Development of a digital platform for the implementation of distributed control and navigation systems for underwater robotic systems performing technological operations in Arctic

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Abstract. The paper proposes the architecture of a digital platform for the implementation of distributed control and navigation systems for underwater robotic systems that perform technological operations in Arctic. A system of command has been developed for this platform, which provides flexible assignment of various types and purposes of underwater robots missions. The concept of creating distributed control systems of the underwater robots is proposed. It provides the compatibility of existing on-board underwater robots systems with the proposed solution based on compact hydroacoustic systems of global hydroacoustic navigation developed in PAO “Dalpribor” (Vladivostok).

1. Introduction

Currently, in the offshore zone of Russia (and especially in the Arctic seas), a lot of work are carried out to extract hydrocarbons and other minerals using surface and underwater robotic systems. Work is underway to efficiently navigate ships in the difficult ice conditions of the northern seas. Technical means of underwater extraction and transportation of this raw material (especially under the ice) and the wiring of ships in the ice require continuous monitoring of their performance, possible repairs, and security (protection against unauthorized entry). The traditional use of autonomous underwater vehicles mainly allows performing relatively simple survey operations \cite{1, 2}, and more complex ones \cite{3}, implemented near underwater structures and objects \cite{4}, are performed using remote operated vehicles, the use of which is possible only in the absence of ice cover, as well as in the presence of expensive support vessels and numerous highly qualified maintenance personnel.

At the same time, to solve the problems of control, navigation, and communication with the underwater vehicle, traditional hydroacoustic systems are used, which require a long deployment and configuration, special acoustic communication systems that have a very low bandwidth and a limited distance of this communication. All this does not allow to provide effective high-quality navigation
and control of the underwater vehicles performing complex technological works (especially in the presence of variable and unknown underwater currents). The solution to this problem is the use of hydroacoustic stations and complexes equipped with sensors (receivers and transmitters) of a large range, which can determine the exact coordinates of all surface and underwater objects, as well as provide the exchange of navigation information between these objects, implementing a global navigation control system over long sea areas.

Currently, one of the key tasks is to reduce the complexity of the application of underwater vehicles, which is achieved by using a new type of hydroacoustic navigation systems. This navigation systems eliminate the lengthy installation and calibration procedure of traditional systems with a long base in the work area. This task can be solved in two directions. The first is the creation of networks of stationary bottom hydroacoustic stations that allow providing coverage of the underwater situation in a given area of the World Ocean. An example of the implementation of an underwater acoustic network is the Telesonar and SeaWeb systems [5-9]. Telesonar connects distributed underwater nodes, combines them into a single resource, processes information and transmits it to the underwater space. SeaWeb provides command transmission, communication, and navigation infrastructure to coordinate autonomous nodes to perform assigned tasks anywhere in the underwater environment. However, the use of such networks has significant disadvantages, consisting in the high cost of deployment and operation, as well as fixing their position in a specific area of work. Another approach is to use mobile autonomous navigation systems that provide navigation of the underwater vehicle during its operation with the help of surface autonomous vehicles [10]. However, such systems, providing navigation support for the underwater vehicles when they perform work in previously unprepared areas, cannot implement simultaneous monitoring of the underwater and surface situation, track the current position of the underwater vehicle, as well as give it new target designations in accordance with the information received.

Currently, the main elements of the basic components of compact hydroacoustic information navigation systems (HINS) for creating global navigation have already been developed and partially tested at PAO "Dalpribor" (Vladivostok). These components allow one to create an underwater communication and monitoring infrastructure that implements digital systems for complex automation of many underwater technological operations.

To successful use of HINS it is necessary to develop a new creation principle for underwater vehicles information control systems (ICS). It will ensure effective cooperation among themselves and with the elements of underwater infrastructure for the successful solution of the tasks above. The paper describes the architecture of the proposed digital platform (DP) for the implementation of distributed navigation and control systems based on these HINS, as well as the results of preliminary studies of its operation.

2. The concept of a distributed control and navigation system of underwater vehicles based on HINS

The line of high-precision HINS developed by PAO "Dalpribor" (Vladivostok) is shown in Figure 1, and their main characteristics are given in Table 1.
a)

Figure 1. General view of the new hydroacoustic stations developed at PAO "Dalpribor"

Table 1. The main technical characteristics of HINS

|                | a)            | b)            | c)                        |
|----------------|---------------|---------------|---------------------------|
| Distance       | up to 1500 m  | 700 m         | ≈ 40,0 km (deep seas, Japan, Okhotsk, and so on) |
|                | ± 0.1 m (up to 1500 m), 0.5° | bearing 1.0° 2% from distance | ≈ 15,0 km (shallow sea, Barents, Azov and so on) |
| Accuracy       |               | bearing 1.0° 2% from distance |                           |
| Overview sector| 120°          | 360°          | 360°                      |
| Power          | up to 20 W    | up to 100 W   | up to 3…5 kW              |
| Weight in the air | 9 kg         | 9.4 kg        | with support equipment up to 3000 kg |

Based on proposed ICS and HINS, it is planned to create a basic underwater monitoring, communication, and control infrastructure for complex automation of many underwater technological operations. However, the absence of modern robotic systems that can effectively interact with underwater hydroacoustic stations and elements of underwater infrastructure does not yet allow us to successfully solve the above tasks.

Thus, the creation of the autonomous underwater robotic complexes (UV), which includes the underwater vehicles, HINS, payload modules, as well as support and maintenance tools, will provide the development of solutions, which will allow performing technological operations in the Arctic.

The developed DP is designed to automate the following activities: monitoring the state of underwater infrastructure objects (communication lines, pipelines, mining equipment, etc.), mapping and geodesic work, determining the parameters and boundaries of physical fields, zones of distribution of chemical compounds (pollution zones) and bioresources, protection of underwater and surface infrastructure objects (underwater mariculture farms, borders of water reserves, etc.), tracking moving objects, searching for objects of a given type (biological, man-made, etc.), performing underwater technological operations (welding, cutting, cleaning, etc.).

The general scheme of DP for interaction with the UV based on the HINS is shown in Figure 2.
As can be seen from the presented Figure, the interaction between the operator's automated workplace (AW) and the UV occurs through a hydroacoustic communication channel implemented in the HINS. Through this channel from the AW to UV formed mission and individual commands are transmitted. The HINS sent UV position in the global coordinate system. At the same time, from UV to AW information about the current state of the UV, its equipment, and the occurrence of specified events (detection of the desired object, the end of the mission, etc.) is transmitted through the specified channels.

To implement the described concept, an approach to the creation of ICS for UV was developed. It ensures the compatibility of existing onboard control system of UV with the proposed solution based on GINS, as well as a command system that provides flexible assignment of UV missions of various types.

3. Implementation of the ICS UV compatible with the digital platform for the creation of distributed control and navigation systems

The general scheme of the ICS implementation, which ensures the compatibility of the onboard ICS UV with the digital platform is shown in Figure 3.

As one can see from the presented Figure the ICS UV consists of two main parts. The first part is the initial onboard UV control system, which ensures its movement to a given point in space with a given speed, receiving data from on-board sensors, as well as controlling the operation of on-board equipment. The second part (see HLCCS in Figure 3) provides the possibility of interaction of the UV through an acoustic communication channel with HINS and AW.

The specified part has a modular structure, each module works independently of each other in separate threads. The message receiving/transmitting module performs the following tasks:
- receiving data over the TCP/IP or UDP/IP protocol from the hydro acoustic modem (HM), which supports communication with the HINS though acoustic communication channel;
- decoding the received data and forming a message that can be processed by the manager, and stored it in the message queue available to the manager;
- selecting a message from the message queue formed by the manager during its operation, encoding the message into the digital platform format and transmitting it via TCP (UDP) to the acoustic modem for sending to the AW.

The Mission Manager performs the following tasks:
- analysis of the queue of messages received from the HINS, and performing the actions prescribed by these messages (formation and correction of missions, forwarding the data received in the messages to the onboard ICS UV);
- control the execution of the current mission and trigger the behavior corresponding to the current mission command;
- identification and processing of external events that require the formation of a message and sending via an acoustic channel to the operator's console;
- generating and sending internal onboard ICS UV messages containing navigation information received from the HINS, and messages containing program signals of UV movement generated by the behavior implementing the current mission command.

The main task performed by the behavior module is to generate program motion signals set by the corresponding mission command and its parameters.

The algorithm of each behavior consists in calculating in real time the position of the program point that sets the desired position of the UV on the trajectory corresponding to the type of command. In this case, the program point is moved at the speed specified in the command. When the UV enters the specified neighborhood of the end point of the trajectory, the behavior sets a flag for successful command finished, after which the mission manager activates the execution of the next mission command.

The basis of the proposed digital platform is a message system that provides information transfer and interaction between the operator and the UV in the framework of this digital platform.

The message is a telegram (packet, frame) of variable length (depending on the type of command), which has the following structure:

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HEADER - DATA - CHECKSUM.
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The command header has the same structure for all types of commands and consists of the following consecutive fields:
- message type is 8 bits;
- command number is 8 bit;
- the recipient's address is 15 bits;
- sender address is 15 bits;
- confirmation flag (CF) is 2 bits (1 bit is whether the message is confirmation, 2 bits is whether confirmation is needed);
- data size-fixed for each message type;
- checksum (CRC) – 8 bits.

1. Commands of Mission execution sequence Management - allow to change the prescribed order of execution of commands in a mission, suspend or terminate it ahead of schedule. These commands are:

- **OK** - confirmation of the successful finish of the current mission command.
- **FAILURE** - the command finished with an error (the command cannot be executed).
- **GOTO** - unconditional transition to the specified mission command.
- **BACK** – return to the starting point.
- **STOP** - abort the current mission and wait for commands or a new mission to arrive.
- **PAUSE** – to pause the mission. Resume from the current command after the START command.
- **START** – start the mission to complete or continue the mission after PAUSE.
- **UP** – emergency ascent.
- **WAIT** – the waiting mode for a specified time interval/up to a specified time point.
- **ACKN**-confirmation of receiving the message.

2. Commands that control the loading of the mission which provide the process of remote loading and correction of the URC mission.

- **LOAD_MISS_ST** – beginning of loading missions.
LOAD_MISS_END – end of loading the mission.
REMOVE_CMD - the removal of a sequence of commands from the mission.
UPLOAD_MISS_ST – start of uploading the mission.
UPLOAD_MISS_END – the end of the upload of the mission.
NON_CORRECT_MISS_TRANSF – the received mission is incorrect.
GET_HASH_MISS - request for the mission hash.
HASH_MISS – the hash of the mission.

3. Information messages which are used to request and transmit information between the UV and the operator's console. Information messages are not included in the mission and can be transmitted independently of the mission command being executed.

NAVIG – information about the current position of the UV received from the hydroacoustic station
GET_STATUS - request for the UV status.
STATUS_00 – the current composition of the UV equipment.
STATUS_01 – the number of the mission command being executed.
STATUS_02 – current navigation data.
STATUS_03-STATUS_35 – hardware status.
EVENT_HAPPEN - message about the occurrence of the event.
SET_EVENT - setting the event and its threshold value to which the UV should respond.
REMOVE_EVENT - delete the event that the UV should respond to.
SET_PARAM – set the value of the parameter.

4. The mission commands set the route and mode of movement of the UV [11]. Each command provides the movement of the UV from its current position to the position specified by the command, in accordance with the desired mode of movement [12]. The main primitives of movement are:

- movement to a given point (the resulting trajectory does not matter),
- movement in a straight line,
- movement along a spline.

The method of implementing the modes of movement of the UV set in the mission commands is not specified and depends on the features of the onboard ICS of a particular UV.

The following commands are defined as basic commands:

MOVE2P - moving to a point with the specified coordinates at the specified speed.
MOVE_STR - moving to a point with the specified coordinates at the specified speed in a straight line.
MOVE_SMOOTH - move to a point with the specified coordinates with the specified orientation.
SEARCH_SPR - search in a given area using the Archimedean spiral trajectory.
SEARCH_SNAKE - search for a divergent snake.
MOVE_ALONG – movement along an extended object.
EQUIP – equipment management.
TRACKING – tracking the specified object.

5. Commands for realization of group control. As a group control, one considers the formation control mode, which implements the "leader-followers" strategy. In this mode, one UV-leader is set in the UV group, and all the others are set as UV-followers. The mission is loaded only on the UV-leader, and the UV-followers must follow the leader, holding the specified position relative to the leader.

The basic group movement commands are defined as:

GR_SET_ROLE - set the role of the UV in the group (leader or follower).
GR_LIDER_FOLLOWING – follow the leader.
GR_MOVE2IP - exit to the starting position for the movement behind the leader.
GR_DISMISSED – the dismissed the group.

It should be noted that the described set of messages can be expanded if the message format is preserved.

4. Simulation results
Mathematical simulation of data transmission between the AW and the UV by using proposed digital platform was conducted in the V-REP. Two nodes placed on different distances (see the Distance column in Tables 2 and 3) during this simulation. The first node was the HINS, which transmitted test mission to the second node through the simulated hydroacoustic communication channel. The second node was the UV. This test mission has a form of a sequence of commands (messages) in DP’s format. The HINS position coordinates were constant with a value of (0,0,0) in all experiments.

![Figure 4. The UV movement trajectory formed by the main mission](image)

| №  | Distance, m | Transfer rate, Kbps | Receiving message probability | Average number of commands, msg per min | Missed messages number | Main mission transfer time, seconds |
|----|-------------|---------------------|-------------------------------|----------------------------------------|------------------------|-------------------------------------|
| 1  | 100         | 7                   | 0.99                          | 268.9454243                            | 2                      | 9.369930744                         |
| 2  | 400         | 4                   | 0.9                           | 75.70242279                            | 7                      | 33.28823447                         |
| 3  | 400         | 0.8                 | 0.8                           | 36.02922293                            | 25                     | 69.94322371                         |
| 4  | 1500        | 0.8                 | 0.8                           | 17.60655195                            | 13                     | 143.1285357                         |
| 5  | 7000        | 0.2                 | 0.65                          | 2.120489948                            | 46                     | 1188.404596                         |

| №  | Distance, m | Transfer rate, Kbps | Receiving message probability | Average number of commands, msg per min | Missed messages number | Main mission transfer time, seconds |
|----|-------------|---------------------|-------------------------------|----------------------------------------|------------------------|-------------------------------------|
| 1  | 100         | 7                   | 0.99                          | 290.9631414                            | 0                      | 2.474540234                         |
| 2  | 400         | 4                   | 0.9                           | 58.89287018                            | 5                      | 12.22558856                         |
| 3  | 400         | 0.8                 | 0.8                           | 33.25837225                            | 9                      | 21.64868426                         |
| 4  | 1500        | 0.8                 | 0.8                           | 12.74355427                            | 8                      | 56.49915123                         |
| 5  | 7000        | 0.2                 | 0.65                          | 2.253563759                            | 12                     | 319.4939559                         |

The two operation modes were investigated in simulation. The first mode is investigation of mission transmission to the UV and the second mode is mission correction. For simulation, a typical UV’s mission was chosen. This mission presents a survey-search movement consisting of a sequence of rectilinear traverses covering a given sea area (see Figure 4). The main mission consisted of 40 MOVE2P commands, which set the coordinates of the meander nodal points and the UV’s movement velocity (1.5 m / s) on each straight section. The Y-coordinates for all nodal points were constant, as shown in Figure 4, and the X-axis coordinates were shifted relative compare with initial position of the
UV. Therewith, two additional commands were sent to enable and disable the mission loading mode: LOAD_MISS_ST and LOAD_MISS_END, respectively. The first, the LOAD_MISS_ST command was sent from the HINS to the UV, then the main mission of 40 movement commands with given points and velocity was transmitted. Last command LOAD_MISS_END was sent in the end. Confirmation messages were transmitted from the UV to the HINS in the process of mission transmitting. This procedure provided guaranteed receiving mission. The correctness of the entire mission was ensured by checking the hash total for all commands of the transmitted mission.

It should be pointed that the main mission was generated automatically by using unified instructions offered by DP, which were implemented as library of functions. The transmission of all messages between the HINS and the UV was carried out through a simulated hydroacoustic communication channel. The following parameters of this communication channel were simulated: 1) transfer rate, 2) receiving message probability, 3) speed of propagation of a sound wave in water, which was constant and amounted to 1500 m/s.

The simulation results have shown that the proposed DP provide reliable missions loading and obtaining information about the state of the UV at different speeds and in different operating conditions of the acoustic communication channel (see the Tables 2 and 3).

5. Conclusion
The paper proposes the DP architecture for the implementation of distributed control and navigation systems for the UVs performing technological operations in Arctic conditions. This platform also proposes a command system that provides flexible assignment of various types of the UV's missions. The proposed DP is built based on compact global hydroacoustic navigation system, developed by PAO “DALPRIBOR”. The simulation research has confirmed the performance, efficiency, and reliability of the proposed architecture and solutions.

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