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Integrated Positioning System of Autonomous Underwater Robot and Its Application in High Latitudes of Arctic Zone

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1. Introduction

Nowadays various robots are developed and used for deep-water operations and oceanic research including autonomous unmanned underwater vehicles (AUV), which are particularly effective for operations at great depths, under ice, and in other extreme surrounding. A considerable number of such vehicles have been developed in several countries. They are designed for object search, bottom configuration survey, geological survey, scientific research and a wide range of military missions.

Modern underwater vehicles generally comprise positioning systems that include onboard autonomous, acoustic and satellite positioning systems (Romero & Lester, 2000; Theseus AUV; Maridan AUV). For example, the autonomous vehicle *Hugin* by *C&C* is equipped with an inertial positioning system (IPS) based on fiber-optic gyros, which is integrated with an *RD Instruments* Doppler log, a depth sensor, a height sensor and an ultra-short base acoustic system (USBL) by *Konsberg Simrad*. The *Maridan* company jointly with the Technical University of Denmark and *Kearfott Guidance and Navigation Corporation*, USA, have developed the *Marpos* system to be installed onboard an AUV. *Marpos* is an integrated Doppler inertial positioning system with the high-precision strap-down inertial positioning system *KN5053* as its core equipped with laser gyros, which was developed by the *Kearfott* company. The IPS is adjusted using the data of the *RDI* Doppler log, which measures the vehicle speed over the bottom or through the water while a *DGPS* receiver is used for surface positioning.

The similar method was applied for development of the *Oracle* vehicle by *Thales-Bluefin*. Its positioning is based on the *Litton LN-250 MIMU* system consisting of three fiber-optic gyros and three accelerometers installed on the inertial unit. In addition the positioning system incorporates the following: a digital quartz pressure (depth) sensor, an ultra-short base acoustic positioning system, and a 600 kHz Doppler log.

The positioning system of *Boeing/Fugro/ Oceaneering* vehicles is based on total integration of all the available sensors including an *IPS*, a Doppler log, a height sensor, a depth sensor, long-base systems and ultra-short base systems.

Russian Institute of Marine Technology Problems (IMTP) FEB RAS has many years of experience of developing and using AUVs for solving practical tasks at depths up to 6,000 m

(Ageev et al., 2005). This also includes experience of development and operation of various positioning devices. The positioning devices that had been developed over the past years had various operating ranges, various precision rates and differed considerably in the system integration approach but in general they were designed to solve the tasks of enabling secure and reliable positioning of AUVs for various applications.

Judging from the experience of all previous work the list of the said problems includes the following:

- determination and display onboard the carrier ship of the current AUV position in the shallow sea and deep sea,
- secure performance of operation missions near the sea bottom and bottom-level obstructions,
- mission performance control onboard the ship,
- obtaining the AUV system status information onboard the ship,
- current AUV positioning onboard the AUV,
- efficiency improvement and expansion of the positioning system operation range by eliminating the fixed devices (beacons),
- high-speed data exchange between the AUV and the ship via an acoustic communication link,
- transporting the vehicle into the acoustic devices operation range and providing communication for short-range control.
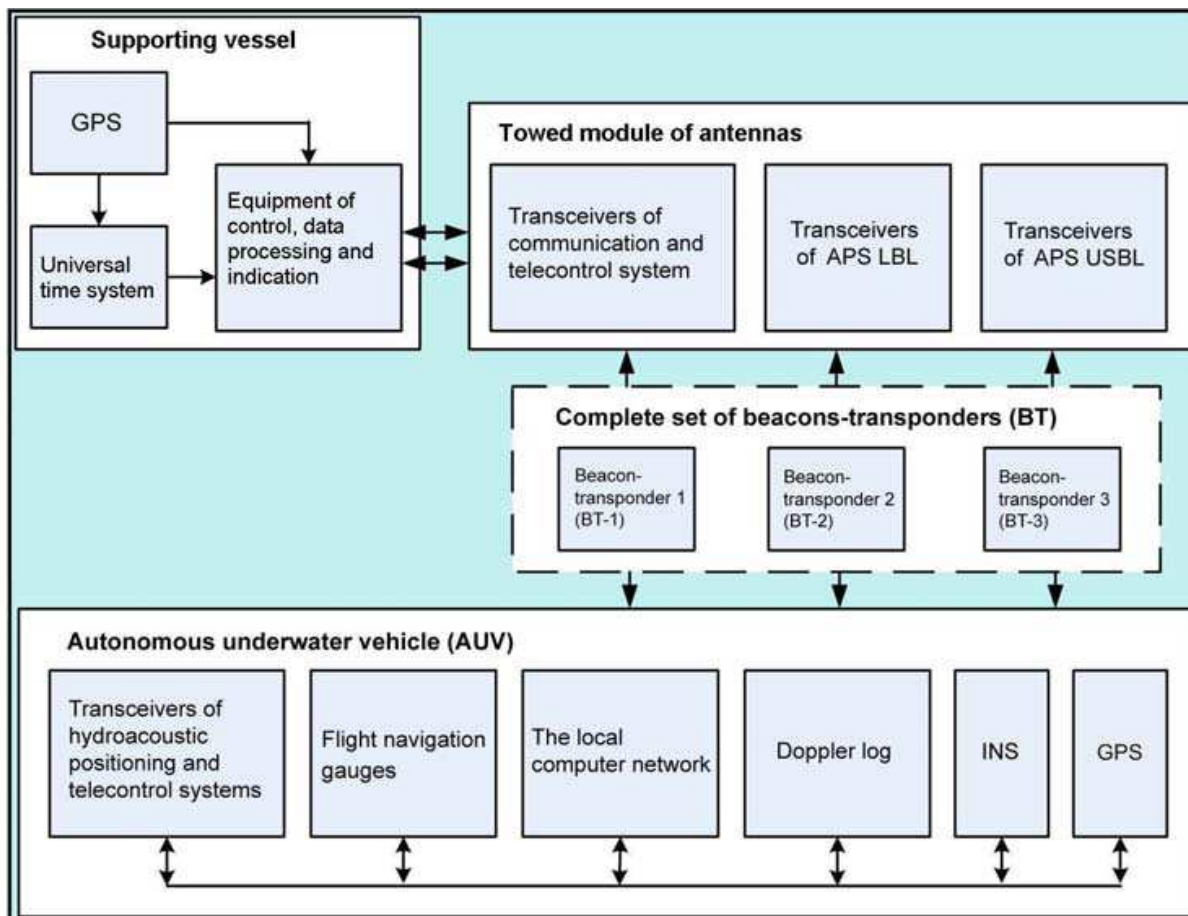

Fig. 1. AUV positioning devices

The positioning equipment of modern vehicles developed by the IMTP FEB RAS comprises units of onboard autonomous, acoustic and satellite positioning systems (Ageev et al., 2005; Kiselyov et al., 2004; Inzartsev et al., 2007a; Inzartsev et al., 2007b). Each system in its turn is a system of devices incorporated in the integral base configuration of AUV systems and shipboard equipment (fig. 1).

Let us consider next some architecture features and characteristics of particular systems incorporated in the navigation complex.

2. Acoustic positioning complex

The core of the AUV navigation system is an acoustic positioning complex which incorporates a long-base (LB) and ultra-short base (USB) acoustic positioning systems (APS). The complex integrates structurally shipboard antennas of the systems, shipboard support equipment, software is unified. The operation mode of the complex is selected based on the current tactics of the AUV application.

The complex enables structuring the configuration of navigation facilities depending on a type of the problems to be solved and operating environment. As a rule the following complex configurations are used:

- LB-APS with the range up to 15 km and relative error of 10^{-3} can be combined with a low-speed remote-control system (Table 1);
- USB-APS with the range up to 10 km and relative error of 10^{-2}; it can be integrated with an LB- APS (Table 2);
- ACS, an acoustic system for the AUV communication with the carrier ship with the range of 6-10 km, 4,000 bit/s speed and error rate of 10^{-2}.

The positioning complex equipment consists of a set of transponders, a set of AUV transceiving equipment and a set of shipboard equipment. As a whole the complex ensures navigation, remote control, telemetry and search operation control by analyzing video images or sonar images transmitted from the AUV. The acoustic system and its modifications, where, besides the positioning system, a telemetry system and a remote-control system were implemented, too, have successfully enabled actual AUV maritime operations during the last three decades.

Operation depth	Up to 6000 m
Range	10-15 km
Range relative measurement error	No more than $0{,}5*10^{-2}$
Bandwidth	11-14 kHz
Beacon self-sustaining period	Up to 0.25 of a year
System installation time (with transponders positioning)	Up to 6 hours in shallow sea and up to 24 hours in deep sea
Size of shipboard electronic equipment	0.6 x 0.55 x 0.12 m
Size of transponder (diameter x length)	0.14 x 0.85 m
Size of towed antenna module	0.9 x 0.4 x 1.8 m

Table 1. LB-APS performance characteristics

Operation depth	Up to 6000 m
Range	Up to 10 km
Bearing angle error	No more than 1-2°
Range relative measurement error	No more than $0.5*10^{-2}$
Operating frequency	11.75 kHz
System installation time	1 hour
Size of shipboard electronic equipment	0.6 x 0.55 x 0.12 m
Size of towed antenna module	0.9 x 0.4 x 1.8 m

Table 2. USB-APS performance characteristics

Let us cite as an example the results of search operations in the area of the military helicopter crash near the coast of the Peter the Great Bay of the Japan Sea (Ageev et al., 2005). During the first phase of the operations when the site of the helicopter crash was searched for, a large area was surveyed using side scan sonar (SSS). The motion path is shown in fig. 2a.
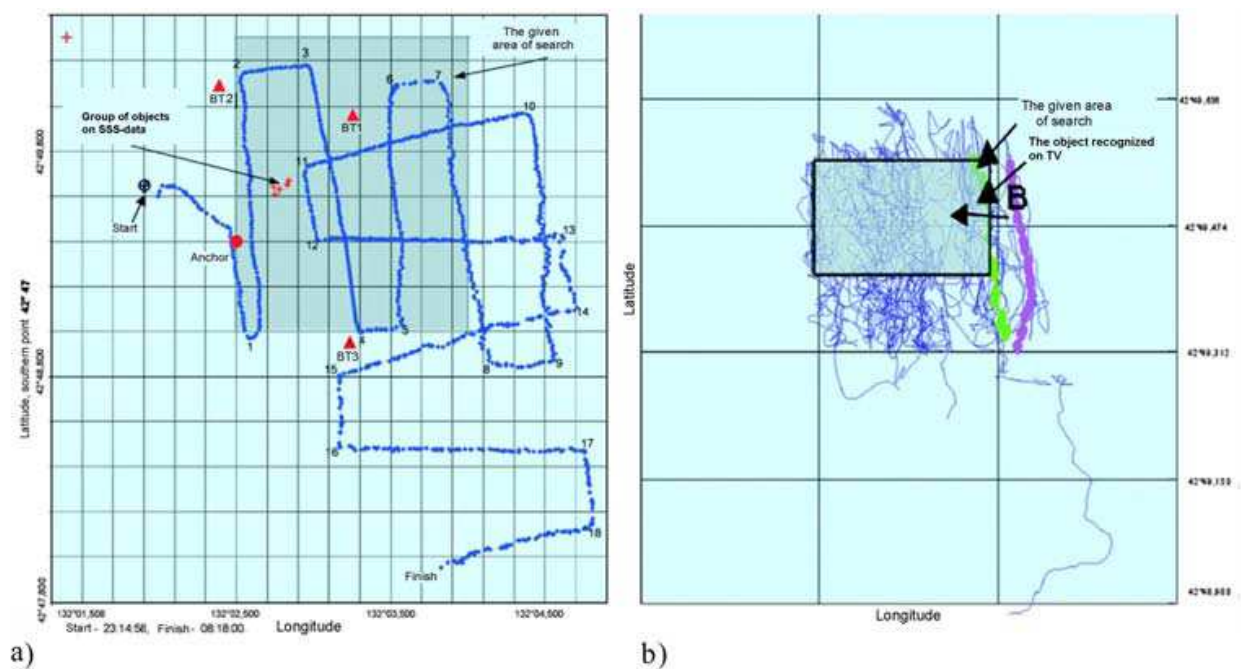

Fig. 2. Area path investigation during helicopter search. a) large-scale SSS survey,
S = 22 sq. km, Δ = 20 m; b) detailed video survey, S=0.16 sq. km, Δ = 5 m

Points of beacon locations, the carrier ship anchorage, and a series of targets detected on the SSS screen are marked on the path. The total survey area was equal approximately to 22 sq. km. The depth of the site in the operations area was approximately 70 m, the horizontal range was up to 6 km, and the target positioning accuracy was approximately 20 m. During the second phase close search was carried out for precise positioning of the detected targets. In the area of 400 x 400 m the search was carried out with the use of video system with the vehicle travel height equal to 5 m. In order to avoid gaps in the search square the vehicle motion was remotely controlled in short straight-line tacks at a distance

of several meters from the preceding ones. The results of the search operations in the area are given in fig. 2b where the AUV paths for three launches are shown; each launch has 5 to 6-hour duration and they are overlapped in the search square. The total area of video observation was no less than 100,000 sq. m, and tack positioning accuracy was less than 10 m which allowed accomplishing the mission: to detect and to position the targets.

3. Onboard autonomous positioning complex

The onboard autonomous navigation system (BANS) generally encompasses positioning and steering sensors (a depth gauge, a magnetic compass, a gyroscopic compass, a heel sensor, a pitch sensor, a specific velocity meter, an absolute velocity meter, i.e. an electromagnetic log and a Doppler log (EL, DL), angular-rate sensors, an inertial positioning system (IPS), an echoranging system (ERS), a GPS receiver). Depending on the BANS configuration the data provided by the measuring devices is used to enhance reliability and accuracy of the system operation.

The BANS itself represents a stratified module formed by a dead reckoning system, the IPS and the GPS receiver operated by a local area network. Autonomous navigation facilities of that configuration can enable performance of complex programmed missions and gathering data on the vehicle condition during its motion. Solving the problems of objects investigation and work of the vehicle under conditions of autonomy brings to necessity of development of positioning complex, which allows perform autonomous motion correction by the current vehicle coordinates and the given coordinates of targets or references.

When the AUV autonomous operation time is extended it is important to provide positioning with as much accuracy as possible using integrated BANS. In general navigation error during determination of vehicle coordinates by means of dead-reckoning depends on a number of factors: instrumental errors of measuring devices, in particular, gyros drift, initial data input errors, velocity measurement errors, especially at unaccounted stream, and IPS initial alignment errors.

It's obvious that when there is no correction from external measuring devices the cumulative positioning error accumulates in time, and when the vehicle operation time is extended it becomes intolerably large. When the vehicle operates in shallow area error can be corrected due to the possibility to make corrections with the help of GPS during episodic vehicle surfacing.

The following variants of integration and correction of navigation information onboard the AUV are of the greatest practical interest at present.

- Correction of IPS (in the complete configuration or in a gyros mode) with regard to DL (near the bottom) and GPS (on the sea surface);
- Reciprocal correction of gyroscopic and magnetic compasses in various AUV operation modes;
- Integrated processing of the information from BANS and LB (USB) APS onboard receiver;
- correction of BANS via an acoustic communication link and remote control using APS and GPS data.

Let's note some peculiarities of navigational calculations, and cite as an example integrated positioning system of AUV "Klavesin".

AUV onboard positioning complex is realized in two configurations. They differ in the type of used IPS. In one of them a fiber-optic gyroscopic compass "Octans III" by French company iXSEA is used as IPS, in the other one the IPS is mechanical without dynamic tuning gyros. In this system speed correction is programmatically provided by the use of measurements of acoustic Doppler log. Kalman filter is used for combined data processing from both internal (gyros, accelerometers) and external sources (DL, GPS receiver).

As it was mentioned, positioning (local and absolute) in autonomous system is performed by means of dead-reckoning. Velocity vector data received with the help of water speed log or bottom speed log is used for it. In these cases velocity vector components $V=(V_x,V_y)$ against are given by:

$$V_x = V^{rel} \cos\psi \, \cos\varphi \, , \ \ V_y = V^{rel} \cos\psi \, \sin\varphi \, , \tag{1}$$

$$V_x = V_x^{abs} \cos\varphi + V_y^{abs} \sin\varphi \, , \ \ V_y = V_x^{abs} \sin\varphi + V_y^{abs} \cos\varphi, \tag{2}$$

where V^{rel} – speed against the flow, V_x^{abs}, V_y^{abs} - average values of longitudinal and cross stream velocity components, measured by Doppler log, ψ , φ – path and vehicle trim difference, measured by IPS.

When the vehicle operates in a limited area or in the carrier-ship tracking mode, autonomous coordinates can be corrected through combined processing of the BANS and APS data or through positioning data transmission to the vehicle via acoustic communication link together with telemetry data and remote control commands.

BANS task consists in path and speed measuring, measurements of speed projections on coordinate axis according to these data, and measurements integration for positioning. If water speed log is used then available current data (V_{Tx}, V_{Ty}) is taken into account during measuring. System operation can be described by formula:

$$X_c = X(t_0) + \int_{t_0}^{t} (V^{rel} \cos\psi \, \cos\varphi + V_{Tx}) d\tau \, ,$$

$$Y_c = Y(t_0) + \int_{t_0}^{t} (V^{rel} \cos\psi \sin\varphi + V_{Ty}) d\tau \, , \tag{3}$$

or

$$X_c = X(t_0) + \int_{t_0}^{t} V_X^{abs} \cos\varphi \, d\tau \, ,$$

$$Y_c = Y(t_0) + \int_{t_0}^{t} V_y^{abs} \sin\varphi \, d\tau \, ,$$

where X_c, Y_c – coordinated reckoned with the help of BANS, $X(t_0)$, $Y(t_0)$ - reference coordinates entered before start.

Range evaluations r_i ($i = 1...n$) from vehicle to transponders with coordinates (X_i, Y_i) and evaluations of the vehicle coordinates (X_{abs}, Y_{abs}) which can be received by APS are connected by equations:

$$\left(X_{abs}-X_i\right)^2+\left(Y_{abs}-Y_i\right)^2 = r_i^2, \ i=1,..n \ . \tag{4}$$

The task of integration and correction (Romero & Lester, 2000) consists of elimination of large initial dead-reckoning errors of current positioning and current vector evaluation. To do it data of different systems is used at each step of navigational calculations. Integrated positioning algorithm performs: positioning on the basis of navigation-piloting sensors, response selection from hydroacoustic transponders, hydroacoustic positioning on the basis of distance-measurement information, coordinates correction and current speed evaluation. Reckoning system input parameters are the path of gyroscopic and magnetic compasses, pitch, relative or absolute velocity, and preliminary evaluation of current velocity components (when water-speed log is used). Output parameters are course made per one correction cycle, and coordinates. The process of signals selection from APS transponders provides false signals filtration, which was caused by refraction effects and multipath condition, and formation of distances for the following positioning.

The variants of integration and system accuracy evaluation given above were tested during repeated field tests in the deep and shallow sea. Some results of positioning characteristics experimental tests during AUV performing different operations are given below.

3.1 Positioning process in AUV control system

Positioning process takes an important place in AUV control system. To a large extent system architecture of control is defined by requirements of organization of navigational calculations. Let's mention some peculiarities of this process.

1. Navigational calculations are made in distributed environment of AUV's local area network (LAN) (fig. 3). Positioning process is organized as a combination of informative interrelated tasks performed on separate computers and LAN microcontrollers. All navigation facilities (IPS, positioning and steering sensors, APS signal transducers, etc.) are the abonents of several segments of this network, and two computers perform navigational calculations simultaneously.
2. In many cases navigational calculations have "interactive" character. In other words positioning process can require from AUV control system performance of several additional actions (not foreseen by program-task) for accuracy improvement or disambiguation in positioning. Suchlike situations can happen during operations at great depths (for vehicle reference coordinates positioning after long descent.
3. "Interactivity" of positioning process is developed in set of commands of program-task (mission) used for required motions specifying.

Navigational calculations are organized on two AUV control system hierarchy levels. The basic calculation process is performed on the execution level. Positioning process besides sensors data receiving and processing specifies data and commands exchange and enquiry messages to AUV control system nucleus (by means of distributed data base).

The basic operation process consists of integrated calculations for integration of LB APS transducers responses or USB APS data and BANS reckoned data. As a rule, such mode doesn't affect performing AUV major mission. In disadvantageous conditions when there is a large positioning error according to data of different systems, a necessity to perform test motions (for disambiguation) arises. This situation becomes obvious during positioning process and is based on the rate of convergence of iterative loop calculations, value of

closure error, etc. At the same time a corresponding enquire is formed to the highest (coordinating) hierarchy level for performing such motions.
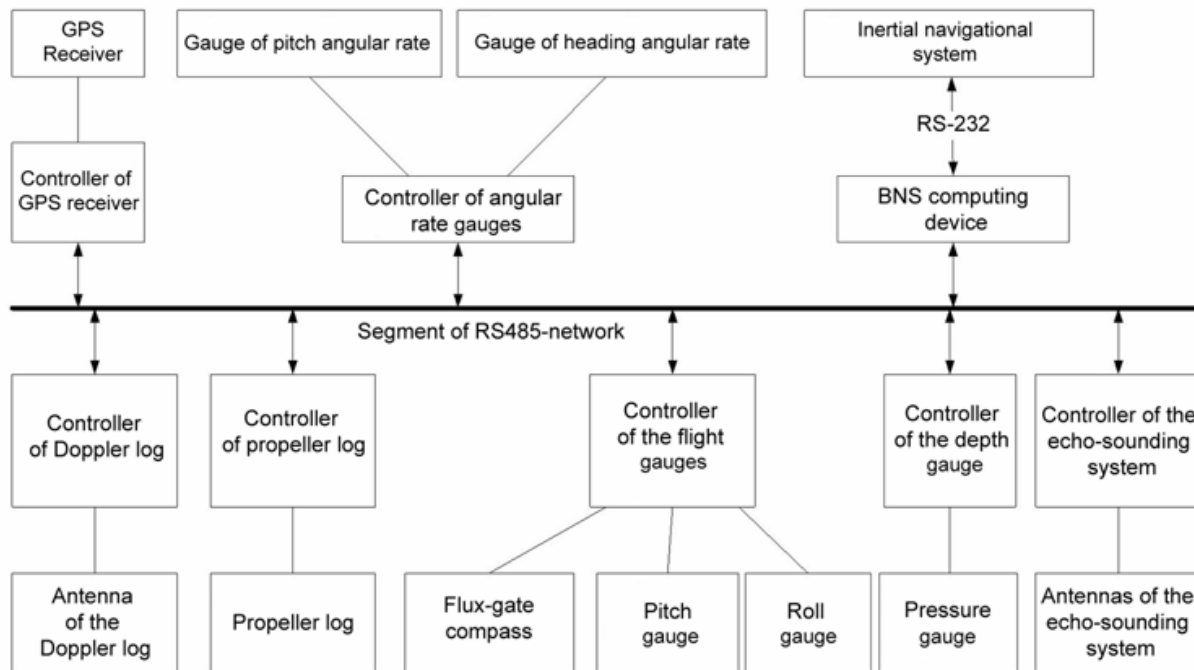

Fig. 3. Elements of local area network

Depending on the status of the scheduler this requirement can be denied, queued or immediately executed. In the last case performing of the program-task is discontinued, and the processing procedure starts (standard or described in mission). As a rule, standard processing procedures are performed during hovering mode or motion along the special search path. Certain parameters of the said procedure performance can be defined by positioning process itself. From mission support of such AUV behavior consists in the use of several operation control functions (Ageev et al., 2005):

- description of desired path configuration: TACK_…(…), POSITION_…(…);
- defining of conditions of navigational devices (for example, IPS): GET_…();
- loading out-of-order inquiry processing of positioning process SIGNAL(…).

The functions of the first two categories are also used in standard libraries of coordinating level. A corresponding notification is sent to the carrier-ship through acoustic communication link in the beginning of unplanned part of the mission performance.

4. Results of sea trials and experimental operation

4.1 AUV positioning complex accuracy test in shallow sea

The tests of positioning complex were carried out on AUV "MT-98" during trajectory measurements under ground test conditions in one of the Peter the Great Bay creeks.

It follows from the comparison of the results of the multiply conducted experiments that average runout rate for BANS positioning is minimal when an IPS (in a gyroscopic compass mode) is integrated with a Doppler log. Relative error averaged according to several vehicle launches comprised 28.5 m/h, which corresponds to the positioning error of approximately 1% for the whole distance covered.
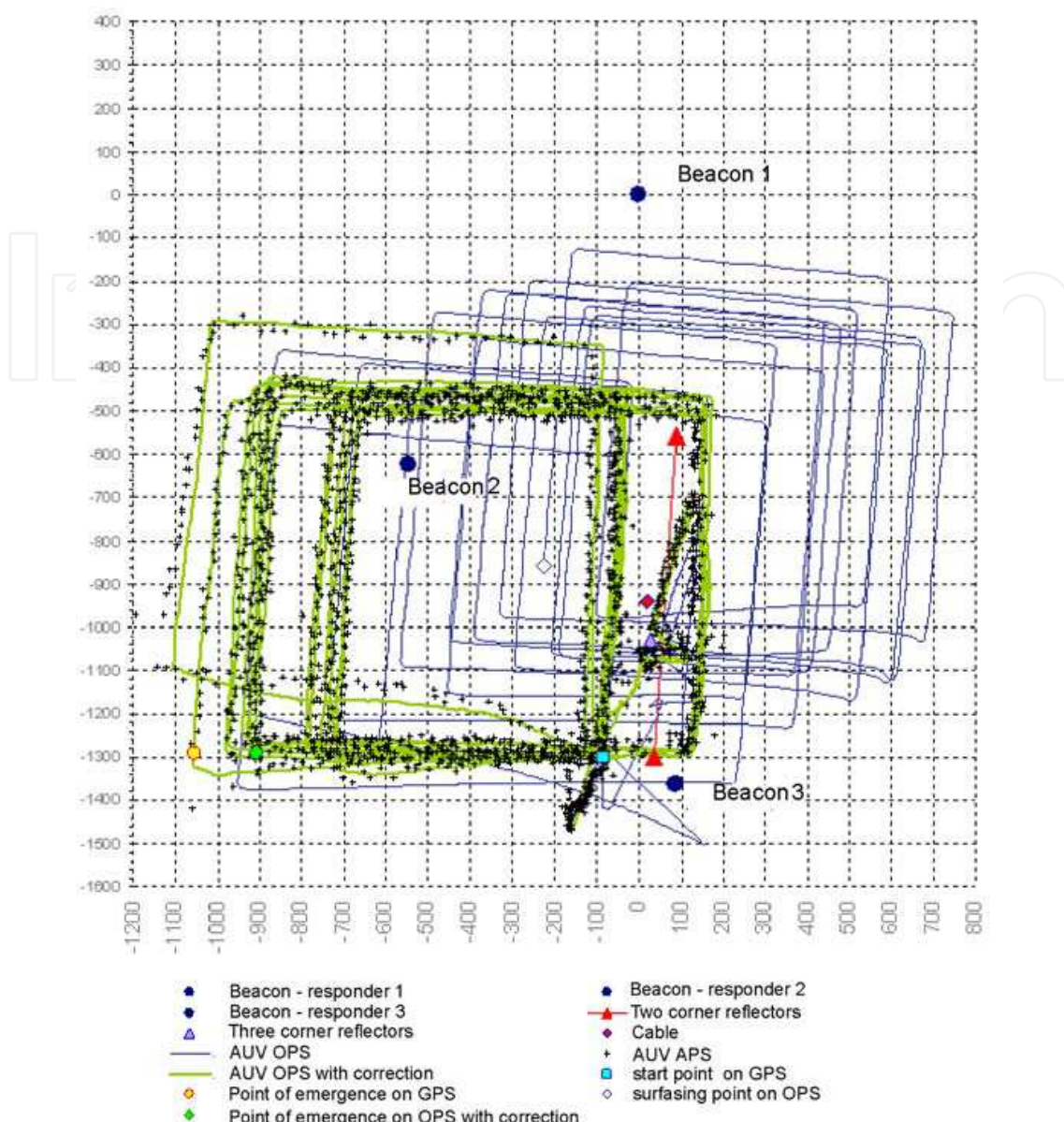
Fig. 4. AUV motion path during positioning complex tests

Further system modification was connected with increasing the AUV autonomous operation time. Fig 4 shows the AUV motion paths obtained during a 17-hour vehicle launch while it was positioned using APS, BANS and GPS devices. The programmed path was set in the form of repeated squares within the range of the three APS transponders. Various types of the AUV motion paths shown in figure correspond to the following test conditions. Positioning process using the BANS was carried out according to the gyroscopic compass and electromagnetic (impeller) log data. The obtained BANS coordinates were simultaneously corrected based on the LB-APS distance-measurement information. To compare the obtained results and to determine a BANS accumulating error the LB-APS and GPS measurement data was used (during surfacing). In addition it was assumed that the LB-APS internal "point" error with respect to the actual position of an object and a similar observation error according to GPS data do not exceed 10 – 15 m, which allows adopting these systems as a "reference". Under these conditions the BANS reckoning error (without

corrections based on APS data) accumulated upon completion of the program with regard to the surfacing location coordinates based on GPS data was 933 m which corresponds to the runout rate of 54 m/h. The BANS and LB-APS integration virtually enables reducing the BANS reckoning error down to the corresponding LB-APS level (15 m).

4.2 AUV preparation for operating in the polar latitudes

In different periods of North development and research to perform operations, always hot and difficult, the most perfect technologies were used. Nowadays in Arctic Zone underwater vehicle, among them vehicles-robots, are used. We all know about the operations performed by underwater vehicles under the ice on evaluation of bottom configuration in places where cables and pipelines are installed and about the operations on fiber-optic cable installation. The importance of the operations is specified by growing interest to the resources within seabed covered by solid ice. Until now the Arctic Ocean seabed has been explored using individual sounding carried out by icebreakers or drifting polar stations. Though modern atomic icebreakers can bring scientific expeditions to any part of Arctic Zone, they cannot provide all range of necessary polar research. Application of underwater robots operated onboard icebreakers appears to be the most appropriate method to investigate bathymetric, physical, and geomorphologic characteristics of the Arctic seabed in the area of widespread ice cover. The first operational experience in high latitudes of the Arctic zone using underwater robots was received in August 2007 in the Arctic Ocean near Lomonosov Ridge (Inzartsev et al., 2007a). The expedition of the atomic icebreaker "Russia" investigated the geological characteristics of the seabed at depths of 1,500-1,600 meters in the area of over 50 sq. km.

Fig. 5. AUV "Klavesin" onboard the atomic icebreaker "Russia"

Preliminary integrated checkout of the vehicle efficiency in high latitudes was carried out earlier onboard the atomic icebreaker "Russia" during the expedition to the North Pole in summer 2007.

Further the paper discusses the stages of preparation to the research in Arctic, gives some scientific data received during the deep-water descents, and evaluates research results.

The operations were carried out with the help of AUV "Klavesin" (fig. 5). This vehicle developed by IMTP FEB RAS is designed for supervisory and searching tasks under conditions of open water at depth up to 6000 m.

However, normal work of the vehicle under conditions of polar latitudes and solid ice cover demanded serious changes in organization of its operation, navigation and communication facilities, descent and ascent technologies.

These adjustments were dictated by the extreme operating environment which includes:

- AUV descent and ascent operations through the ice opening, which size is comparable to the size of the carrier,
- ice drift in the exploration area;
- latitude dependence of accuracy of the magnetic sensors and gyroscopes.

During preparations for the high-latitude expedition the ways of solving a number of problems due to these factors became basic. Several details of the preparation work are given below.

4.3 Accommodation of AUV onboard control system to the operations in high latitudes

AUV "Klavesin" is a multi-purpose system equipped with sophisticated facilities for autonomous and acoustic positioning and communication, a configurable control system enabling search operations in an autonomous mode or using acoustic remote control equipment. To fit the polar conditions the AUV standard equipment was supplemented with a series of special function modules and base units:

- the system performing the procedure of AUV automatic transporting to the onboard antenna was developed; the procedure is initiated when the mission is accomplished;
- for AUV precision control during AUV ascent in the ice opening a standard set of remote-control commands transmitted via acoustic communication link was changed;
- to make the vehicle stay on the surface when the mission is accomplished to decrease its floatability under conditions of desalination of surface layer of water a special mode of stabilization with the help of vertical thrusting propulsions was introduced.

The most important task was to develop and debug a system of the AUV homing to the carrier ship. After completing simulation research and full-scale experiments a sequence of operations was determined for the AUV to implement the homing algorithm.

At the first stage the AUV performs search motion along the path in the shape of circle, forms array of range value to the shipboard antenna depending on the current path, and takes a bearing corresponding to maximum speed of range attention. Having found required direction the vehicle moves to the carrier-ship along the fixed route. When AUV approaches to the shipboard antenna not closer than 100 m it starts moving in the "figure-of-eight" (in the center of which the shipboard antenna stays), and waits for the commands from the shipboard. The final stage of the control during AUV homing to the ice opening is carried out by the operator in the acoustic remote control mode.

The elements of the described algorithm were tested in the sea during AUV preparation. Figure 6 shows one of AUV motion paths during its homing to the shipboard antenna in the open-water at the initial distance of 750 m.
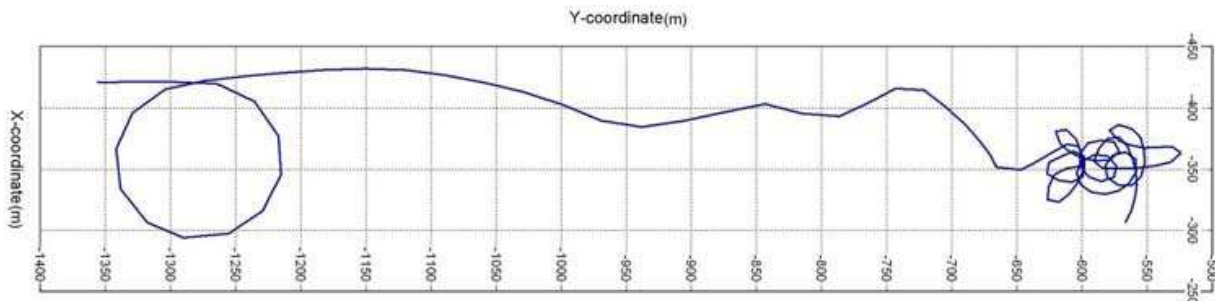

Fig. 6. An example of AUV autonomous homing path to the shipboard antenna

These trials proved that homing to the carrier is performed rather quickly. In the mentioned experiment at cruising speed 1 m/s an average speed of approaching to the antenna comprised taking into account all movements of the vehicle 0.57 m/s, and not taking into account initial search movement – 0.8 m/s.

The AUV's operation under ice is necessary not only for accurate positioning of the current operations, but also for monitoring and ensuring the AUV return to the carrier ship. When the vehicle moves 10-15 km away from the launch ice opening it is important to ensure reliable acoustic link with the shipboard antenna module. At the same time, it is imperative to provide ongoing monitoring of the communication link condition in order to avoid risks of losing acoustic contact. In this case antenna module becomes a towed acoustic beacon to which AUV is homed when the mission is accomplished. For open-water and mid-latitude operations AUV "Klavesin" is equipped with hydroacoustic navigation and control facilities the application of which on the North Pole in normal operations mode is limited by a number of circumstances.

Operation of USB APS requires no transponders. It is usually equipped with a magnetic course sensor, which has low accuracy in polar latitudes. Installing bottom acoustic transponders, both return and single-use, and the LB APS on the site are ineffective due to drift of ice floe. If the homing acoustic antenna drifting with the ship moves too far off, conditions for acoustic monitoring and operation control onboard the ship deteriorate dramatically. Installing surface LB APS transponders also has its shortcomings. Firstly, each transponder current positioning requires integrating with the regular navigation receiver, as well as with coordinates transmitter in the control desk; then the data input is required. Secondly, it is necessary to install the transponders at the depths of at least 250-300 m to provide their proper work taking into account the peculiarities of vertical distribution of sound speed in Arctic latitudes. The sizes of the ice opening, and, thus, the transponders' measuring base are limited. At the same time unpredictable drift of transponders, installed on flexible umbilicals, brings to considerable errors and failures of navigation system operation.

Basic elements of the positioning complex include an inertial positioning system (IPS) and an acoustic Doppler log. During preparations for the high-latitude expedition operation procedure was worked out for the gyrocompass "Octans-III" by French company iXSEA and the Doppler log developed by the IMTP FEB RAS. As a result the following scheme was implemented for AUV positioning guidance.

Three maximum-spaced LB APS transponders were installed around the ice opening chosen for AUV descending – ascending. The transponders' coordinates were determined at the time of their installation and directly before AUV starting. Then they were entered into the positioning program as persistent data. Transponders' location was measured at regular intervals, and updated measurements were entered into the positioning program. The current ship's position and its antenna position were determined by regular satellite positioning receiver. Taking into account received data the ice floe drift and the location of transponders' measuring base were evaluated.

AUV starting point coordinates on the surface were recorded. Then the AUV mission starting point at the bottom and the starting point of the onboard positioning system operation respectively were determined based on the LB APS data. During the mission the AUV current path was reckoned based on readings of the absolute velocity meter, the course indicator, the depth gauge, the heel sensor and the pitch sensor installed onboard.

Based on the telemetry data transmitted from the AUV via acoustic communication link the AUV motion path was monitored onboard the carrier ship in real time. Navigational plot simultaneously displayed the drift path of the carrier ship with the base of transponders and AUV motion path in respect of drifting transponders' base (fig. 7). The reckoning system's resultant error was corrected by a series of discrete points where the AUV position was calculated based upon the LB APS data using the refined coordinates of the transponders.
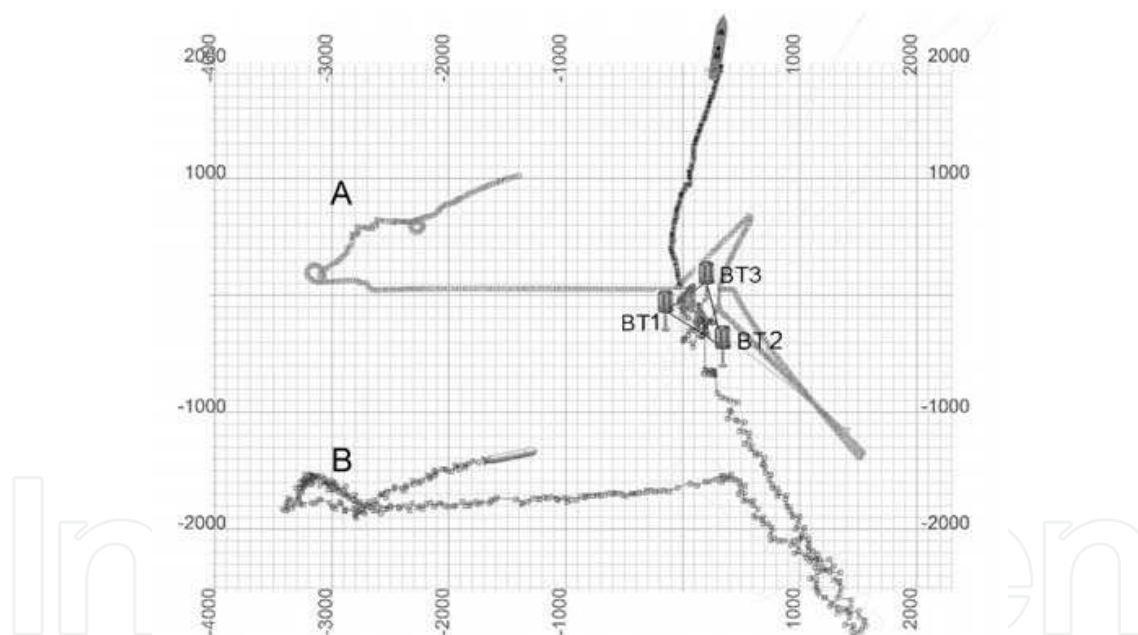

Fig. 7. AUV motion path displayed on the navigational plot: A - in respect of the bottom according to the onboard positioning system data; B - in respect of drifting transponders' base according to the LB APS data.

After its mission had been accomplished, the AUV performed automatic location of the shipboard acoustic antenna module. At the final homing stage before its ascent the AUV position in the ice opening was controlled using the vehicle distance from the antenna module and each transponder. Commands for the last procedures of ascent (ascent from the depth of 20 m and then 5 m) were sent when the AUV was in the nearest position to the shipboard antenna (no more than 20-25 m) and in the center of the ice opening (determined according to the distance from AUV to the transponders).

4.4 The results of the research

The expedition performed operations on the Lomonosov Ridge in the area of the point with the coordinates 84°40' N and 149°10' E at the condition of ice cover approximately 9.5 points (solid ice cover with single rare ice openings sized up to 100 m.) and with the speed of drift of ice floe up to 0.5 knots. Firstly, a trial AUV descent at the depth up to 100 m for ballasting and checking system operation was carried out. The received results allowed coming to a decision about deep-water launches.

Two operational descents with echo-ranging survey of the bottom, environment measurements, acoustic profiling and photographing of separate bottom areas were performed. During operational launches AUV position was controlled onboard the carrier-ship with AUV motion path displayed in real time and presenting AUV current condition parameters – coordinates, speed, course, depth, height, and direct distance from shipboard antenna.

The navigation scheme and technique described above enabled AUV positioning and control, monitoring its mission accomplishment, and ensuring the vehicle's precise arrival at the ice opening for ascent. At the final stage of AUV mission – ascent after 22 hour of self-contained operation - the control of vehicle direct distance from carrier ship antenna and installed transponders was provided. Range measurement error didn't exceed 10 m at that moment, and when appearing on the surface AUV was in 10-15 m from the board of the carrier ship and in 20-30 m from its antenna.

Analyzing available data positioning accuracy can be approximately evaluated. During the 22-hour long launch cumulative uncorrected error of the onboard positioning system, which was defined as deviation between the ascent point coordinates determined by the onboard positioning system and the coordinates obtained during GPS observation, was equal to 1,370 m or approximately 60 m/hour. This error had been accumulated and formed from the following sources:

- error of geographical coordinates for the mission starting point at the bottom. AUV starting point coordinates on the surface were determined rather accurately, but during descent (approximately 50 min) AUV moved along complicated path, and its location was monitored by APS using drifting transponders' base. Estimated position of the starting point according to APS was corrected by compensation of transponders' base drifting with error approximately 50 m.

- dead-reckoning error of the onboard positioning system. According to the results of the experiments carried out during system debugging the cumulative reckoning error was less than 1% of traversed path. It comprises less than 50 m/h at speed 1 m/s.

- dead-reckoning error during AUV ascent and homing at depths excluding Doppler log efficiency. Vehicle speed data was worked out by water speed log, and its accuracy is essentially lower than that of a Doppler log. Total operation time of the reckoning system in a homing mode was at least 3 hours, it also influenced cumulative error.

Evaluation listed above is not final, as accepted configuration of navigation facilities has additional possibilities of correcting reckoned coordinates and considerably reducing positioning error. Reduction of error is achieved by means of positioning separate points of reckoned path to the points calculated at this period of time according to LB APS with the use of drifting transponders relocation. Error in determination of coordinates calculated according to the LB APS data can be compared to the relative range measurement error (no more than one percent for the disadvantageous working conditions) and comprises 60 m at the range of 6000 m. Then, as it was mentioned, onboard the carrier ship besides speed and

course data necessary for reckoning, the telemetry data on depth and height are received, and direct AUV range from the homing antenna with precise coordinates are continuously controlled. If the vehicle performs rectilinear equal tacks, then drift parameters of the carrier ship and abovementioned basic data allow positioning the vehicle according to changes of range data from the homing antenna using simple mathematical models. These coordinates positioning error comprises about 2% from the current range (for the conditions of carried out operations – about 100 m).

Good positioning facilities of AUV "Klavesin" allowed efficiently perform a number of research operations during deep-water descents under ice in High Latitudes. During abovementioned expedition the following operations were carried out with the help of underwater vehicle:

- bathymetric survey of seabed area equal 50 sq. km,
- echo-ranging survey of seabed surface,
- acoustic profiling,
- strip survey of some seabed areas,
- sea water temperature and electric conductivity measurements.

Let's mention some results of the performed operations.

Bathymetric survey was carried out by means of direct measurements of vehicle descent with the use of depth sensor, and measurements of AUV distance to the bottom with the use of echoranging system. At AUV speed 1 m/s discreteness of the data received comprises 1 m. Bathymetric cumulative error doesn't exceed 3 m. All measurements are made in international reference coordinate system WGS-84. A bathymetric map of the area is made according to the measurement data.

Echo-ranging survey of seabed area was carried out with the help of low-frequency and high-frequency side-scan sonars (LF SSS and HF SSS). A combined SSS-image (plot) of operation area and separate high-resolution fragments of bottom and biological payloads were received. The results of SSS-survey illustrate the character of seabed and bottom objects of different nature.

Seabed acoustic profiling was performed during vehicle motion at 30 m from the bottom. The swath was approximately 30 m, profiling depth 30-50 m. Geological structure of deep-sea and sediment layers were explored. It allowed evaluating morphological characteristics of the bottom structure.

Hydrologic research included sea water temperature and electric conductivity measurements. This data was used for sound velocity calculation. The character of temperature dependences on depth and formation of vertical distribution of sound velocity is detected. Vertical temperature profiles, electric conductivity and sound velocity profiles as well as map of near bottom temperature field were made on the basis of these measurements.

Seabed photo survey was carried out at 0.75÷5.1 m. Photos of many biological payloads sheltered in silt with exit openings are of a great interest.

5. Conclusion

1. An autonomous unmanned underwater vehicle for scientific research was used for the first time in the world history under ice in the Arctic polar latitudes. The possibility of its use for bottom characteristics research was practically proved.

2. As a result of the research the unique information about the seabed characteristics, which cannot be accessed using any other equipment was obtained. Based on the obtained data a bathymetric map and a sonar image plot of the explored seabed area were composed. Acoustic sounding bottom profiles, vertical temperature, electric conductivity and sound velocity profiles were generated.

3. The materials gained during the expedition can be of a scientific interest for the maritime law, marine biology, geology, and marine science specialists.

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Motion Control

Edited by Federico Casolo

The book reveals many different aspects of motion control and a wide multiplicity of approaches to the problem as well. Despite the number of examples, however, this volume is not meant to be exhaustive: it intends to offer some original insights for all researchers who will hopefully make their experience available for a forthcoming publication on the subject.

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