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One approach for group navigation of unmanned underwater vehicles

Alexander F. Scherbatyuk
Institute of Automation and Control Processes of the FEB RAS, http://www.iacp.dvo.ru/
Vladivostok 690041, Russian Federation
E-mail: alex-scherba@yandex.ru
Yury V. Matvienko
M.D. Ageev Institute of Problems of Marine Technology FEB RAS, http://www.febras.ru/
Vladivostok 690950, Russian Federation
E-mail: ymat33@yandex.ru
Venedikt M. Kuz'kin
Prokhorov General Physics Institute of RAS, http://gpi.ru/
Moscow 119991, Russian Federation
E-mail: kumiov@yandex.ru
Sergey A. Pereselkov
Voronezh State University, https://www.vsu.ru/
Voronezh 394006, Russian Federation
E-mail: pereselkov@yandex.ru
Vladimir I. Grachev
Kotel'nikov Institute of Radioengineering and Electronics of RAS, http://www.cplire.ru/
Moscow 125009, Russian Federation
E-mail: grachev@cplire.ru

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Abstract: **A method for the group navigation support of autonomous underwater vehicles performing a common mission in shallow waters is described. This group includes a lead underwater vehicle equipped with high-precision navigation tools. The operation of all vehicles is synchronized and involves informational interaction between them. The determination for coordinates of the vehicles is based on measuring the distances between them and the lead vehicle. An algorithm for estimating the individual vehicles locations is considered. The numerical modeling results are provided, confirming the functionality and required accuracy of the considered algorithm.**

Keywords: **navigation algorithm, underwater unmanned vehicle, numerical modeling, particle filter**

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Contents

1. INTRODUCTION

Currently, to perform tasks associated with underwater missions, great importance is attached to the use of groups of autonomous unmanned underwater vehicles (AUVs). The value of the information obtained by a AUVs group significantly depends on the accuracy of their navigation reference. The approaches traditionally used for navigation of a single AUV do not provide operational navigation for a group of AUVs. The state of the issue of approaches designed to solve problems of navigation of AUVs groups is presented in the review [1]. The article describes one of the priority ways of providing navigation support to a group of specialized underwater vehicles (SUV), based on the presence in it of one AUV leader with high-precision navigation tools for determining angular orientation, speed and depth.

2. NAVIGATION ALGORITHM FOR A UNMANNED VEHICLES GROUP

It is assumed that the AUV and all SUVs have synchronized clocks, are equipped with hydroacoustic modems and synchronously exchange navigation packets with each other containing the time stamp of the packet emission, an estimate of the coordinates of the underwater vehicle at the moment of the packet emission, as well as the AUV movement parameters. The onboard complex of navigation and flight sensors of each SUV includes inexpensive angular position sensors (heading, roll and trim sensors), pressure sensors for measuring depth and estimating the speed of movement relative to the water column. When carrying out work, the SUV launches from the sea surface from points with coordinates determined by means of a satellite navigation system.

To determine the coordinates of the SUV on board the AUV by measuring the propagation delays of the sound signal between the SUV and the AUV by the hydroacoustic communication system, information is generated on the ranges D_{lk} and the mutual ranges between the SUV $D_{ljk}, l, j = \overline{1, L}$, where L is the number of SUV, k is the number of the current step of the navigation system. Relationships connecting AUV ranges and coordinates:

$$D_{lk}^2 = \left(x_{Ak} - x_{lk}\right)^2 + \left(y_{Ak} - y_{lk}\right)^2 + \left(z_{Ak} - z_{lk}\right)^2, \quad (1)$$

$$D_{ljk}^2 = \left(x_{jk} - x_{lk}\right)^2 + \left(y_{jk} - y_{lk}\right)^2 + \left(z_{jk} - z_{lk}\right)^2. \quad (2)$$

To measure ranges within one cycle of operation of the navigation system, all devices in the group alternately emit a signal and receive responses from other devices. Let us denote by Δ the time interval between the emissions of individual devices, then one cycle of operation takes time $T = (L + 1)\Delta$. Let, for example, the group be localized in an area with a diameter of 600 m and include L = 4 spas. Then the time interval Δ is equal to 0.8 s (taking into account the speed of propagation of the sound signal in water of about 1500 m/s and the propagation of the sound signal from the source to the receiver and back). One cycle of operation of the described navigation system is T = 4 s.

2.1. Location estimation of the vehicles

Location estimation of individual SUV at the k-th step of the navigation algorithm is performed on board the AUV based on solving the system of equations (1), (2) with respect to the unknowns (x_{lk}, y_{lk}, z_{lk}) taking into account the constraint

$$\left(x_{l(k-1)}, y_{l(k-1)}, z_{l(k-1)}\right) \ni R_{l(k-1)}, \quad (3)$$

where $R_{l(k-1)}$ is the area of uncertainty of the location of the l-th navigation system, formed at the (k – 1)-th step of the navigation algorithm. It represents an area centered at a point $(\hat{x}_{l(k-1)}, \hat{y}_{l(k-1)}, \hat{z}_{l(k-1)})$, calculated on the basis of the covariance error matrix $Q_{(k-1)}$. Relation (3) connects the actual SUV coordinates $(x_{l(k-1)}, y_{l(k-1)}, z_{l(k-1)})$ with the measured coordinate estimates $(\hat{x}_{l(k-1)}, \hat{y}_{l(k-1)}, \hat{z}_{l(k-1)})$, and the covariance error matrix $Q_{(k-1)}$ determined on (k – 1)th step of the navigation algorithm.

Considering that the depth of all underwater vehicles is measured with the required accuracy, for simplicity we will limit ourselves to considering the movement of AUVs and SUV in the horizontal plane at the same depth. At the initial moment of time, all SUV are on the surface and their coordinates are determined using a satellite navigation system with a known error σ_l. The actual coordinates of the l-th SUV $(x_l(t), y_l(t))$ are related to the actual values of the velocity module $u_l(t)$ and heading $\varphi_l(t)$ by kinematic equations

$$x_l'(t) = u_{lx}(t),\ \ y_l'(t) = u_{ly}(t), \tag{4}$$

$$u_{lx}(t) = u_l(t)\cos\varphi_l(t),\ u_{ly}(t) = u_l(t)\sin\varphi_l(t). \tag{5}$$

The measured and actual values of the SUV parameters are related by the relations

$$u_{lx}(t) = \left(\hat{u}_l(t) - \xi_u\right)\cos\left(\hat{\varphi}_l(t) - \xi_\varphi\right) + w_x(t), \tag{6}$$

$$u_{ly}(t) = \left(\hat{u}_l(t) - \xi_u\right)\sin\left(\hat{\varphi}_l(t) - \xi_\varphi\right) + w_y(t), \tag{7}$$

$$w^2(t) = w_x^2(t) + w_y^2(t). \tag{8}$$

where $\hat{u}_l(t)$ and $\hat{\varphi}_l(t)$ are the measurements of the speed and course of the SUV; ξ_u and ξ_φ – random errors in measuring the relative speed and course of the SUV; $w(t)$ – current speed in the work area.

The task is to obtain estimates of the location of each SUV, provided that the range measurements in equations (1), (2) contain systematic and random errors associated with inaccurate knowledge of the speed of propagation of the sound signal in water $(\overline{c}, \xi_c)$ and the arrival time $(\overline{\tau}_l, \xi_\tau)$ of the signal. The actual and measured range values are equal

$$D_l = c\tau_l,\ \hat{D}_l = \hat{\tau}_l\hat{c}, \tag{9}$$

where $\tau_l = \hat{\tau}_l - \overline{\tau}_l - \xi_\tau$, $c = \hat{c} - \overline{c} - \xi_c$. In the time intervals between the operation cycles of the hydroacoustic communication system, when the current navigation signals are being generated, the SUV coordinates. The movement of the SUV is calculated on the basis of data on its speed and course transmitted by it at each cycle of operation to the AUV.

Let us assume that the trim and roll angles are small and their errors can be neglected. To determine the movements of a group of underwater vehicles, a coordinate system is used in which the *OX, OY* and *OZ* axes are directed north, east and vertically downwards, respectively.

Let us illustrate what has been said on one cycle of operation of the navigation system for the case with four SUV, which includes five polling cycles. Since signals are emitted by different underwater vehicles with an interval Δ, the equations relating the ranges and coordinates of underwater vehicles when emitted by AUVs and individual SUV have the form

$$D_{lk}^2 = \left(x_{Ak} - x_{lk0\Delta}\right)^2 + \left(y_{Ak} - y_{lk0\Delta}\right)^2 \tag{10}$$

– for AUV radiation,

$$D_{ljk}^2 = \left(x_{jkl\Delta} - x_{lkl\Delta}\right)^2 + \left(y_{jkl\Delta} - y_{lkl\Delta}\right)^2 \tag{11}$$

– for the radiation of the l-th SUV, $l=\overline{1,4}$. Here the subscripts 0Δ and $l\Delta$ denote the moments of time $(k-1)T+\Delta$ and $(k-1)T+(l+1)\Delta$. In (10), (11) it is assumed that the movements of underwater vehicles within the survey cycle from the moment of emission to the moment of signal reception are insignificant and can be neglected.

In the first cycle of the k-th work cycle, the survey is performed by the AUV. By the time it ends, the AUV receives responses from all SUV with time delays τ_{lk}, from which the distances from the AUV to the SUV are calculated $-D_{lk}=c\tau_{lk}$, which are related to the coordinates of the AUV and SUV by relations (1), (2). Next, the survey is performed alternately by the SUV, and they move during each cycle Δ. As a result, we obtain relations connecting the coordinates of the SUV at the time of interrogation with the ranges

$$D_{ljk}^2=\left[\left(x_{jk}-x_{lk}\right)+l\Delta\left(u_{jk}\cos\varphi_{jk}-u_{lk}\cos\varphi_{lk}\right)\right]^2+ \\ +\left[\left(x_{jk}-x_{lk}\right)+l\Delta\left(u_{jk}\sin\varphi_{jk}-u_{lk}\sin\varphi_{lk}\right)\right]^2, \quad (12)$$

where $l,j=\overline{1,4},\ l\neq j$. Thus, according to (1), (2) and (12), there are 16 quadratic equations with 8 unknowns (x_{lk},y_{lk}), which are linearized with respect to the unknowns. In addition, there are restrictions on the admissible range of solutions (3).

2.2. Particle filter as the algorithm basis

Let us assume that the random errors of all measurements are independent, with known distribution densities, not necessarily Gaussian. Recently, particle filter options have been increasingly used to estimate the location of mobile objects, including AUVs [2]. The algorithm based on it is efficient in nonlinear and non-Gaussian environments. Consider using a particle filter to estimate the location of the lth SUV. At the beginning of work, the coordinates of the SUV starting point coincide with the coordinates (x_{l1},y_{l1}), obtained using a satellite navigation system and the center of the particle cloud is located at the specified point. Let us assume that I particles are used to estimate the location of the SUV and at the initial moment of time the particles are distributed uniformly in a circular region of radius σ_1, and the weight of all particles p_i is the same and equal to $1/I$. The weight of a particle determines the probability that the coordinates of a given particle coincide with the coordinates of the SUV.

The operation cycle of the estimation algorithm based on a particle filter includes two stages – prediction (extrapolation) and coordinate correction. At the extrapolation stage, the state vector $(\hat{x}_{lk},\hat{y}_{lk})$. is calculated. For this, the estimates $(\hat{x}_{l(k-1)},\hat{y}_{l(k-1)})$. obtained at the previous step are used. The predicted locations of underwater vehicles at the beginning of the current step at time $t=Tk$ are formed taking into account the movement during the step. For a situation where during a stroke the speed and heading of the SUV u_l and φ_l are constant, we obtain

$$\hat{x}_{lk}=\hat{x}_{l(k-1)}+T\hat{u}_l\cos\hat{\varphi}_l,\ \ \hat{x}_{lk}=\hat{x}_{l(k-1)}+T\hat{u}_l\sin\hat{\varphi}_l. \quad (13)$$

At the prediction stage, the uncertainty region R_{lk} of the location of the l-th SUV at the k-th step of the navigation algorithm is formed taking into account $R_{l(k-1)}$, obtained at the $(k-1)$-th step and the possible movement of the SUA at the k-th step over time T.

At the correction stage, after measuring the signal arrival time at the kth step of the hydroacoustic communication system, the particle coordinates are calculated based on solving equations (1), (2) and (12). Next, the particle weights are corrected [2]. The particle weight increments Δp_{lki}, are calculated, taking into account the degree of discrepancy between the particle coordinates and the obtained distance measurements. The newly obtained particle weights p_{lki} are normalized according to the condition $\sum p_{lki} = 1$. After this, particle regeneration is performed as necessary. Only a small number of particles will have weights other than zero. Most particles degenerate, their weights decrease and become negligible. Particles with low weights are removed and new particles are created in their place, which are distributed in a certain area around the remaining particles in proportion to their weights. The weights of all particles from the newly formed cloud are then normalized.

An estimate of the location of the l-th SUV at the k-th step is formed either based on the coordinates of a particle with a maximum weight exceeding a given threshold, or by calculating the average value of the coordinates of all particles (x_{jlk}, y_{jlk})

$$\hat{x}_{lk} = \sum_{i=1}^{I} x_{lki} p_{lki}, \;\; \hat{y}_{lk} = \sum_{i=1}^{I} y_{lki} p_{lki}. \quad (14)$$

To assess the accuracy of the obtained solution at the k-th step of the algorithm, the covariance error matrix Q_k is used, which for a cloud of particles $X_{lki} = (x_{lki}, y_{lki})$ is equal to

$$Q_k = \sum_{i=1}^{I} p_{lki} \left(X_{lki} - \hat{X}_{lk} \right) \left(X_{lki} - \hat{X}_{lk} \right)^T . \quad (15)$$

It characterizes the degree of scattering of the particle cloud relative to the obtained estimate of the location of the underwater vehicle. The R_{lk} region is formed at the correction stage based on $R_{l(k-1)}$ using the covariance matrix Q_k.

2.3. Algorithm modeling using the particle filter

Assessment of the accuracy and performance of the navigation algorithm for determining the location of the SPA was carried out within the framework of numerical modeling using a particle filter /PF/. Model experiments were performed in the IDLE environment (Python 3.12 64-bit). The situation is considered when the group includes a leader AUV and four SUV. The GANS period was 1 second, the number of GANS cycles within one cycle of radiation from all AUVs was 5. The propagation speed of the sound signal was 1500 m/s.

When implementing the work of the PF, 1000 particles were used, which, during initialization, were uniformly distributed in the region of uncertainty. At the correction stage, in each step, particles were determined that in total provided a probability of 0.90, the rectangular area they occupied was calculated, and the missing particles were randomly added to it with a uniform distribution. When calculating range discrepancies, data from the AUV was taken into account with a larger coefficient compared to the SUV, since the location of the AUV was determined with higher accuracy compared to the SUV.

It was assumed that the AUV is located at the origin of the coordinate system and is motionless. Initial location, speed and heading SUV 1 (-200 m, - 200 m, 1.0 m/s,

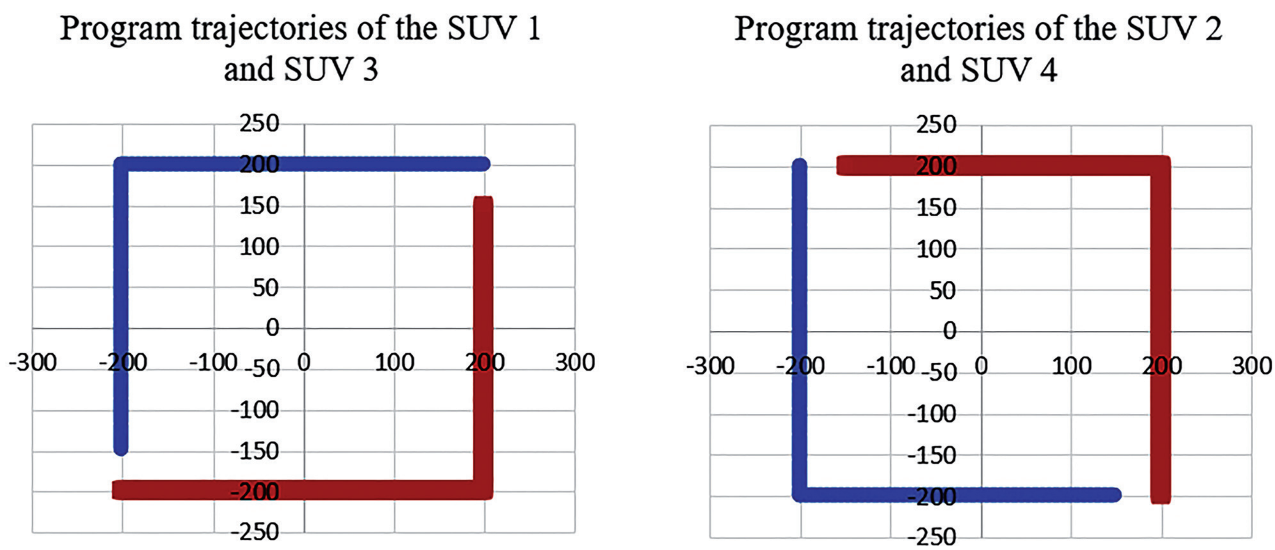

Fig. 1. *Program trajectories of SUV 1-4 during 150 cycles of the system operation.*

0.0 deg.), SUV 2 (200 m, -200 m, 1.0 m/s, 90.0 deg.), SUV 3 (200 m, 200 m, 1.0 m/s, 180.0 deg.), SUV 4 (-200 m, 200 m, 1.0 m/s, 270.0 deg.).

During the modeling process, the location of SUV 4 was estimated based on data from the on-board dead reckoning system and mutual range measurements based on GANS between the AUV and SUV 1-4. The areas of uncertainty in the location of SUV1, SUV2 and SUV3 were circles with a diameter of 15 meters relative to the current program value of each SUV during the entire experiment. The random error in determining the speed of SUV1-4 was in the range of (0, 0.1) m/s, the random error in determining the course of SUV1-4 was in the range of (0, 1.0) degrees. The error in the speed of sound signal propagation in water was taken to be 15 m/s.

Fig. 1 shows the program trajectories of SUV1-4 (counterclockwise movement) during 150 cycles of system operation, which are used when patrolling the border of a given area. The distances between the program positions of the AUV and SPA1-4 during 150 cycles of system operation are shown in **Fig. 2.** The error in estimating the location of SPA1-3 (row 1-3) during 150 cycles of system operation are shown in **Fig. 3**.

The simulation was performed using the Monte Carlo method, with each experiment performed in a loop 100 times with different random errors, and the mean and variance were calculated based on the results obtained. In this experiment, the average error in determining the location of SUV 4 was 5.15 m, the standard deviation was 2.73 m, the average error in determining the speed was

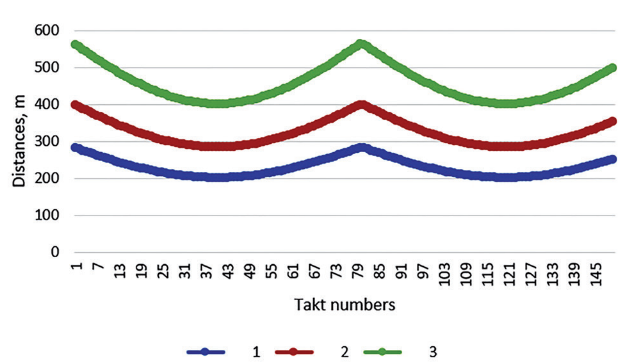

Fig. 2. *Ranges between the program positions of the AUV and SUV1-4 (row 1), neighboring SUV (row 2) and non-neighboring SUV (row 3) during 150 cycles of system operation.*

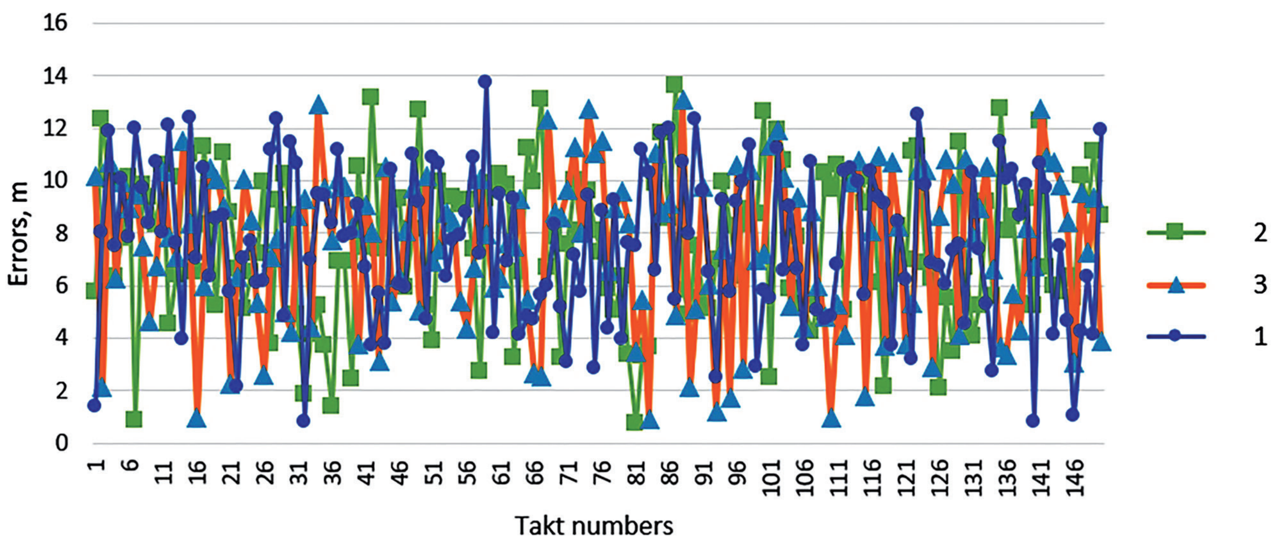

Fig. 3. *Error in estimating the location of SUV1-3 (row 1-3) during 150 cycles of system operation.*

0.011 m/s and its standard deviation was 0.014 m/s.

Fig. 4 shows the movement trajectories of SPA4 with marked points of its location during 150 cycles of system operation, which was obtained in one of the experiments. The distance traveled was about 750 meters and the travel time was about 12.5 minutes. Errors in estimating the trajectory of SUV4 movement during 150 cycles of system operation with and without correction are shown in **Fig. 5**. From the graphs it follows that the error in determining the location of SUV4 without correction for the specified movement time is about 30 meters, and with correction does not exceed 10 meters.

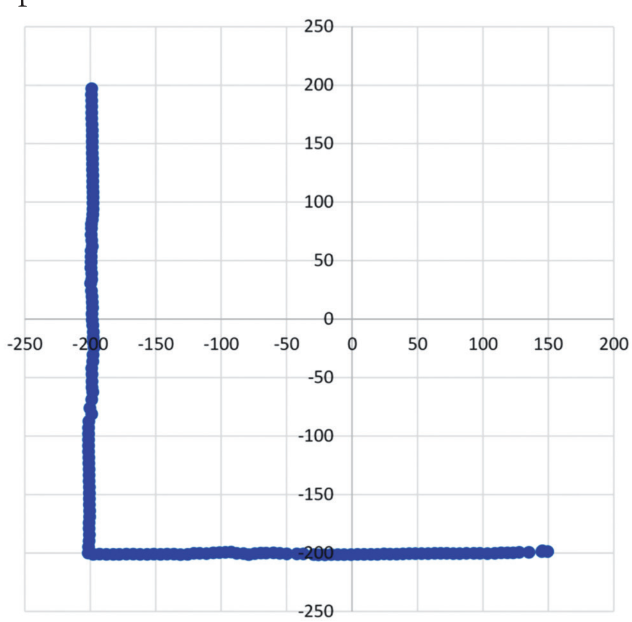

Fig. 4. *Trajectory assessment of SUV4 movement during 150 cycles of system operation.*

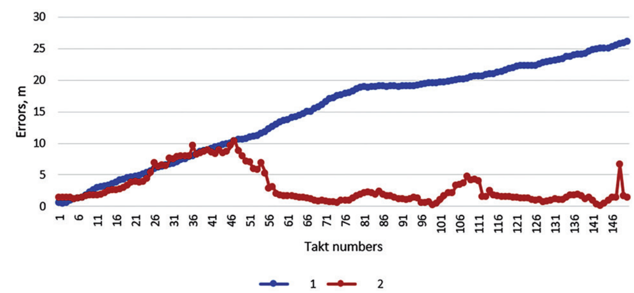

Fig. 5. *Error in estimating the position of SUV4 with correction (row 2) and without it (row 1) during 150 cycles of system operation.*

3. CONCLUSION

An algorithm for group navigation support of the specialized underwater vehicles is considered, based on the presence of the leader autonomous underwater vehicle with high-precision navigation tools for determining of position, angular orientation, speed and depth. One version of particle filter was used for positioning and tracking the location of mobile objects. The numerical modeling results are presented, confirming the performance and required accuracy of the considered algorithm.

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