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TESTING A HETEROGENEOUS GROUP OF AUTONOMOUS UNMANNED UNDERWATER VEHICLES FOR SEARCH OF OBJECTS ON THE BOTTOM

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Abstract. The results of model and in-situ tests of control algorithms providing coordinated movement of a group of heterogeneous underwater robots in an uncertain three-dimensional moving environment in order to search for sunken objects on the bottom are being considered in the paper. Autonomous optical navigation of each robot, simulating the use of SLAM algorithms based on side-scan sonar (SSSI), interaction of robots with each other by means of surface buoys or a hydroacoustic modem, transfer of the detected objects` coordinates between robots in the group, and building a digital bottom map in the memory of each robot are used. The proposed control algorithms can be used both in centralized and decentralized control. Simulation model and field experimental data, confirming the performance of the proposed algorithms and protocols, are presented. The developed algorithms can be used in the control systems of mobile robots for their group control in uncertain 3D environments.

Keywords: group control, robot, group of robots, control system, AUV, underwater mapping, optical navigation

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Научная статья
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ИСПОЛЬЗОВАНИЕ РАЗНОРОДНОЙ ГРУППЫ АВТОНОМНЫХ НЕОБИТАЕМЫХ ПОДВОДНЫХ АППАРАТОВ ДЛЯ ПОИСКА ОБЪЕКТОВ НА ДНЕ

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Аннотация. В статье рассматриваются результаты моделирования и натурных испытаний алгоритмов управления, обеспечивающих согласованное движение группы разнородных подводных роботов в неопределенной трехмерной подвижной среде с целью поиска затонувших объектов на дне. Автономная оптическая навигация каждого робота, имитирующая использование алгоритмов SLAM (одновременная локализация и построение карты) на основе гидролокатора бокового обзора (SSSI), взаимодействие роботов друг с другом посредством надводных буев или гидроакустического модема, передача координат обнаруженных объектов между роботами в группы и построения цифровой карты дна в памяти каждого робота. Предложенные алгоритмы управления могут использоваться как при централизованном, так и при децентрализованном управлении. Представлены имитационная модель и данные полевых экспериментов, подтверждающие работоспособность предложенных алгоритмов и протоколов. Разработанные алгоритмы могут быть использованы в системах управления мобильными роботами для их группового управления в неопределенных трехмерных средах.

Ключевые слова: групповое управление, робот, группа роботов, система управления, АНПА, подводная картография, оптическая навигация

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Introduction

Autonomous unmanned underwater vehicles (AUVs) are successfully used to perform search and monitoring tasks in various types of water areas, and the objectives can be different: searching for underwater objects in emergency situations, searching for sunken objects, demining the territory, searching for minerals or bioresources. When carrying out such works an important task is to increase their efficiency, reducing the time spent and, consequently, the cost [1]. At present, AUVs are traditionally used singly with cyclic repeated launches including surveying (photo, acoustic, electromagnetic, etc.), AUVs return to the "base", information readout, received information processing by specialists, planning subsequent launches in areas with refined coordinates [1].

It is necessary to use the AUV groups equipped with mutual positioning and communication systems simultaneously, so that AUVs do not interfere with each other during execution of the common task, to increase the efficiency of works. Transfer of information processing functions to the AUV and organization of decision-making system for changing group behavior, when detecting specified objects in the group, will make the group autonomous, not requiring constant control and management [1–12].

Taking into account that the AUVs can malfunction or be exposed to artificial obstacles during their tasks in deep waters, the group of AUVs should be stable to the change of number and inexpensive if possible. It is proposed to abandon universal AUVs in favor of specialized ones, each of which does their job well at minimal cost, to reduce costs. For example, some of the robots have greater autonomy, speed, and search facilities. The objects detected by these robots are surveyed by less numerous vehicles, but more expensive and better equipped for vision and classification, and in case of successful classification, specialized robots, capable of lifting to the surface the detected objects, are involved. An example of a group of such specialized AUVs is BLUEFIN [1].

Considering that AUVs are moved in mobile environment (the mobile in mobile), that there is no global positioning system as GPS under water, that local systems require time for deployment and have a lot of their limitations, the task of AUV independent positioning during any work under water is very actual, especially when working in a group. It is connected with both safety (so that AUVs do not interfere with work of other AUVs), and with efficiency of site survey by different AUVs. fdf

Thus, this paper examines the most functional AUVs and their capabilities for joint work at the same area, underwater robots developed at St Petersburg Marine Technical University (SMTU), describes a mathematical model of robots collaboration and positioning, proposes a model for studying the joint autonomous work by a group of AUVs developed by SMTU with positioning based on optical ArUco-tags [6] located on the bottom of the pool, the results of full-scale tests in the pool of such a system are presented.

The joint work of AUVs with the results of full-scale tests is a rare topic in scientific articles. Reviews of such articles have been discussed in detail at [10—12]. This work that describes the results of full-scale experiments on the absolute positioning of a group of heterogeneous AUVs is relevant and timely.

Overview of existing submarine group control projects

CoCoRo (Collective Cognitive Robotics).

This is the most famous of the research projects on the control of large groups of underwater robots [2], aimed at studying the algorithms and possibilities of the underwater robots interaction in a group. It is being funded by the European Union for more than 12 years, both the small robots themselves and the group control system for them have been developed. The core of the CoCoRo group consists of 20 relatively large Jeff robots with high maneuverability, autonomy up to several hours and capable of moving at a speed of 1 meter per second. The rest of the group's underwater robots belong to a different class, Lily, are smaller in size and speed and act as the "brain" of the collective intelligence "swarm" of robots. These robots provide communication and information transfer between Jeff robots, the base station and the rest of the surrounding world, and participate in making collective decisions. The third type of robot is a docking station for the first two types of robots.

Each robot in the CoCoRo group is able to act independently, performing its own task; to perform more complex tasks, robots are combined into small groups, but to perform global (for this group of robots) tasks the whole group is used, forming a "swarm" based on the available collective data. Using the "swarm" ideology, the group becomes versatile, adaptable to changing conditions, resistant to changes in the group composition.

One of the practical application scenarios for such "swarms" of underwater robots is underwater search operations. In this case, the Jeff robots will search directly, moving quickly in a variety of directions and constantly coordinating their actions. Once a target has been located, they will use the Lily robots to tell each other and relay that information to the surface.

The CoCoRo team has already been tested in natural bodies of water, lakes and rivers, showing its simplicity and effectiveness.

Bluefin Robotics. It is another popular project of underwater robots collective control [3]. The project has developed both the heterogeneous submersibles themselves and a group control system for them. To search for sunken objects it is proposed to use the most numerous group of BLUEFIN-9 vehicles, which

Fig. 1. Example of Lily group of robots

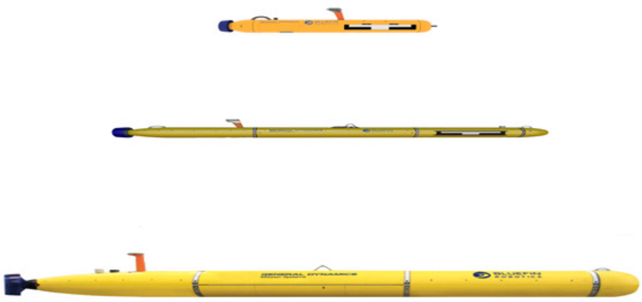


Fig. 2. Example of BLUEFIN-9, BLUEFIN-12 and BLUEFIN-21 AUVs

moves along the bottom, detects objects and transmits information to a less numerous group of BLUEFIN-12, which check and classify detected objects, determine their exact coordinates, then inform the smallest BLUEFIN-21 vehicles, which collect information, process and either decide on further actions themselves or send a message to a human by hydroacoustic or radio channel. Autonomy of such robots is 8–12 hours.

Kongsberg. It is actively advertised as very reliable and high quality multifunctional AUVs. It has good maneuverability, depth and speed according to open data. These are the "HUGIN" AUVs. [4]. They can be equipped with a wide range of additional equipment and can be used both autonomously and with remote control or under supervision. Autonomy is 24–74 hours, length is 5.2–6.4 m, external diameter – 0.75 m, weight – 1000–1500 kg, diving depth – up to 4500 m, speed – 2–6 knots.

The types of tasks solved by these AUVs both individually and as a group are not disclosed on the website, but the promotional videos include corrective search for sunken objects and monitoring the condition of pipelines.

ACOBAR (Acoustic Technology for Observing the interior of the Arctic Ocean). The task for the developers was to monitor the state of the marine environment in the Arctic Ocean. The complexity of the Arctic Ocean research is that the surface is almost always covered by ice, and the support vessel cannot constantly stay above the surface under study, so all submersibles are autonomous with great autonomy and accurate positioning system in ice conditions. Such vehicles include various underwater gliders, AUVs and autonomous surface boats.

Thus, the development and introduction of control systems for groups of submersibles is actively developing in the world. Such groups make it possible to perform search and monitoring work in large water areas much faster, more reliable and efficient than single robots, as well as to automatically take into account changes in operating conditions and changes in the group composition (failure or replenishment).

Fig. 3. Example of HUGIN AUV

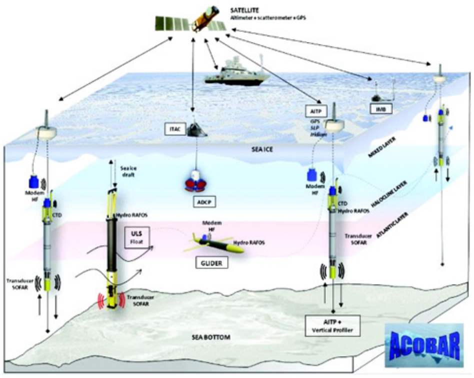


Fig. 4. Example of an ACOBAR monitoring system

But the CoCoRo project is devoted to the smallest AUVs with small autonomy and is intended for working out of interaction algorithms, while other considered projects are large deep-water AUVs with high autonomy and high price. It is necessary to develop and test a group of AUVs that can independently survey the bottom in the water area of several square kilometers, have onboard a video camera for search, communication and positioning system, as well as autonomy of not less than 4–6 hours.

Developed group of heterogeneous robots

The following AUVs were developed to solve the problem of bottom survey:

• "Akara" micro AUV. Working depth is up to 50 meters, hull diameter is 100 mm, length is about 1 m, maximum speed is 2.5 knots, weight is not more than 10 kg, which allows launching and receiving AUVs from hands, autonomy is not less than 2 hours and can be increased by additional compartments with batteries. Akara-M is an upgraded version developed as part of research work on the creation of a multi-agent sensor-communication network based on marine robotic platforms (MRP).

• "Goupi" micro AUV. This AUV is designed to teach schoolchildren the basics of underwater robotics. Hull diameter is smaller than that of Akara and is 70 mm, length is 750 mm, weight is 3 kg, autonomy is 2 hours, max speed is 2.5 knots, max depth is 50 m. Control system is built on Linux operating system, ROS, it contains 720HD high resolution video camera and inertial navigation system.

• "Trionix" ROV is a telecontrolled submersible vehicle of micro class with the overall dimensions of 450 × 340 × 140 mm, weight of 3.5 kg, cable length up to 20 m, 720HD video camera, roll, trim, temperature and depth sensors, LINUX operating system, ROS framework. The autonomy of such a robot is not limited, since power is supplied via control wires, but the range is limited by the cable length.

Collaborative robot operation

The task assigned to the group is to search for sunken objects in clear water. A radio channel is used for communication, a float with an antenna moves behind each robot for radio channel operation by an underwater robot. The robot group needs to be augmented with a positioning system to accomplish the task.

Fig. 5. “Akara” AUV

Fig. 6. “Akara-M” AUV

Since the robots have an inertial navigation system (INS) and a high resolution video camera, inertial navigation is used to tie the coordinates of the robots to ArUco tags located on the bottom, and inertial navigation is used between the tags [6].

Inertial navigation is based on processing signals from angular velocity sensors (gyroscopes) and acceleration sensors (accelerometers) along three spatial axes. The result of processing (time integration) of the gyroscope signal is the rotation angle of the robot. The accelerometers are only used to calculate the roll and trim angles, while the current speed and the distance traveled are determined by the control signals of the thrusters. In this case navigation errors occur [7–21].

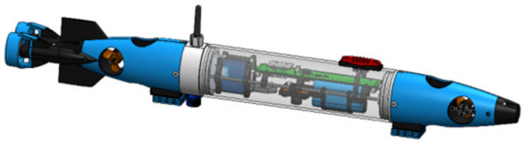
For example, if we assume that the output of the gyro signal on each of the axes contains a useful signal and noise component (which is 1...2 low-order bits of ADC), then during integration we get the following angle:

$$\alpha(T)=\int_0^T(\omega(t)+n(t))\,dt=\int_0^T\omega(t)\,dt+\int_0^T n(t)\,dt=A(T)=N(T)+C,$$

where $\alpha(T)$ is the rotation angle, $\omega(T)$ is the angular velocity, $n(T)$ is the noise, $A(T)$ is the true rotation angle, $N(T)$ is the noise integral and as a consequence the angle error, C is the initial angle setting.

Thus, the resulting angle is the sum of the time integral of angular velocity and the time integral of noise. When the angular velocity measurement has an asymmetric error with respect to zero and noise (and in practice, absolute symmetry is technically impossible), the noises begin to give an increasing error $N(T)$ with time at the current angle of rotation $\alpha(T)$.

Similarly, with the accelerometer error accumulation at double integration, the error starts to grow with time even if the gravity acceleration is cut out correctly:



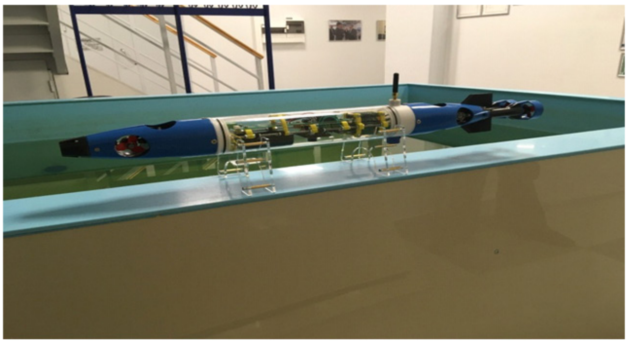


Fig. 7. “Goupi” AUV

$$x(T)=\int_0^T\int_0^T\left(a(t)+n(t)\right)dtdt=$$
$$=\int_0^T\int_0^T a(t)dtdt+\int_0^T\int_0^T n(t)dtdt=X(T)+N(T)+(V+Nv)*T+X_0,$$

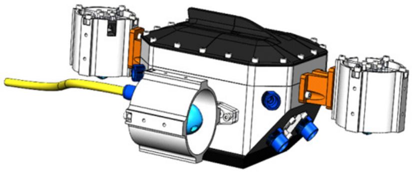
where $x(T)$ is the current coordinate, $a(t)$ is acceleration from the accelerometer, $n(t)$ is accelerometer noise, $X(T)$ is the true coordinate, $N(T)$ is the double integral of accelerometer noise, V is the initial speed, Nv is the constant component of the first integral of time noise, X_0 is the initial displacement.

The typical inertial module (MPU-9250) consists of three independent uniaxial vibrational angular velocity sensors (gyroscope MEMS) that respond to rotation around the X-, Y-, Z-axes. Two suspended masses perform oscillations on opposite axes. With the appearance of angular velocity, the Coriolis effect causes a change in vibration direction $\overrightarrow{F_k}=-2m\cdot\left[\vec{\omega}\times\overrightarrow{v_r}\right]$, which is detected by a capacitive sensor [22–30]. The measured differential capacitive component is proportional to the displacement angle [26–30]. The resulting signal is amplified, demodulated, and filtered, yielding a voltage proportional to angular velocity. This signal is digitized with a 16-bit ADC built into the board. The samplerate can be programmed from 3.9 to 8000 samples per second (SPS) and user configurable LPFs (low-pass filters) provide a wide range of possible cutoff frequencies. The LPF reduces the variance of each measurement, but does not compensate for the static error.

Thus, with a 16-bit gyro the amount of error is one low bit. If the total angular velocity amplitude is 300 degrees per second, the error will be on the order of 0.0045 degrees per second, and when accumulated over 100 seconds, the angle error will be 0.45 degrees, increasing linearly with time. Using a larger ADC and reducing noise will reduce this error, but the error will still increase over time.

Additionally, the gyroscope readings are affected by the rotation of the Earth, which leads to a predictable error of the gyroscope readings for one minute as $\Delta\alpha = 360/24/60 \times \sin(\varphi)$, where φ is the latitude of the place. For example, at the latitude of the city of Sochi, this error would be 0.17 degrees per minute. Such an error can be predicted and compensated programmatically during tests.

Position error accumulates even faster: for example, at full 3G ADC amplitude and 16-bit resolution, the error can be $\pm$ 4.5e^{-4} м/s^2. This small amount of error results in an error of 4.5 meters in 100 seconds. The use of the counting method, i.e., predicting its own motion from the signals received by the marching and steering engines and thrusters, also contains an uncompensated cumulative error, which depends on



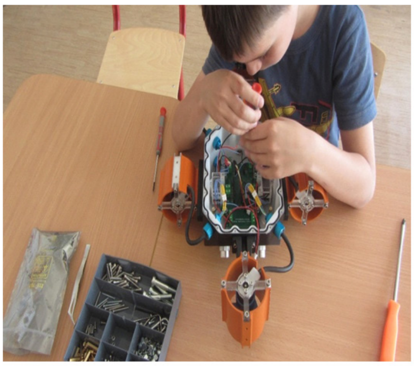


Fig. 8. “Trionix” ROV

the hydrodynamics of the submersible hull, but can be used as one of the methods for determining the distance traveled.

Errors in the inertial system and the counting method are cumulative, and can only be eliminated by referencing to absolute coordinates.

Autonomous non inertial referencing of AUV (by external environment parameters measuring means) can be carried out by absolute and relative coordinates. Relative coordinates are velocity readings relative to water that do not take into account currents and internal waves, so such coordinates contain uncompensated error and cannot be used for long-term navigation. Absolute coordinates are the binding of current AUV position to the position on the map relative to absolute reference points located on the bottom and marked on the map. Such coordinates do not contain error that accumulates over time and can be used for long-term navigation. If reference marks are unambiguously detectable and marked on the map, this problem has been solved long ago and is used by surveyors. But if both landmarks and map are missing, the SLAM (simultaneous localization and mapping) technology can be used for positioning. It is a technology (a set of algorithms) where each robot moves relative to the stationary bottom (for AUV), detects “special points” on the bottom, classifies them and records on the map. Thus, moving along the bottom, a map is constructed, which can be transferred to other AUVs, and can be used for own positioning during the next passage of the surveyed area [6].

Thus, absolute positioning without a predetermined map consists of the following stages:

1. Detecting “special points” on the bottom
2. Identifying “singularities” for further use
3. Classification for mapping
4. Re-detection and positioning

Only sonar gives maximum detection range in water, among sonars maximum resolution and coverage area is given by SSS (side scan sonar), so SSS signals are the most promising for SLAM task.

But it is inexpedient to use SSS when testing AUV in the pool – the walls in the pool are flat and smooth, the acoustic signal has nothing to be reflected from. That is why it is suggested to replace the picture, obtained by SSS when passing over the bottom section, with the image from the video camera, located under the ANPA bottom. The image structure is comparable and suitable for the task of interaction algorithms testing.

The usage of contrasting flat black and white marks lying on the bottom is proposed in order to simplify the task of detection, determination of "features" and classification. Such markers will be detected from any direction, the shape of the pattern on the marker is unique for each marker, so the "features" detection and classification of such markers is a solved problem. The most popular markers for computer vision systems are ArUco markers [6].

The use of ArUco markers allows to imitate inhomogeneities on the bottom and simplify their identification. Such codes are placed either at pre-known coordinates or randomly placed on the bottom, then detected by video cameras of robots and allow to determine and correct their own position relative to the codes. The detection accuracy depends on the resolution of the video camera matrix and the distance from the video camera to the code:

$$\delta x = \frac{r\Delta\varphi}{N},$$

where r is the distance to the bottom, $\Delta\varphi$ is the angular solution of the video camera, N is the number of points in the image for a given dimension.

This error is absolute and does not accumulate over time.

The number and location of such tags is chosen so that for the time of tracking from one tag to another, the robot, when using an inertial system, is brought down to a distance no greater than the width of the bottom inspection by the video camera.

The following options for using the tags:

- When there are many random heterogeneities on the bottom, the very shape of their location is an identifying feature, and then the whole space on the bottom under the AUV can be conditionally divided into a rectangular grid, each cell of which is a label on the map with its parameters and features. It is proposed to set ArUco marks in the nodes of orthogonal grid nodes to model the situation.
- Where the bottom itself is sufficiently uniform, and it is possible to detect individual sparsely located heterogeneities, which cannot be seen several at once in one frame, we have to detect, determine the “features” and classify each such heterogeneity separately. And then the map will have separate randomly located marks, which can be modeled by random arrangement of ArUco tags.
- Another variant of tag arrangement is the random arrangement of repeating or closely shaped heterogeneities that cannot be unambiguously classified individually. But if we analyze the sequence of passing tags, the probability of correct classification and positioning is significantly higher. It is proposed to use randomly arranged repetitive ArUco tags to simulate the situation.

Arrangement of the ArUco tags in the orthogonal grid nodes

An orthogonal grid is placed on the bottom of the reservoir, at the nodes of which the tags are located. The distance between the tags is chosen so that during the time of movement from one tag to another the error of position according to the inertial and counting method does not exceed half the distance between the tags, and the camera found the tag, having corrected its own position. An example of such a grid is shown in the Fig. 9.

Scenario of the robot group`s work:

- robots are assigned an area of work (part of the water area) in advance;
- robots are unleashed at a predetermined location, where they can find their own position and course using a marker on the bottom;
- after launching, the robots start moving towards the pre-set area and survey it if they find an object they are looking for on the bottom, they determine its coordinates, surface and report to the processing center.

An example of the trajectories of two robots obtained from the model is shown in the following Fig. 10.

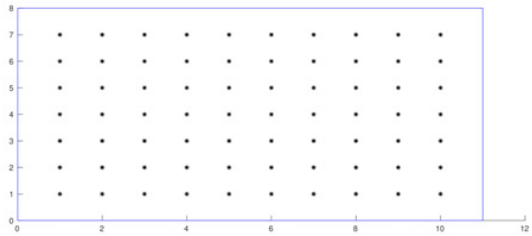


Fig. 9. Example of an orthogonal grid of ArUco tags

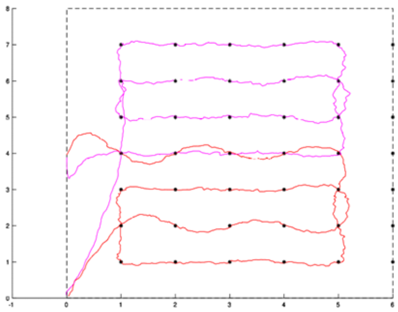


Fig. 10. Example trajectories of robots moving along the nodes of an orthogonal grid over ArUco tags

The figure shows that the robots correct their position according to the data from the tags, but the presence of inertia and errors of inertial navigation and counting leads to a curvilinear movement trajectory of movement. But with the current location of the tags, there is enough accuracy not to go off the set trajectory of the bottom survey. The number of points and the maximum distance between them is determined by the range of vision of the robot video cameras and the distance from the robot to the bottom so that the robot could not pass between the tags and not see a single one.

Random arrangement of the ArUco tags

With randomly positioned tags, only the position of the starting mark is set, by which the robots determine the initial position and course, and the remaining tags can only be used to refine their own position when redetected. For this purpose, SLAM (simultaneous localization and mapping) – the method used to build a map in an unknown space or to update the map in a known space with simultaneous control of the current location and traveled distance – is applied. Popular methods of approximate solution to this problem are particle filter and extended Kalman filter. Such particles will be ArUco tags. The SLAM problem is to compute an estimate of the agent's location x_t and the environmental map m_t from a series of observations ot over a discrete time with sampling step t. All the listed quantities are probabilistic. The goal of the problem is to compute the maximum posterior probability of being at point x_t on map m_t when observing a series ot $o_t : P\left(m_t, x_t \middle| o_{\{1:t\}}\right)$. Applying Bayes' rule is the basis for updating the posterior location sequentially:

$$P\left(x_t \middle| a_t, m_t\right) = \sum\nolimits_{m(t-1)} P\left(o_t \middle| x_t, m_t\right) \sum\nolimits_{x(t-1)} P\left(x_t \middle| x_{(t-1)}\right) P\left(x_{(t-1)} \middle| m_t, o_{(1:t-1)}\right) \Big/ Z.$$

Similarly, the map can be updated sequentially:

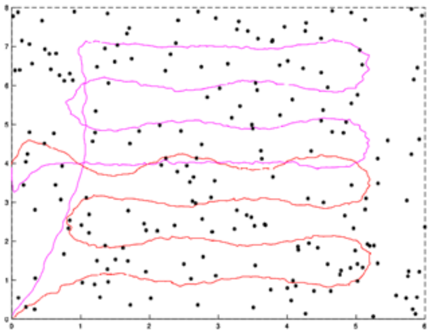


Fig. 11. An example of the trajectory of robots moving on randomly placed tags

$$P\left(m_t \middle| x_t, m_t\right) = \sum\nolimits_{x_t} \sum\nolimits_{m_t} P\left(m_t \middle| x_t, m_{(t-1)}, o_t\right) P\left(m_{(t-1)}, x_t \middle| o_{(1:t-1)}, m_{(t-1)}\right).$$

It is possible to arrive at a local optimal solution by applying the EM algorithm, while operating with two probabilistic variables, as is the case in many other problems of logical inference.

An example of robot trajectories positioned by randomly arranged Arcso-tags is shown in the Fig. 11.

Fig. 11 shows that when the tags are randomly placed, there are areas where it is impossible to determine the absolute position from the tags. The trajectory must be such that with each next tack a portion of the tags that were visible during the last pass is captured, but in places where there are not enough tags, there are failures. Therefore, in order to successfully navigate a group of robots with a random arrangement of tags, it is necessary to provide a significantly higher number of tags on the bottom than in the orthogonal arrangement in the grid nodes.

Using repeating or similar tags for positioning

When using heterogeneities as tags, there is an ambiguity in the classification of such heterogeneities due to the fact that, unlike uniquely structured ArUco tags, where each tag can be identified, heterogeneities are simply protrusions or pits on the bottom. Depending on the angle of observation, these inhomogeneities may have different shapes, create different shadows, and merge with other inhomogeneities. But if we solve the problem of classification of such heterogeneities or artificially simplify it (create heterogeneities of known classes, for example, by the number of vertices), then the positioning problem is reduced to the previous one – by a random set of tags. But such tags will not be unique, i.e. repetitive.

Therefore, it is desirable to limit the number of types of randomly placed tags for modeling. But then for unambiguous positioning of robots on their routes it is necessary to arrange tags so that the positioning is unambiguous, that is, on the next tack robots should see some of the tags that were on the previous tack from the next one. An example of this arrangement is shown in Fig. 12.

Thus, positioning by random heterogeneities has its own difficulties, but they can be solved for each specific case, including basin tests.

Conducting full-scale tests of the AUV group

A pool with transparent water was used for full-scale tests, ArUco tags were placed at the bottom of the pool, and the task of underwater robots was to search for a bright red object on the bottom using a video camera located on the AUV. The AUV positioning was based only on the information from those ArUco tags and the inertial navigation system.

An example of one AUV position during the search of a sunken object on the bottom is shown in Fig. 13.

According to the results of numerous experiments, it was shown that the AUV successfully detects the tags lying on the bottom, determines its position, corrects its trajectory, and not a single case of trajectory

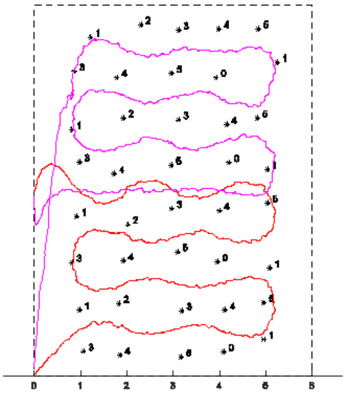


Fig. 12. Example location of heterogeneities for unambiguous positioning

Fig. 13. Example of AUV position when moving "in a loop" during a site survey

failure was detected. The sunken object was detected in 100% of experiments. The frequency of tag placement was determined by the pool depth, the width of the AUV camera view, and the trajectory shape - at least one tag should be visible in each corner of the trajectory. The size of the pool is 4×2 meters, depth is 0.5 meters. AUV movement speed is 0.2 m/s.

When several heterogeneous robots (AUVs and ROVs) were in the pool simultaneously, the navigation also showed its reliability – the robots did not interfere with each other, successfully positioned themselves and compensated for the turbulent flows that they created for each other in the limited volume of water. An example of the mutual positioning of the robots during the tests is shown in the Fig. 14.

Each AUV has a trajectory laid down to capture some of the tags that were visible during the last pass, but there are failures in places where there are not enough tags. Therefore, for successful navigation of a group of robots with random arrangement of tags, it is necessary to provide their significantly greater number on the bottom than with orthogonal arrangement in grid nodes, and trajectories of each AUV are formed so as to reduce the number of possible crossings and parallel tack.

According to the results of the conducted experiments, the whole group successfully inspected the bottom of the pool and detected the object of interest, which confirms the correctness of the implemented algorithms and mathematical models.

Conclusions

The main projects of controlling groups of underwater vehicles were considered, their advantages and disadvantages were analyzed, a group of heterogeneous underwater vehicles developed at SPbGMTU was described, an algorithm for search of sunken objects on the bottom with positioning by ArUco-tagging was

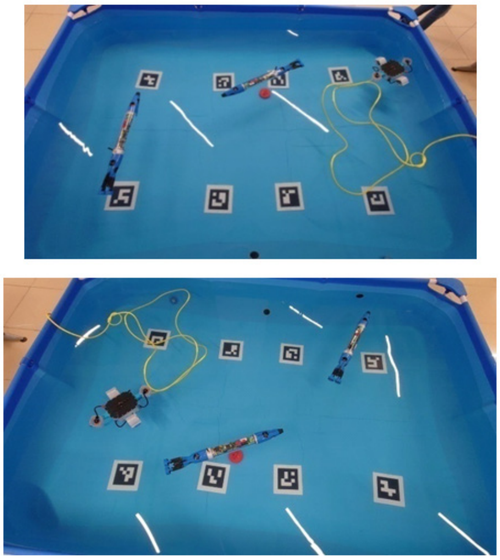


Fig. 14. Examples of simultaneous operation of several robots in a limited water area

proposed during the work. Optical navigation simulating absolute lag, inertial navigation system, communication between robots, transfer of coordinates of detected objects and construction of the bottom map are used.

Model and field tests of control algorithms providing coordinated movement of a group of robots in an uncertain three-dimensional moving environment with possible obstacles to search for sunken objects on the bottom were conducted.

The proposed algorithms can be used for both centralized and decentralized control, which allows using the group as a single telecontrolled object or as an autonomous group performing work without human control.

Model and experimental data confirming the performance of the proposed algorithms and protocols are presented. The developed algorithms can be used in the control systems of mobile robots for their group control in uncertain 3D environments.

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