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EFFECTIVENESS EVALUATION OF MULTI-AGENT CONTROL SYSTEMS FOR AUTONOMOUS UNDERWATER VEHICLES FOR UNDERWATER OPERATION

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Abstract. The need to use groups of homogeneous and heterogenous robots in a confined space leads to the need for robots to interact with each other to prevent accidents and interfere with the work of other robots. And limited in speed and range communication channels do not allow remote control of each robot separately, that leads to the need to create multi-agent control systems or the ability of a group of robots to solve emerging problems without human intervention. This article discusses the effectiveness of such a group depending on the technical constraints of each robot and the number of robots in the group. The paper shows that an increase in the number of AUVs in a group leads to a significant increase in efficiency, but when a certain number is reached, the efficiency drops, because large groups of AUVs spend much more time changing lanes, and the increase in efficiency with an increase in the number of AUVs disappears.

Keywords: robotics, underwater robotics, group application, AUV, multi-agent control, efficiency

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Научная статья
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ОЦЕНКА ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ СИСТЕМ МУЛЬТИАГЕНТНОГО УПРАВЛЕНИЯ АВТОНОМНЫМИ НЕОБИТАЕМЫМИ ПОДВОДНЫМИ АППАРАТАМИ ДЛЯ РАБОТЫ ПОД ВОДОЙ

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Аннотация. Необходимость применения групп как однородных, так и разнородных роботов в ограниченном пространстве приводит к необходимости взаимодействия роботов между собой с целью предотвращения аварий и помех другим роботам. Ограниченность каналов связи по скорости и дальности не позволяет удаленно контролировать каждого робота, что приводит к необходимости создания систем мультиагентного управления, то есть способности группы роботов решать возникающие проблемы без участия человека. В статье рассмотрен вопрос эффективности такой группы в зависимости от технических ограничений каждого робота и числа роботов в группе. Показано, что увеличение числа автономных необитаемых подводных аппаратов (АНПА) в группе приводит к существенному увеличению эффективности, но при достижении определенного числа эффективность падает, поскольку большие группы АНПА тратят на перестроение значительно больше времени, и прирост эффективности при увеличении числа АНПА пропадает.

Ключевые слова: робототехника, подводная робототехника, групповое применение, АНПА, мультиагентное управление, эффективность

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Introduction

The issues of group application of underwater vehicles for various tasks have recently been paid close attention to [1–6]. This includes search for submerged objects, including search for minerals, technical inspection of underwater facilities and their maintenance.

The underwater vehicles in the group are supposed to have a channel of information exchange with each other and a positioning system [4]. But the peculiarities of such channels underwater are the limited range and speed of information transfer.

Implemented autonomous underwater vehicles (AUV) groups are known, for example, for the submerged objects search [7]. It is proposed to use leading vehicles (nominally Bluefin-12) there, they directly explore the bottom in search of submerged objects, then an intermediate link is introduced – communication and navigation facilities (each equipped with an inertial navigation system and communication system). These vehicles (nominally Bluefin-21) provide the small (lead) vehicles with the information and communication channel necessary for their navigation. Finally, there are vehicles that re-find the marked objects and further investigate them if necessary.

Three levels are introduced when building a control system for a group of vehicles: strategic, tactical and operational ones [4]. A group of vehicles has a common task (mission), to solve which all the resources of the group are used. As a rule, it is possible to accomplish the mission by different algorithms. The optimality criterion (if there are several criteria, then their convolution) is used to select a specific algorithm from the set.

The upper, strategic management level determines the division of the entire mission for a AUV group into subtasks for each AUV separately, determines ways to control the mission accomplishment, makes distribution of subtasks (goals) among specific vehicles of the group. The strategic management level is not the property of a single vehicle, but is the property of the group. Moreover, both division of the mission into subtasks and distribution of subtasks between vehicles can be changed promptly if the general task changes or, for example, one vehicle of the group fails and functions redistribution among the remaining vehicles of the group is required. The tactical level receives information which determines how a particular vehicle performs a subtask (mission) from this level. This subtask contains a goal which is independent of the other vehicles, and allows to control its execution. For example, the trajectory of the vehicle, its place in the formation, the area surveyed, and the amount of information collected.

The tactical level is part of each vehicle's control system, it breaks down the current goal into a set of actions or trajectories needed to achieve the goal, and monitors their execution. This level exchanges information with neighboring vehicles in the group to clarify, for example, their position in the group and adjusts the trajectory transmitted to the operational level. The task of the tactical level is to make a decision to bypass arising obstacles and return to their place in the formation.

At the operational level, control actions are generated on the available control resources of the vehicle to maintain the specified trajectory and collect the required information. Such resources include thrusters (marching, vertical and horizontal thrusters), rudders, stabilizers (passive or active), roll levelling mechanisms, buoyancy change system and shifted center of gravity.

The decentralized control systems for a group of vehicles, such as a multi-agent control system, are undoubtedly of great interest [2, 7].

In this case, one mission is assigned to the entire group of vehicleson the strategic level, for example, search for submerged objects in a limited area, which is pre-marked with underwater beacons, and the size of the survey strip (area) by one vehicle. The width of the survey strip is assigned based on the capabilities of the acoustic complex of the given vehicle to detect a submerged object with a given probability P_d. The same considerations determine the depth and speed of the vehicle. The mission will be understood as: geographical coordinates of the territory to be surveyed, characteristics of the flooded object (criteria for deciding that it is a flooded object) and the required probability of its detection. Each vehicle evaluates its efficiency in surveying the areas closest to it and transmits the information to neighboring vehicles, which in turn report their efficiency in surveying these areas, after which the areas are surveyed by the vehicle that can survey them in the minimum time and having spent the minimum amount of resources. Resolution of conflicts between vehicles is considered in works on the "consensus problem" [7, 13–15].

Since the main task of the AUV group is to accomplish the mission (for example, detect objects on the bottom) in the minimum time with the maximum probability, let us set the AUV group "efficiency" criterion as the ratio of the detection probability to the time of the entire group operation

$$Eff_{gr}(n) = \frac{P_{gr}(n)}{t_{gr}(n)},$$

where n is the group size, P is a given probability of object detection, t – group operating time (maximum operating time of the AUV in the group).

If the economic component, i.e. the necessity to take into consideration an increase of cost of the group and its service with increase of its number, is taken into account, then there appears one more criterion – *economic efficiency*, i.e. efficiency of use of each AUV in the group:

$$Eff_{gr}\left(n\right)=\frac{P_{gr}\left(n\right)}{t_{gr}\left(n\right)\cdot n}.$$

The following approach is used to estimate the probability of finding an object in a given area [9]: the object (objects) sought for is on the bottom of the area surveyed by AUV with width L and length d (Fig. 1). The area is rectangular. The AUV passing along the strip with its locator captures the whole surveyed strip (by width). All values are evenly distributed.

The scheme has the following notations: d is the width of the strip surveyed by one AUV; L is the length of the strip surveyed by one AUV; dL is the distance covered by AUV during the time dt; $S_s = d\cdot L$ is the area of the site surveyed by AUV.

The area surveyed by the AUV during the time T_s (search time) is shaded in Fig. 1. Then the probability P of finding an object in the strip according to the geometric definition (probability) can be defined as follows:

$$P=\frac{d}{S_s}\int_0^{T_s}V_{\mathrm{AUV}}(t)dt=\frac{\int_0^{T_s}V_{\mathrm{AUV}}(t)dt}{L},$$

where $V_{\mathrm{AUV}(t)}$ is the speed of AUV during the site survey.

The operating time of the whole group t_{gr} is determined by the longest operating time of each AUV in the group. Working time of each AUV t_i^{AUV}:

$$t_i^{\mathrm{AUV}}=t_{w\_i}^{\mathrm{AUV}}+t_{re\_i}^{\mathrm{AUV}}, \tag{1}$$

where t_i^{AUV} is the survey time of the area allocated for this vehicle for the selected trajectory; $t_{w\_i}^{\mathrm{AUV}}$ – the time of the search for flooded objects (work); $t_{re\_i}^{\mathrm{AUV}}$ – the time of rearrangement to enter the working trajectory.

Calculations of rearrangement time and exit to a given trajectory are considered in the moving objects control theory and are well reviewed in [10, 11].

Probability of contact with an object caught in the range of observation P_c means (GAS AUV):

$$P_c=1-e^{\frac{kD_d\Omega}{V_{\mathrm{AUV}}T_0}},$$

where $k=\frac{\pi}{2\cdot 360}=0.00436$ is the conversion factor when Ω is given in degrees; Ω – the sector of the survey by the observation vehicle (AUV); T_0 – the time of the sector survey by AUV SONAR; D_d the mathematical expectation of the range of the technical means of detection (AUV SONAR) – the average expected detection range.

Probability of detecting an object in a given time interval P_d:

$$P_d=1-e^{-\frac{uT_s}{S_s}},$$

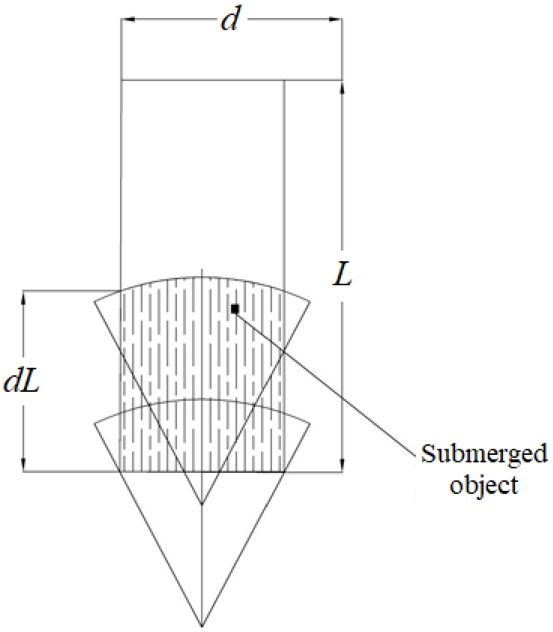

Fig. 1. Scheme for calculating the location of an object in a given area

where u is the search performance, taking into account the probability of obtaining contact with it; T_s – the search time (the time of AUV being in the search site with area S_s).

The search performance is defined as $u = W_{sb}V_{\text{AUV}}P_c$, where W_{sb} is the effective width of the AUV SONAR survey band. In case of one AUV W_{sb} is equal to $W_{sb} = 2D_d$.

For a group AUV consisting of N_{AUV}:

$$W_{sb} = \left(N_{\text{AUV}} - 1\right) d_{\text{AUV}} + 2D_d,$$

where d_{AUV} is the distance between the AUVs when surveying the area.

The mathematical expectation of object detection time T_d shows how long from the start of the search an object can be expected to be detected on average:

$$T_d = \frac{S_s}{u}.$$

The mathematical expectation of the number objects MO_d, detected during the search time T_s is as follows:

$$MO_d = N_{a1}P_{d1} + N_{a2}P_{d2} + \ldots + N_{an}P_{dn} = \sum_{i=1}^{n} N_{ai}P_{di},$$

where N_{ai} is the number of objects in the i-th search area; P_{di} is the probability of detecting objects in the i-th search area.

It is planned to search objects by m types of AUV with different search productivity in the site of S_s area.

N_{t_1} is the number of the first type AUVs with search capacity u_1;

N_{t_2} is the number of the second type AUVs with search capacity u_2;

...

N_{t_n} is the number of the n-th type AUVs with search performance u_n.

$$\frac{S_1}{S_s}=\frac{N_{t\_1}u_1}{N_{t\_1}u_1+N_{t\_2}u_2+\ldots+N_{t\_n}u_n},$$

$$\frac{S_2}{S_s}=\frac{N_{t\_2}u_2}{N_{t\_1}u_1+N_{t\_2}u_2+\ldots+N_{t\_n}u_n}, \ldots,$$

$$\frac{S_n}{S_s}=\frac{N_{t\_n}u_n}{N_{t\_1}u_1+N_{t\_2}u_2+\ldots+N_{t\_n}u_n}.$$

Note: $S_s = S_1 + S_2 + \ldots + S_n$.

It is assumed that the detection of each of n flooded objects are independent events A_i, where $i \in 1, 2, \ldots, n$. Then the probability of detecting of at least one flooded object is as follows:

$$P_d\left(A_1+A_2+\ldots+A_n\right)= \\ =1-\left(1-P_d\left(A_1\right)\right)\left(1-P_d\left(A_2\right)\right)\ldots\left(1-P_d\left(A_n\right)\right).$$

Modeling the behavior of a group of AUVs with efficiency calculations

Having received the general mathematical model of the work efficiency of a group of AUVs for detecting underwater objects, let us carry out numerical simulation of the received model taking into account technical opportunities and restrictions at search in real conditions of the Baltic sea.

Suppose the search area is 20 × 20 km. The search width with one AUV based on requirements of detection probability ($P = 0.95$) is 50 m. The autonomous operation time of one AUV is 4 hours, the speed is 5 m/s.

Survey with one AUV would take 10 km·(10 km / 50 m)/5 m/s = 111 hours or 4.6 days. The survey is practically impossible when it is necessary to return the AUV every 4 hours and recharge [12]. But suppose the time of survey (taking into account descent/rise and accumulators recharging 28 times) is not less than 6 days, and take 0.95 probability of detection by serviceable device, the efficiency would be equal to $Eff = 0.95/111 = 0.00855$.

Increasing the number of AUVs in group up to N means decreasing time of territory survey but in this case if the group moves by lines, the more group the more time will be required for rearrangement. Trajectories of AUV movement can be different, but they all become more complicated with increasing the number of AUVs in a limited territory. The probability of failure of each robot is constant and conditionally accepted as 0.1. Therefore, the efficiency of group operation when moving in a line, depending on the number of AUVs in the group, is as follows:

Figure 2 shows that in the left part of the graph increasing the number of AUVs in the group leads to a significant increase in efficiency, but the efficiency drops when reaching a certain number. This is due to the fact that large groups of AUVs spend considerably more time for rearrangements, and the increase in efficiency with increasing number of AUVs disappears, thus, the efficiency drops.

If the economic contribution in efficiency calculation, i.e. efficiency of each AUV in the group, is taken into account, the following characteristic are obtained (see Fig. 3).

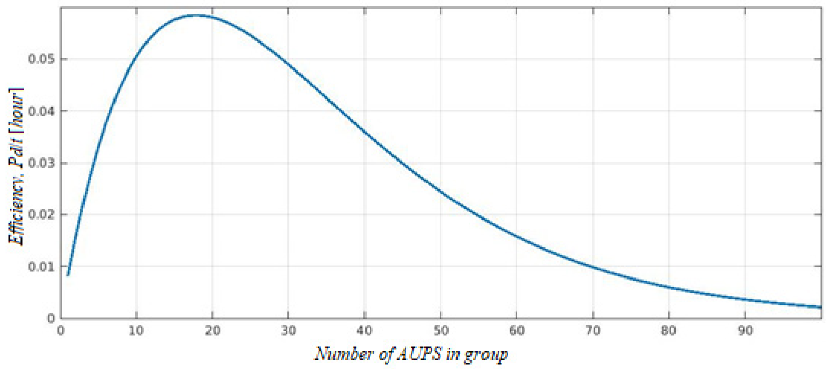

Fig. 2. Efficiency of the AUV group depending on the number of agents

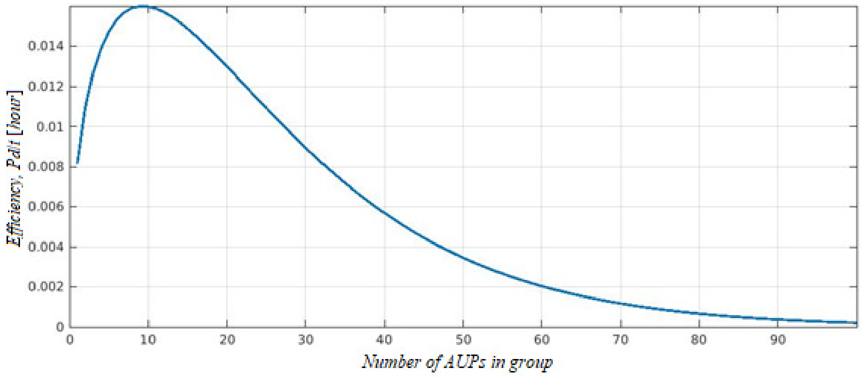

Fig. 3. Efficiency of the AUV group depending on the number of agents

Figure 3 shows that there is the maximum efficiency of application of each AUV application with the smaller number of AUVs in the group than at calculating efficiency of all the group. It is due to the fact that although addition of new AUVs increases the efficiency of the whole group, the efficiency increase turns out to be small and it does not cover economic expenses for purchasing and servicing additional AUVs.

Conclusion

It is reasonable to choose either such a group of AUVs that will survey the territory in the minimum time with a given probability, or will do this with a minimum number of AUVs, maximizing the economic effect. At the same time, the efficiency of using each AUV to solve a common problem is maximum.

In the available literature, there is no mathematical criterion for optimizing the composition of the group, the composition of the group was assumed to be predetermined, therefore, this article proposes a new method and a new optimization criterion that allows, with minimal financial costs (the minimum number of devices used), to perform the search task with a given probability in a time close to the minimum, that is, to ensure the maximum efficiency of the group.

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