Open-Source Modular μAUV for Cooperative Missions

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Abstract. This paper examines the results of work undertaken by Saint-Petersburg State Marine Technical University (SMTU) as part of a project involving research into the creation of a multi-agent sensory network based on marine robotic platforms (MRP). In the context of the works mentioned, creation of a micro autonomous underwater vehicle (μAUV) is considered. High maneuverability, the availability of a modular architecture and functions of the group use are required for the developed μAUV. The article describes steps of the vehicle creation: concept development, modeling, design, construction, simulation of the implementation of various vehicle group mission scenarios (Solving the task of monitoring the seabed area). A standard chassis which allows the assembly of all systems, units and mechanisms of the device in minimum dimensions, has been established. Within the project, a software and hardware architecture of the information system of the vehicle was developed, as well as a model of interaction between the μAUV, the wave glider and control center. The work results in two full-scale experimental samples of μAUV capable of working in a group together with the wave gliders, performing the functions of a repeater signal through the environmental boundary, and simulation results of implementing the mission by a group of developed μAUV.

Keywords: Marine multi-agent sensor network · Marine robotic platform · Micro autonomous underwater vehicle · Wave glider-retranslator · Group missions

1 Introduction

In 2016 in the SMTU an initiative project was carried out in the development of research [1–4] on the creation of a multi-agent sensory network of marine robotic platforms.

Within this project, a mathematical and simulation model for the interaction of homogenous/heterogeneous robots was developed, micro autonomous underwater vehicle (μAUV) samples were made, functioning as underwater network agents, as well as control algorithms were transferred from the simulation model to the real controlled objects. As a result, a complex of full-scale experimental samples of

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autonomous unmanned vehicles was created, consisting of a wave glider, acting as an environmental gateway node between an underwater and a surface environment, and a group of μAUV, which is the main task performer of searching for objects and monitoring of the underwater environment.

The innovative aspect of the implemented project is the development of a modular μAUV, able to independently detect objects on the seabed, as well as unification of an open group of different types of robots into a self-organizing network that is stable both to a change in the number of interacting robots and to a low speed of interaction, depending on the mutual arrangement of robots among themselves and on hydrology.

Also the following performance characteristics were required: depth up to 50 m, battery lifetime – not less than 3 h, weight - not more than 10 kg, maximum speed – not less than 3 knots.

Vehicle payload assumed to consist of the main part, presented in all the configurations (CTD sensor and underwater vision system), and some optional parts (side scan sonar, an electromagnetic field detector etc.).

Mathematical modeling of the hydrodynamic and strength characteristics of the vehicle was performed, two full-scale experimental μAUV models were designed, fabricated and assembled, software and hardware architecture of the information system was worked out, and research of vehicles group application was carried out.

Below is a brief description of the main stages of the project.

2 Vehicle Architecture

For μAUV in the basic configuration, the following module composition was defined (Fig. 1): nosecone module, fore variable buoyancy engine (VBE) module, fore through-hull tunnel thruster for vertical motion (TT), electronics and hydro acoustics module, power supply/replacement battery module, aft through-hull tunnel thruster for vertical motion (TT), aft variable buoyancy engine (VBE) module, main thrusters module.

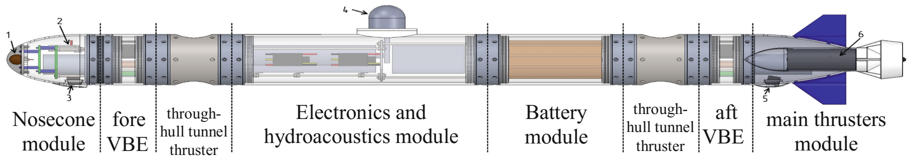

Fig. 1. μAUV modular architecture (1 – forward looking ultrasonic sonar, 2 – temperature, depth, pitch & roll sensor, 3 – fore light, 4 – hydro acoustic modem antenna, 5 – aft light, 6 – main thruster module)

3 Vehicle Functional Systems

Variable buoyancy engine (VBE) provides μAUV buoyancy adjustment for maintaining its position at a given depth. VBE is a piston driven mechanism, changing dry volume of the vehicle. The vehicle has two VBEs –fore and aft VBE modules.

A **sonar system with ultra-short base location** (USBL) modem is used for positioning and navigation. Modem EvoLogics S2C 42/65 USBL was used [7].

Surface radio communication system is built on the basis of WiFi module D-Link DWA-137/A1 with a plug-in external antenna.

Range detection system (Forward looking ultrasonic sonar) was developed and manufactured on the basis of the overall dimensions allocated for a piezoelectric antenna, placed in a vehicle nosecone module, and necessary technical characteristics [7]. Maximum range is 10 m, antenna is circular hemispherical with a radius of 20 mm, located objects must be more than 50 mm, central frequency is 460 kHz. The width of the transducer directivity characteristic is about 70°.

Vehicle CPU module is presented by board Beaglebone Black [7], operating under Linux OS. The main advantages of the board are compactness and a large number of integrated peripherals.

Temperature, depth, pitch & roll sensor, located in the nasal module, is built on the basis of the OpenROV IMU/Compass/Depth Module [7]. This module is well proven in use on the ROV previously developed by the authors [7]. Overall size of the selected module is comparable with the leaders according to the declared characteristics and provides the necessary technical characteristics of the vehicle.

Underwater vision system includes camera module, fore and aft lights. As a module of the video camera, the board Aptina RB HD Camera Cape for BeagleBone Black A0-01 [7] was used. As a fore and aft lights of the underwater vision system OpenROV External Light Cube models were selected, [7].

Power supply system μAUV built on Li-ion rechargeable batteries. As a basic element, the element Samsung 18650 was used, which, due to its geometric characteristics, allowed to fill the battery module space quite efficiently. To obtain the required voltage and capacity, 28 such elements are used. The battery assembly provides a voltage of 14.8 V and a capacity of 18.2 Ah, which gives the required power consumption for 3 h.

Propulsion system of the vehicle is based on two main thrusters CrustCrawler 400HFS [7], placed in a vehicle tailcone module.

Module of through-hull tunnel thruster for vertical motion is based on the brushless motors Turnigy Aerodrive DST-700 [7] with a corresponding driver.

The use of the above components determined the overall performance of the vehicle module and of the assembled μAUV.

4 Simulation of the Main Vehicle Characteristics

For preliminary hydrodynamic analysis, assessment of hydrodynamic forces and moments in longitudinal-vertical and longitudinal-horizontal planes was carried out. The Ship Dynamic Software (SMTU) generates hydrodynamic characteristics on the basis of information about the shape of the object.

Based on the results of the calculations, it was concluded that the dynamic stability of the rectilinear μAUV motion is ensured in both the vertical and horizontal planes, which is an extremely important condition for a high-quality automated control of a moving object in a target tracking mode, searching, monitoring of the water area and vertical self-balancing.

Required level of damping components hydrodynamic characteristics is completely provided by propellers nozzles, without requiring the installation of additional tail empennage elements. As to the positional hydrodynamic characteristics, it can be noted, that they, in general, are a completely traditional for objects of this type.

An important element is the depth control system of the vehicle. On the developed vehicle two systems are used, allowing to control its depth of immersion: tunnel thrusters for vertical motion and VBE. The method used for depth control is a combination of proportional-derivative (PD) controller for propulsion and steering complex and PID controller for VBE. The aim of the method is to combine vehicle fast-moving to a given depth with low power consumption in a steady state. The flowchart of the algorithm is given on the Fig. 2:

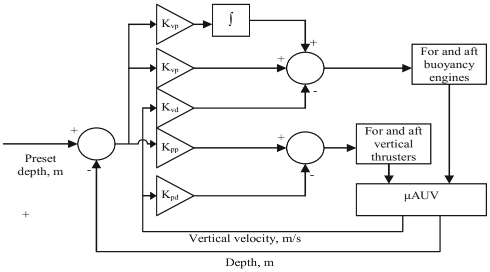

Fig. 2. Block diagram of depth control algorithm

As a basis for PID controller implementation the classical construction principle with a modification of the calculation of the integral component was adopted:

$$\begin{cases} F(t) = K_p e(t) + K_d v(t) + \sum_{\tau=0}^{t} I_q \\ I_q = K_i T \dfrac{V}{a \cdot e(t)} \end{cases}, где \begin{cases} V = 0, |v(t)| \geq b \\ V = 1, |v(t)| < b \end{cases}, \tag{1}$$

where K_p, K_d, K_i – PID controller coefficients, $e(t)$ – residual of the parameter to be stabilized, $v(t)$ – rate of change of the parameter to be stabilized, T – integration period, a, b – customizable coefficients.

It follows from Fig. 3 that through-hull tunnel thrusters for vertical motion operate for a short time, providing a vertical speed at the initial stage of functioning, VBE starts to work in parallel, and within 15 s the vehicle stabilizes at a new depth without help of thrusters for vertical motion and additional energy costs.

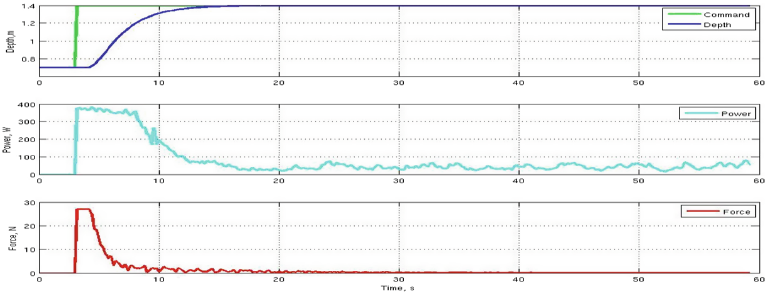

Fig. 3. Graphs of the main depth control algorithm parameters

Result of manufacturing µAUV (in its basic configuration) is shown in Fig. 4.

Fig. 4. µAUV appearance (in the basic configuration)

5 Software and Hardware Architecture of the Vehicle Information System

Functionality of the software and hardware complex is divided into two levels - upper and lower. Functionality (subroutines) of the low-level functionality is responsible for the basic elements of the device's operation ensuring trouble-free operation of the device, protection from over-reaching of acceptable ranges of operation, as well as the functioning of high-level subroutines. The main difference between the functionality of the lower and upper levels is that the lower layer itself is not responsible for the solution of the problem, instead it facilitates the performance of high-level tasks.

The basic functions (subroutines) include: holding the preset depth, transitioning between different layers of depth, remaining within specified coordinates, avoiding collisions with obstacles directly in the vehicle's path, finding the vehicle's own coordinates, movement to a point with given coordinates, recognition of objects on the sea floor.

High-level functionality (subprograms) includes: construction of a survey route by the perimeter of the water area, informing the control center about changing the status of the mission (the object was found in the selected zone, the object was not found), changing the operating mode according to the control center command, returning the vehicle to base.

The hardware architecture of the µAUV information network is based on the “star” topology, in which the Beaglebone black processor plays the role of the network central module, and the peripheral elements are the sensors and actuators. Communication between the central module and peripheral devices is provided through various communication channels: SPI, I2C, PWM, UART.

The electronics and hydroacoustics module is the most loaded with electronics. There are: a hydro-acoustic modem, central processor, video camera and drivers for all brushless motors in the device. The modem antenna is also attached to this module, Fig. 5.

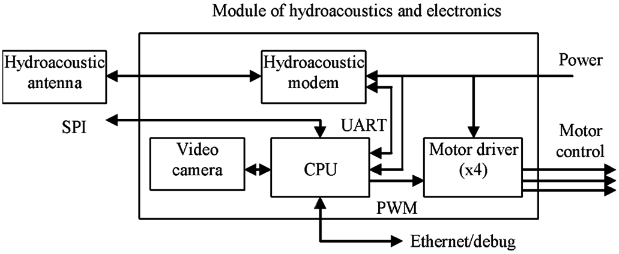

Fig. 5. Functional diagram of the electronics and hydroacoustics module

In the stern module there are two main thrusters and a stern light source. The software of the device is based on the ROS framework [7].

6 Data Flow Repeater of Data Flow from µAUV to the Control Center

Retransmission of the data flow between the µAUV and the control center is carried out over a mixed hydroacoustic/radio channel using the wave glider repeater located in the mission area of the µAUV grouping.

Retranslation of data between µAUV and control center can be constructed either by full retransmission of all data between µAUV and control center, or by preliminary processing and reduction of the transferred data.

7 Control Center

The control center post interacts primarily with the surface module of the wave glider repeater. The exchange of information between the surface module and the control center is carried out via WiFi.

To determine the coordinates of underwater vehicles, the surface wave module of the wave glider must know its own coordinates and course, for which in open water conditions it is supposed to use a GNSS receiver of the coordinates and course, and under test conditions in the experimental pool - an ultrasound system for positioning inside the room.

Software for the control center is based on NS2 by Nonius Engineering [7], and provides the following basic capabilities: display of positions: underwater vehicles, surface wave module of a repeater glider, search area, the ability to specify the search area, sending commands to the mission execution unit (return to the base, assigning a new area, etc.).

8 Group Application of Vehicles

Upon completion of the test phase, it is proposed to use group vehicles with multi-beam echo sounders as a payload. Consider the effectiveness of the application of a group of such similar μAUVs for solving the problem of monitoring the sea surface of a complex shape. The communication between μAUV, mutual positioning and control is limited by relatively low-speed modems and limitations on the range of communication. Therefore, the task of managing the μAUV group is to coordinate the actions of individual μAUVs in such a way as to achieve high efficiency in solving a common problem with a limited information transfer rate between the μAUV. The question remains - how does the number of μAUVs in the group affect the effectiveness? How many μAUVs are needed to effectively solve the problem?

Several variants of the solution of this problem were modeled:

a. Use of one AUV with a predetermined sequence program;
b. Use of the AUV group moving in a line to increase the width of the investigated area in one pass;
c. Use of the AUV group with the simplest group management algorithms, such as “flock” or “swarm”;
d. Use of the AUV group with algorithms of multi-agent systems (MAS).

The simulation was carried out in the Matlab package. When using a multi-beam sounder in one pass of one AUV, it is possible to survey an area of no more than 10 m at a depth of 8−12 m. Thus, one AUV, moving along the optimal path from the point of view of the number of turns of the trajectory at a speed of 3 m/s, by 98 h. An example of a territory survey by a single robot is shown in Fig. 6a:

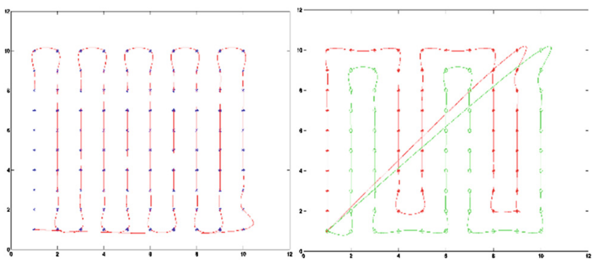

Fig. 6. An example of a trajectory by (a) a single robot (b) two robots side-by-side

Figure 6a shows that the robot moves in a “snaking” path, since it is this type of motion that ensures the least overlapping of the coverage areas when the robot examines an arbitrary territory.

The movement of several AUVs side-by-side sharply increases the width of the surveyed space by the number of AUVs in the group, but at the same time complicates the maneuvers. Thus, when two AUVs moved in the same rank, the time required for the survey was 51 h, that is, almost twice as effective as using one AUV. But with the increase in the number of AUVs to 10, the efficiency drops sharply – about 36 h is obtained during the simulation. No information exchange is required between the AUVs, only mutual positioning is sufficient.

An example of a survey of the territory by two AUVs is shown in Fig. 6b.

Figure 6b shows that in the process of maneuvering, one robot is forced to wait until the second takes the required position for further side-by-side movement. This expectation reduces the effectiveness of this method, especially when a lot of robots are involved in the line and the waiting time is significant compared to the group’s overall working time.

Using the simplest control algorithms that do not require trajectory planning and for which only mutual positioning and marking of the investigated areas is sufficient. The “swarm” type algorithm can be implemented in the form of a desire to take the nearest unexplored site on the map as far from other AUVs. More complex algorithms suggest the development of a non-linear function of the “cost” of each unknown site, when the goal of each AUV is to take unexplored objects of maximum cost faster than other AUVs. Examples of the trajectories of motion along the described algorithms are given in Fig. 7.

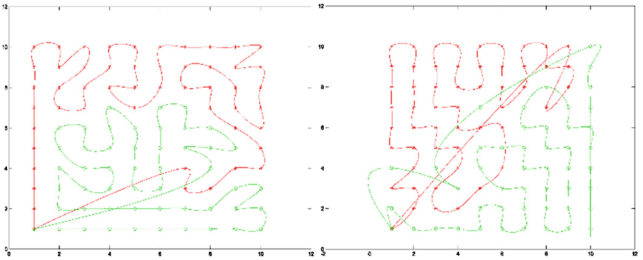

Fig. 7. An example of the trajectory of two robots using the “swarm” and “flock” algorithm

The “swarm” and “flock” algorithms allow to automatically adapt to any shape of the surveyed territory, but they are not optimized for the number of turns and intersections of the trajectories.

Multi-agent control systems (MAS) assume the presence of distributed computing and planning of joint actions. Most of the research on MAS is currently based on the search for a reliable algorithm for ensuring agreement among agents performing a single task [8, 9]. At the same time, restrictions are placed on the speed of information exchange between agents, on the range of communication (not all agents can directly inform everyone else about the information, before some agents the message must be delivered along the chain) and positioning accuracy. Such algorithms are called "consensus problems" in distributed systems [9, 10] and are implemented in open source systems DELLPHIS, Actors, Blackboards and Contract Net Protocol. The protocol of exchange between the AUVs is also standardized and is called JADE.

An example of a survey trajectory for two robots using the MAC algorithm is shown in Fig. 8. It is clear that robots plan their work, their trajectories do not intersect, the number of turns is less than in other algorithms, and none of the robots stand idle in anticipation of another.

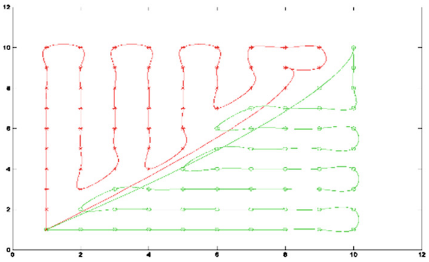

Fig. 8. An example of a motion trajectory of two robots according to the MAS algorithm

The following mission execution and operational control protocol is used:

1. Each agent must know the whole scenario of the execution of the application;
2. Each agent must know the distribution of performers according to the script's work;
3. Each agent should know what kind of actions and what agents are being performed at the moment.

If conditions for the script execution change, the scenario is changed using the Contract NET Protocol (CNP).

As group control efficiency, the criterion of loading time of each μAUV was used for the entire period of the group's work:

$$E = \frac{T_1}{N \cdot T_N} \cdot 100\%, \tag{2}$$

where N is the number of members of the group; T_1 – the time during which one robot can perform the entire task independently; T_N – the time for which the task is performed by a group of N members. Results are shown in Table 1.

As can be seen in Table 1, using MAS algorithms makes it possible to use larger groups of robots more efficiently. Other algorithms considered with an increase in the number of robots are much more losing the efficiency of using each robot than with the use of MAS. This is due, apparently, to the possibility of trajectory planning by each robot, taking into account the movement of the other participants and efficient exchange of current information between the robots.

Table 1. Results of modeling the survey of the territory by the AUV group

Management structure	AUV quantity	Survey time, h	Effectiveness, %
1. One AUV with the given program	1	98:00	100%
2. Movement in a line	2	51:12	95%
	10	35:56	28.8%
3. Algorithm “swarm”	2	50:38	96.7%
	10	32:47	29.9%
4. Algorithm “flock”	2	53:04	92.3%
	10	28:23	34.3%
5. MAS	2	51:07	95.9%
	10	22:15	44.0%
	20	12:27	39.3%

9 Conclusion

While implementing project by the SMTU to create μAUV with the function of group control, the following tasks were solved:

- developed a conceptual model of the joint use of the μAUV group and the wave glider repeater within the multi-agent sensor network;
- μAUV appearance and modular architecture were developed;
- computational estimation of the hydrodynamic, strength, and acoustic, energy characteristics of μAUV is carried out;
- constructive elements of the μAUV hull structure, parts and mechanical parts of the apparatus systems were manufactured;
- two μAUV are assembled;
- basic software for μAUV, wave glider and control center architecture are developed with the possibility of further development and refinement;
- technical solution has been developed, which provides for carrying out experiments with the MRP complex in a towing tank;
- comparative analysis of various μAUV group application algorithms for the water area survey is performed;
- plan for further testing of μAUV in the SMTU towing tank is developed.

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