor their execution.

Thus, this article proposes a mathematical dependence of the effectiveness of a group of AUVs (the probability of completing a task in a given time) on the speed and range of mutual communication, as well as on the size of the subgroups the group is divided into to reduce the number of messages sent. Such an approach was not found in other materials available for analysis.

REFERENCES

1. **Alcocer A., Oliveira P., Pascoal A.** Underwater acoustic positioning systems based on buoys with GPS. *Proc. of 8th ECUA*, June 12-15, 2020, pp. 1–8.

2. **Tang Suhua, Chen Hongbin, Zhu Yi, Zhang Wenwen, Wu Kefei, Yuan Fei.** Underwater acoustic micromodem for underwater Internet of Things. *Wireless Communications and Mobile Computing*, 2022, pp. 1530–1543. DOI 10.1155/2022/9148756

3. **Batista P., Silvestre C., Oliveira P.** GES integrated LBL/USBL navigation system for underwater vehicles. *Proceedings of the IEEE Conference on Decision and Control*, 2012. DOI: 10.1109/CDC.2012.6426614

4. **Batista P., Silvestre C., Oliveira P.** A time differences of arrival-based homing strategy for autonomous underwater vehicles. *International Journal of Robust and Nonlinear Control*, 2010. DOI: 10.1002/rnc.1547

5. **Choukroun D.** Novel results on quaternion modeling and estimation from vector observations. *AIAA Guidance, Navigation, and Control Conference*, 2009. DOI: 10.2514/6.2009-6315

6. **Morgado M., Oliveira P., Silvestre C., Vasconcelos J.F.** USBL/INS tightly-coupled integration technique for underwater vehicles. *Proceedings of the American Control Conference. IEEE Xplore 2014*. DOI: 10.23919/ACC.2004.1383952

7. **Whitcomb L.L., Yoerger D.** Hanumant Singh combined Doppler/LBL based navigation of underwater vehicles. *IEEE T Autonomous Robots*, 2016.

8. **Aparicio J., Jimenez A., Alvarez F.J., Ruiz D., Urena J.** Characterization of an underwater positioning system based on GPS surface nodes and encoded acoustic signals. *IEEE T INSTRUM MEAS*, 2016. DOI: 10.1109/TIM.2016.2552699

9. **Kinsey J.C., Qingjun Yang, Howland J.C.** Nonlinear dynamic model-based state estimators for underwater navigation of remotely operated vehicles. *IEEE T CONTR SYST T*, 2014. DOI: 10.1109/TCST.2013.2293958

10. **Han Yun-Feng, Derek Li, Zheng Cui-E, Sun Da-Jun.** A precision evaluation method of USBL positioning systems based on LBL triangulation. *Acta Physica Sinica*, Chinese Ed., 2015, 64 (9). DOI: 10.7498/aps.64.094301

11. **Pennec S., Touin G., Azou S., Collin L.** On joint acoustic communication and positioning through MFSK-modulated signals and Costas arrays. *IEEE Xplore. OCEANS 2010 IEEE – Sydney*, 2020. DOI: 10.1109/OCEANSSYD.2010.5603656

12. **Korkishko Yu.N., Fedorov V.A., Prilutskiy V.E., et al.** High-precision inertial measurement unit IMU-5000. *2018 IEEE International Symposium on Inertial Sensors and Systems* (*INERTIAL*). DOI: 10.1109/ISISS.2018.8358121

13. **Kin-Hsing Hsieh.** *Visual positioning system and method for mobile user equipment*. Patent US20080153516A1. 2017.

14. **Casimer DeCusatis, Ivan Kaminow.** *The optical communications reference*. Oxford: Academic Press, 2010, 473 p.

15. **Kulik S.Yu., Rodionov A.Yu., Dubrovin F.S.** On reliability of data transmission and distance estimation using mobile underwater acoustic modems. *25th Saint Petersburg International Conference on Integrated Navigation Systems. 2018, May*. DOI: 10.23919/ICINS.2018.8405859

16. **Urik R.Dzh.** *Osnovy gidroakustiki*. Leningrad: Sudostroyeniye Publ., 1978. 448 p. (rus)

17. **Jennings N.R., Sycara K., Woolridge M.** A roadmap of agent research and development. *Autonomous Agents and Multi-Agent Systems Journal*, 2008, Vol. 1, Iss. 1, pp. 7–38.

INFORMATION ABOUT AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Семенов Николай Николаевич
Nikolay N. Semenov
E-mail: semenov@smtu.ru

Михлин Валерий Григорьевич
Valerii G. Mikhlin
E-mail: valeriy_mikhlin@mail.ru

Ахметов Денис Булатович
Denis B. Akhmetov
E-mail: akhmetov@spbstu.ru

Submitted: 09.01.2023; Approved: 11.05.2023; Accepted: 17.05.2023.
Поступила: 09.01.2023; Одобрена: 11.05.2023; Принята: 17.05.2023.