CHAPTER 7

Analysis of modern underwater navigation and design capabilities of underwater cargo vessels

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Abstract

The aim of the study is to analyze the advantages and disadvantages of modern navigation methods for autonomous underwater vehicles and their groups, including the use of neural networks, and to determine their development prospects; as well as to enhance the effectiveness of deep-sea surveying and the execution of various underwater operations through the use of advanced mathematical support for autonomous underwater vehicles; the development of underwater space in the interests of maritime freight transport as such, which increases the carrying capacity of existing sea transport routes, increases energy efficiency and reduces the risks of freight transport, provided there is no negative impact on the movement of the vehicle by wind, surface waves and drift currents.

The challenges of developing a control system for autonomous underwater vehicles have been examined. A new architecture of mathematical support for the control system of autonomous underwater vehicles is proposed, which incorporates both hierarchical and behavior-based control structures. This significantly expands the capabilities of these vehicles, enabling them to solve tasks of various classes under the constraints of onboard computational network resources.

Within the proposed architecture, a behavior-based approach is applied at different levels of the functional hierarchical control system. A methodology is substantiated for constructing a tactical-level agent library based on the functional decomposition of the target task class. The structure of an agent has been developed and studied; it includes a local environmental model, tools for planning actions based on this model, and mechanisms for analyzing the utilized information to assess the agent's operational effectiveness.

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provided there is no negative impact on the movement of the vehicle by wind, surface waves and drift currents. It is proposed to create an extensive system of cargo transportation in the underwater space as an alternative to conventional shipping. It is established that underwater data transmission based on lasers and radio waves is effective for data transmission only in conditions where the underwater transport vessel moves in the near-surface layer of the ocean.

Keywords

Underwater space, autonomous underwater vehicle, hydroacoustic systems, navigation, cargo transportation, behavioral architecture, hierarchical architecture.

7.1 Introduction

In the 21st century, the rapid growth of global trade, increasing congestion of major maritime routes, and the need to reduce the environmental impact of sea transport are driving the search for innovative solutions in maritime logistics. One of the most promising directions that is increasingly attracting the attention of researchers and engineers is the use of underwater cargo vessels as a new class of transport platforms. What only a few decades ago seemed purely futuristic is now being considered a potentially viable solution for transporting strategically important cargo, particularly in conditions of military conflict, sanctions pressure, restricted shipping, or harsh climatic zones.

The development of modern underwater navigation requires a comprehensive analysis – both from the perspective of navigational technologies and from the standpoint of structural implementation of such vessels. Key challenges include optimizing hull design to minimize resistance during submersion, ensuring reliable energy supply, maximizing cargo capacity, and maintaining stability and safety.

It is also worth highlighting that, in the context of geopolitical instability, piracy threats, and restrictions on movement in certain maritime zones, underwater cargo vessels may become a critical strategic asset – both in the commercial and defense sectors.

7.2 Analysis of modern methods and prospects for the development of underwater vehicle navigation

Over the past decade, the development of commercially available, high-accuracy navigation sensors with high update rates – such as Doppler sonars, optical gyroscopes, and inertial measurement units (IMUs) – has significantly complemented traditional underwater sensors like acoustic positioning systems, magnetic compasses, and pressure-based depth sensors.

Long baseline (LBL) systems, in which the vehicle triangulates its position using acoustic ranges from a network of surveyed transponders, and ultra-short baseline (USBL) systems, which use sonar arrays to determine both the range and bearing to the vehicle, are now routinely used in underwater navigation.

External acoustic positioning systems are employed by underwater vehicles to triangulate their position based on range or a combination of range and bearing information between the vehicle-mounted transceiver and multiple external acoustic transponders. A key advantage of these systems lies in their minimal demands on the vehicle's size and power consumption when compared to other navigation techniques. However, unlike some onboard navigation systems, certain types of external acoustic systems require the deployment of seabed-mounted transponders in the operational area [1].

In such systems, the vehicle calculates its distance to each transponder by measuring the time-of-flight of an acoustic signal and estimating the speed of sound in the water column between the vehicle and the transponder. The availability of directional information depends on the geometry of the transponder array. Three primary geometric configurations are used in external acoustic navigation systems: short baseline (SBL), ultra-short baseline (USBL), and long baseline (LBL) [2].

The first developed type of external acoustic system was the **short baseline (SBL)** positioning system, which was primarily used for tracking or navigating underwater vehicles over short distances. These systems consist of a single transponder or transducer mounted on the underwater vehicle and an acoustic network typically installed on the hull of the support vessel.

In the 1970s, **ultra-short baseline (USBL)** navigation systems were developed as a simplified alternative to SBL systems. USBL systems can operate either from the underwater vehicle or its host vessel. USBL systems operating from an AUV (autonomous underwater vehicle), sometimes referred to as inverted USBL systems, enable the AUV to navigate relative to the location of a single external acoustic transponder [3].

Fundamentally, **long baseline (LBL)** navigation systems operate similarly to inverted SBL systems, but differ in that their external transponders are deployed independently in the ocean, rather than being mounted on the hull of a support vessel or on a deployable frame. Typical LBL systems involve deploying between four and twelve acoustic transponders, depending on the mission requirements, although the system can function with as few as two transponders.

An alternative computational algorithm for AUV navigation using an LBL system is based on the Kalman filter (KF). The Kalman filter combines data from onboard sensors with prior knowledge of their inaccuracies and a dynamic model of the system's state-space to provide real-time state estimations.

Despite the cost and time required to deploy and manage the acoustic transponders, LBL navigation systems remain the standard for low-cost deep-sea vehicle operations.

Doppler velocity log (DVL) navigation: the development of high-frequency multibeam Doppler sonars, which can measure bottom velocities with an accuracy of 0.3% or better and an update rate of up to 5 Hz, allows researchers to obtain velocity measurements for navigation near the seabed (within 18–100 meters). This has enabled the development of numerous Doppler-based navigation techniques, including those used to improve state estimation in inertial navigation systems (INS) [4].

NARX-RKF integrated navigation algorithm (nonlinear autoregressive with eXogenous input model with robust Kalman filter): according to recent analyses, navigation parameters are interrelated, and sensor bias is closely linked to external environmental conditions and the vehicle's motion state. Errors in the strapdown inertial navigation system (SINS) evolve according to specific patterns, and the overall navigation status error is strongly correlated with the vehicle's movement history data.

NARX-RKF includes a DVL fault prediction module based on the NARX model and an integrated navigation loop using the robust Kalman filter (RKF). The NARX model can use output data from the inertial navigation system to predict DVL output when it is interrupted, and it employs the RKF for integrated navigation [5].

Inertial navigation. Inertial measurement units (IMUs) offer excellent capabilities for navigation without external references. However, their power consumption (ranging from 12 to 30 V) and cost (often exceeding 100,000 USD) have until recently limited their widespread use in civilian oceanographic vehicles. Typically, IMUs are used together with Doppler velocity measurements and positioning data from GPS or acoustic navigation systems to correct IMU measurement errors. IMUs are often used in high-precision surveys and when vehicles are deployed under ice sheets or in the mesopelagic (mid-depth) zone.

Dead reckoning (DR) and **inertial navigation systems (INS)** are fundamental navigation methods. In both systems, the vehicle receives an initial position and then uses onboard sensor data to continuously update its estimated position.

In DR navigation, the vehicle's speed is integrated over time to estimate its movement path. However, this method provides only an approximate estimate of forward velocity and does not take into account the effects of currents or drift.

Global navigation satellite systems (GNSS) use signals from satellites orbiting the Earth to determine the geographical position of an object on the Earth's surface. The most well-known and widespread GNSS is GPS (Global positioning system). However, GPS signals in the radio frequency range are blocked by seawater, which means they cannot be directly received by deeply submerged ocean vehicles.

Trajectory estimation using diffusion-based observers. This approach is proposed for estimating the trajectory of an underwater vehicle primarily using gyro-Doppler measurements (velocity measurements) and an acoustic positioning system (horizontal positioning). The method relies on the use of diffusion observers, which, unlike traditional state observers, are capable of processing entire segments of a system's trajectory at once [6].

A common solution for group AUV navigation is the use of asynchronous LBL with bottom or surface responder beacons (RBs). This navigation method is based on measuring the response time of a beacon to an outgoing signal from the underwater vehicle. It is assumed that a set of RBs (at least two) is present in the operational area, no more than 10–15 kilometers from the underwater vehicle. By triangulating the received time delays of the beacon responses, the distance from the RBs to the AUV is determined.

In implementing such an approach for group AUV navigation, a key issue arises – the need to allocate the acoustic communication channel to each AUV in the group at an optimally defined frequency to determine its position.

The navigation algorithm for an AUV group within the THESAURUS project uses USBL data and is based on a Kalman filter (KF) that accounts for the specific features of network communication organization. This method is suitable for autonomous underwater vehicles because it does not require any external assistance other than a single seabed station. The core idea is to use mutual acoustic measurements between the vehicle and the single seabed station – the AUV initiates an acoustic query to the seabed station and measures the range between the two units, as well as the bearing of the seabed station relative to the AUV in the AUV's reference frame. Then, the seabed station calculates the bearing of the AUV relative to itself and transmits this information back to the AUV using a similar acoustic device.

Group navigation algorithms based on inter-AUV distance information.

There exists a leader AUV, which determines its position with high accuracy. Other vehicles in the group estimate their positions using onboard navigation sensors and refine those estimates based on distance measurements to the leader AUV. In study [7], a group autonomous navigation system (GANS) with a mobile base is described. In this case, several expensive AUVs equipped with high-precision navigation systems act as beacons for other, simpler and less expensive AUVs.

7.3 A promising structure of mathematical support for autonomous underwater vehicles for surveying sea depths

Autonomous underwater vehicles (AUVs) are a safe and effective means for exploring ocean depths and performing search and survey tasks such as rescue operations, bathymetric measurements, oceanographic and ecological monitoring, as well as mine countermeasures. AUVs can also be used to carry out complex research missions, including automatic inspection of underwater communications, detection of sources of environmental pollution, and anomaly identification [8].

A key challenge lies in the insufficiency of existing methods for task description and control system architectures in general, as well as their software, particularly for survey-related tasks.

Let T represent the set of tasks for seabed survey and underwater operations. Thus, the problem is to decompose the set of tasks T into subtasks T_i, where i belongs to some index set I, in such a way as to optimize the efficiency of solving these tasks. Let $F(T)$ represents a function that estimates the overall complexity of solving a set of tasks T. The goal is to find the optimal schedule $T = \bigcup_{i \in I} T_i$, which minimizes the complexity function $F(T)$, taking into account internal connections and the optimal functional decomposition of the target class of tasks.

Currently, hierarchical, behavioral, and hybrid software architectures are used for control systems in mobile robots. For a more detailed analysis of these architectures, certain requirements are imposed on the information and control systems (ICS) of AUVs: reduction of computational resource usage, resolution of conflicts between different goals, utilization of information from various sensors, reliability, the possibility of incremental functionality expansion, ease of use, and a wide range of implementation options [9].

The hierarchical architecture is knowledge-based and includes an accurate symbolic representation of the surrounding environment. Decisions are made based on formal reasoning, which is one of the advantages of this architecture.

In the behavioral architecture, the control process is divided based on the desired external manifestations of the robot's actions. The robot's behavior is formed from operations executed by independent elements (behaviors or agents). Each behavior is directed towards achieving a specific goal, and its response is based on real-time sensor data.

When developing an architecture for AUVs, it is essential to consider requirements for minimizing resource usage, flexibility, and the ability for sequential expansion. A three-level functional distribution model characteristic of goal-oriented behavior architecture was adopted as the basis for development. This approach allowed the clear definition of explicit tasks for AUVs at the top level while simultaneously meeting resource requirements and enabling stepwise extension [10]. The term "agents" is used to specify the tactical level of behavior. The general structure of the developed software control system for the AUV is shown in **Fig. 7.1**.

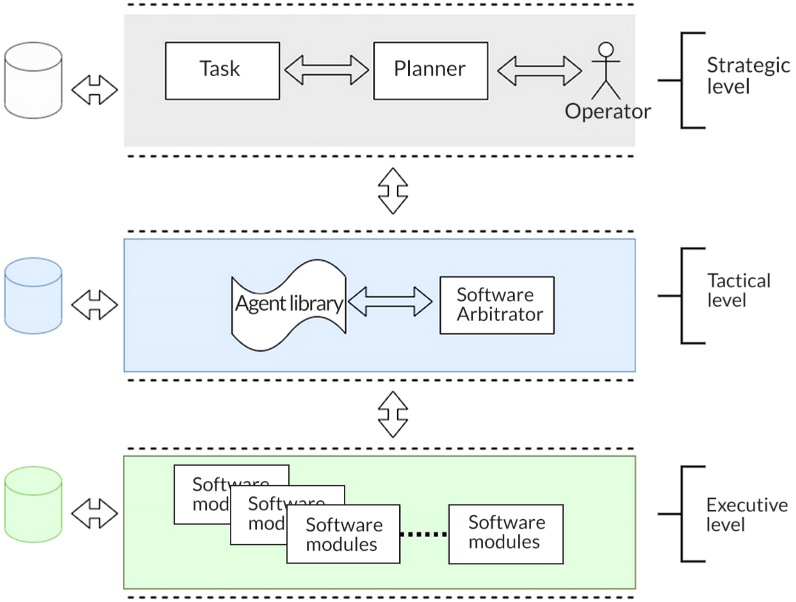

Fig. 7.1 Hybrid three-level architecture of the AUV software system

The system consists of three levels: executive, tactical, and strategic.

The executive level is responsible for controlling the robot's movement and executing reflex functions. The design of this level allows it to perform all functions dependent on the hardware of a specific robot and provides a hardware-independent interface for interaction with the tactical level.

The tactical level is used to organize the execution of the next task set by the strategic level. It directly manages the modes and goals of the executive level. To achieve this, a set of agents and an arbiter are located at this level, where the arbiter maintains the control structure of the agents to solve the current task.

The strategic level of the hierarchy is represented by a task program that contains a description of the current AUV mission objectives. To systematize the achievement of these objectives, a planner is generally used.

Interaction between system components occurs based on a client-server model or through the use of abstract interfaces implemented on the developed software platform, which supports event-driven and publish-subscribe mechanisms.

The tactical level of the system consists of a set of agents, each responsible for solving a specific aspect of the task (**Fig. 7.2**). The input parameters for each agent include the task description received from the strategic level, as well as the necessary data from the executive level. The output parameter is a stream of imperative commands for the executive level.

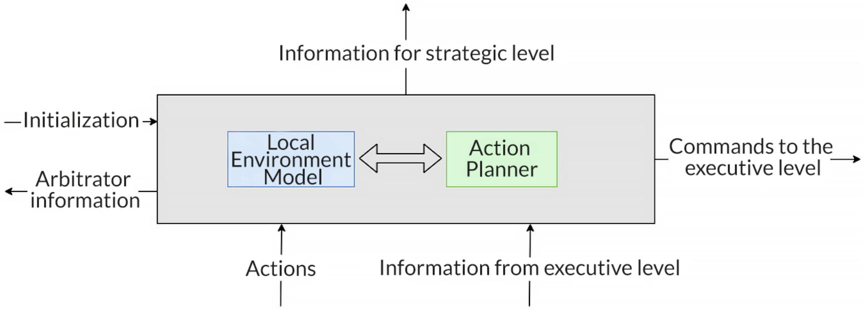

Fig. 7.2 Agent-based structure of the tactical level

The collection of agents is formed so that any task within the target class can be solved by a combination and collaboration of several elements from the collection. The list of agents is passed to the tactical level along with their activation conditions. Thus, the tactical level's task reduces to creating, ensuring the operation of, and terminating the specified group of agents.

An agent can be in one of several states:

1. Active: the agent maintains the model of the external environment in an up-to-date state and forms command lists for the executive level.

2. Passive: the agent maintains the model of the external environment in an up-to-date state but does not generate control commands.

3. Error state: the agent reports to the strategic level that it cannot perform its functions. This state occurs due to erroneous input data or failure of the executive devices controlled by the agent.

The arbiter ensures non-conflicting execution of agents. To do this, based on the assigned task (i.e., the list of agents), it organizes the specified agents into a multilayer control structure (forming layer 0). The priorities of each agent are implicitly set at the strategic level based on task nesting. To the resulting control structure, an additional fixed layer 1 with higher priority is added (**Fig. 7.3**), which serves to organize the response to events unrelated to mission execution (e.g., handling telecontrol commands). Thus, the initial plan can be refined by agents from layer 1 when unplanned situations arise.

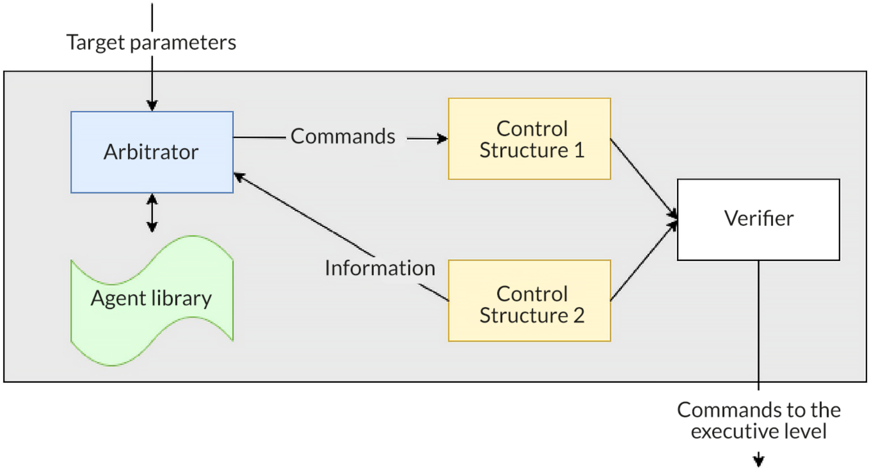

Fig. 7.3 Organization of the tactical level

The tactical level of the system contains an environment model that can be updated during operation by gathering information from the AUVs. This allows for more effective adjustment of target points while moving.

For the task of surveying artificial extended objects (AEO), a set of agents has been developed to ensure the execution of a full cycle of survey operations. These agents include:

1. Typical coverage of the water area with a network of courses.
2. Detection and tracking of AEOs using various AUV detection systems.
3. Re-survey of previously inspected objects.
4. Surveying foreign objects detected during the survey.
5. Return to base.

The indicator of the presence of AEO based on the data of the *n*-th AUV detection system at time *t* is the value p_t^n, which accumulates estimates of the probability of the existence of contacts preceding the current time point

$$p_t^{\Sigma n} = k^n p_{t-1}^{\Sigma n} + p_t^n, \tag{7.1}$$

where $p_t^{\sum n}$ – total value of contacts up to a certain point in time t for the subsystem n; k^n – damping coefficient for the subsystem n.

A multi-level structure of the tactical level is used to organize the survey of artificial extended objects (AEO). The structure consists of three management levels (**Fig. 7.4**):

1. Implementation of the desired trajectory.
2. Survey of the AEO.
3. Survey of foreign objects located near the AEO.

These levels are sequentially activated (and suppress the lower ones) as AEOs and foreign objects in their surrounding area are detected.

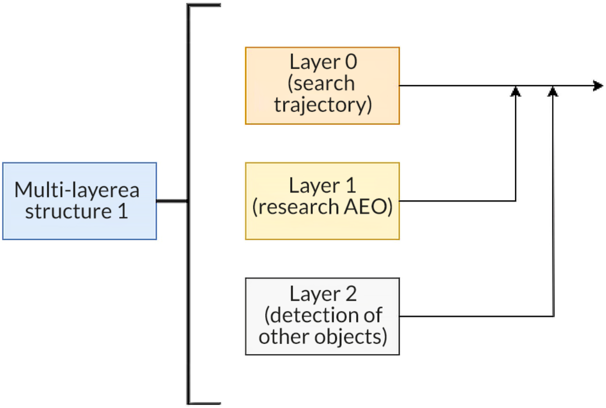

Fig. 7.4 Multi-level structure used for AEO inspection

The executive level of the control system is implemented as a reactive interpreter of the command stream from the tactical level. It interacts with the tactical level via an interface that includes messages and commands of various types (such as movement control, onboard equipment management, and provision of measured parameters).

According to the adopted methodology, at the executive level, tasks controlling identical actuators are combined into a multi-level control structure with precedence (dominance), as shown in **Fig. 7.5**. This structure includes:

- standard movement;
- movement correction (the choice between two options is determined by the goals set by the tactical level);
- reflex actions of the control system and emergency response.

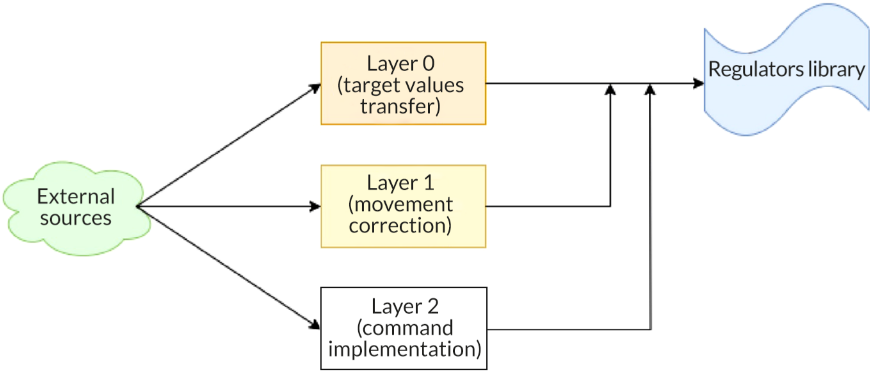

Fig. 7.5 Multi-level behavior structures of the executive level

The practical implementation consists of the following stages (**Fig. 7.6**):

1. Initially, the process of developing an agent library can be started, using the concepts of functional decomposition of the target class of tasks. This may include creating the program architecture, algorithms, methods of integration, and testing.

2. After developing the agent library, it requires testing in various scenarios and tasks related to deep-sea surveys and underwater operations. This includes verifying the operation of individual agents, their interactions, and compliance with declared functions and requirements.

3. Following testing, there may be a need for optimization or improvement of the library's performance. This may involve refining algorithms, increasing execution speed, improving accuracy, or expanding agent functionality.

4. Since the goal is to apply this library in real conditions, further plans include implementing it in underwater vehicle systems for real-world testing. This will allow evaluation of the library's effectiveness and suitability in practice.

5. After successful development, testing, and optimization, it is important to document all steps and results. This may include writing technical reports, articles, or publishing in scientific journals for sharing with the community of researchers and specialists in the field.

Fig. 7.6 Structure of the practical implementation process of the declared objective

Such a cycle can help improve the efficiency of solving deep-sea survey tasks and conducting underwater operations by leveraging advanced mathematical support for autonomous underwater vehicles.

7.4 Concepts of the development of a civil network system of underwater traffic control

Unlike conventional shipping, the sufficient efficiency of traffic control in the underwater space is due to the still unsolved tasks of providing reliable communication, processional positioning, identification of submarines, warning of navigational obstacles. It should be noted that traffic management of the future system of underwater transport corridors will be created taking into account the modern experience of developed maritime countries. First of all, this is the experience of building the information layer of the network-centric system of underwater warfare (underwater positioning and underwater communication) and the sensor layer (illumination of the underwater situation, recognition of underwater targets). The implementation of the mentioned military experience into the civilian system will not be burdened by the specific problems of covert and anonymous use of underwater positioning and communication, may not meet the requirements of invulnerability to means of destruction, may not have a system of recognition of "home-foreign". The engines of underwater vehicles should not be silent, the hydrodynamics of the hull should not provide extremely high speed, and their hull should not be designed for diving to a depth of 6000 m.

Due to this, the cost of civilian underwater vehicles will be many times lower compared to submarines. The large number of submarine collisions with each other should not be alarming, because the reason for these incidents is the noiselessness of their movement. Preventing the collision of underwater vehicles is solved very simply and effectively by installing on them hydroacoustic beacons in the sound range of 1–20 kHz with a range of up to 10–15 km. In addition, the installation of an acoustic beacon with an individual acoustic signature on each vehicle will ensure the operation of the underwater AIS segment.

The means of identification of underwater moving objects are considered by the authors of the work, which describes the tactical and technical characteristics of an AIS-type system that can simultaneously track several underwater objects with the necessary spatial and temporal resolution, demonstrating a realistic trajectory of movement [11]. The acoustic tracking system, designed for long-term tracking, thanks to the solar panel and is based on the principle of trilateration. The algorithm of the difference in the arrival time of the acoustic signal is used to determine the 2D/3D location of the moving object (three receivers provide 2D positioning, and four – 3D positioning). It should be noted that the creation of an extensive system of cargo transportation in the underwater space, in terms of traffic control, requires the development and implementation of the so-called information and sensor layers – permanent network infrastructure - along shipping routes. This is due to the fact that the existing systems of radio communication and satellite geodesy do not work in the underwater space, or have significant limitations. An analogue of the civilian system that will need to be created is a military network-centric navigation and communication system (**Fig. 7.7**), which was put into service in the US Navy in 2005.

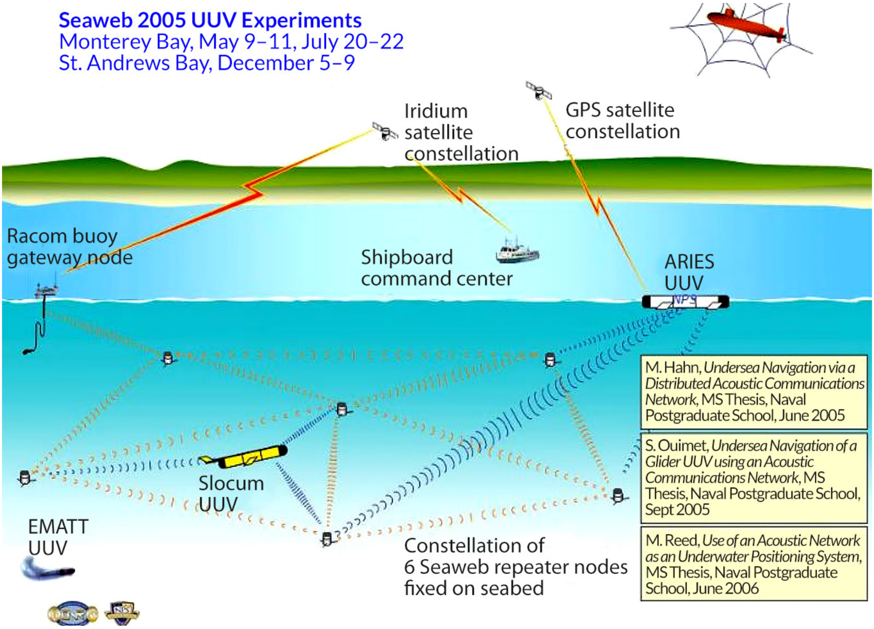

Fig. 7.7 Scheme of bottom infrastructure of underwater positioning

Control of movement in the underwater space is connected with informational and sensory provision of situational awareness of the artificial intelligence of an autonomous unmanned underwater vehicle: own current coordinates; the coordinates of surrounding vessels, which are a navigational hazard and are determined based on the data of the vehicle's own active hydroacoustic system; communication, to transmit commands and exchange data between the underwater vehicle and the shore traffic control center. The coastal center for controlling the movement of ships in the underwater space needs to be provided with data on: current coordinates of the submarine according to AIS data; the current technical condition of the vessel and its navigation equipment. Providing underwater communication and positioning is solved by several methods. In underwater space, hydroacoustics dominates, because the range of propagation of radio and optical electromagnetic waves is limited to the first tens of meters. The minimum range of hydroacoustic communication is 1–2 km, and in deepsea areas, if there is a hydroacoustic waveguide, it exceeds 100 km [12].

In hydroacoustics, data exchange is carried out only in the sound and infrasound frequency ranges, because ultrasound propagates anisotropically and over a distance of no more than 1 km. The modern technical level of the speed of hydroacoustic communication and the volumes of transmitted information are sufficient for the successful control of the movement of underwater vehicles, that is, for the exchange of navigational information and the transmission of commands.

Theoretically, calculating the arrival time of the signal from the source to the receiver is extremely difficult. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex topography of the bottom and that the sound wave, moving from one horizon to another, changes the speed of movement in accordance with the VSSD. Errors in distance measurement by acoustic methods should not be considered significant, depending on the paths along which the acoustic signal propagates and on changes in the speed of sound along these paths. The maximum error can be up to $3 \pm 0.3\%$.

Due to acoustic shadow zones, signal transmission may not occur between the transmitter and receiver installed at a certain distance and at a certain depth, which disrupts communication and underwater positioning. It is immediately possible to say that the specified problem is solved both mathematically and technically. Technically, this problem is solved by using a vertical antenna array instead of one acoustic receiver on the seabed. The characteristics of the vertical antenna array are known. For data exchange at a frequency of 10 kHz, the distance between the hydrophones should be 1.5 m, which corresponds to 10λ (where λ is the length of the acoustic wave) based on the frequency of 10 kHz [12].

The mathematical solution consists in calculating the spatial position of the acoustic shadow zones, ranging and bearing errors. The calculation algorithm is known. In the work [13] sonograms from sound sources placed in the conditions of the real relief of the seabed are given. It is shown that circles of an acoustic shadow with radii of approximately 7 and 15 km are created around the source of the acoustic signal (**Fig. 7.8**).

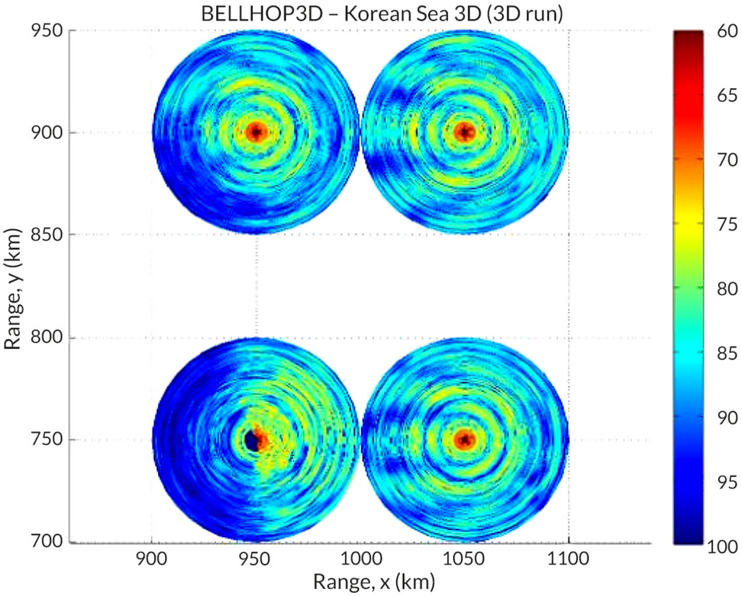

Fig. 7.8 Scheme for calculating spatial losses of an acoustic signal

The spatial position of the acoustic shadow zones depends exclusively on the features of the vertical distribution of sound speed in water. The vertical distribution of sound speed is determined by measurements, but it is very difficult to do technically. Another solution is the use of the acoustic tomography method. Our department conducts research in this direction. The latest article published in the direction of acoustic tomography has a title "Acoustic tomography algorithm for determining the spatial isotropicity of the hydroacoustic field".

One of the primary characteristics of the marine environment is the speed of sound, which very sensitively reflects its smallest changes. Moreover, this characteristic is integral. It inseparably characterizes the state of the system, which is formed by a whole complex of influences and reactions to them. Acoustic tomography is based, among other things, on the sound irradiation of the marine environment and the analysis of the received signal for the purpose of evaluating changes in its characteristics after passing through the water space. Changes in the characteristics of the acoustic signal can occur for annual reasons, one of which is spatial changes in the vertical distribution of sound speed. As a result of theoretical research in the direction of passive acoustic tomography, using the methods of modeling the refraction of acoustic waves, a new type of quantitative characteristics of the acoustic field was determined for the first time. The principle of determining the appropriate reference characteristic of the acoustic field is proposed, on the basis of which the basis for creating algorithms for restoring the vertical distribution of sound speed is developed. The algorithm for determining the reference characteristic, including, includes the calculation of acoustic energy losses, which is translated into the frequency domain to determine the positive extremum of the amplitude spectrum and the calculation of the reference characteristic of the regional acoustic field in the time domain. One of a number of algorithms for determining the spatial isotropy of the vertical sound speed distribution has been adapted. The implementation of the specified algorithm of passive acoustic tomography will provide ship sonar with input data for depth determination, which will increase the safety of navigation.

In this way, the technologies for determining the spatial characteristics of the sound speed distribution have been developed and are continuously being improved. Analysis of volume refraction calculations allows to determine periodic manifestations of acoustic shadow zones. Circles with good (red color) and bad (blue color) transmission of the acoustic signal are formed by the isotropic sound speed field. blue "spots" – zones of poor acoustic signal transmission are formed by the isotropic component of the sound velocity field. Sectors of no acoustic signal transmission are formed by the interaction of the acoustic field and the topography of the seabed. In **Fig. 7.9** shows the scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope [13]. The given calculation scheme explains why in **Fig. 7.8**, zones of sector-type acoustic shadow appear around the emitter of the acoustic signal.

That is, the coordinates of the zones of the acoustic shadow can be determined by calculations. Under the conditions of refraction of acoustic rays in the horizontal plane, bearing determination errors occur. It also happens in areas with significant slopes of the seabed [13, 14].

The article [9] gives an example of the deployment of an underwater hydroacoustic data exchange network with an area of approximately 500 km^2 (**Fig. 7.10**). The diagram shows the acoustic relay network of underwater communication, consisting of 100 stations.

Fig. 7.11 shows that the underwater acoustic communication channel is time-varying. In addition to the distortion of acoustic signal beams due to refraction, multibeam is generated by the formation of numerous interactions of sound with the surface and seabed. This is especially evident in shallow water. Multipath slows communication by creating a delay in sound propagation. In addition, an acoustic signal, which characteristics change along the propagation path leads to the

Doppler effect, which is associated with an increase in the dispersion of changes in the frequency of the acoustic signal. Due to sound reflection from the bottom and surface, the distance measured by acoustic methods is always greater than the actual distance. This effect should not be overestimated. Theoretically, it is very difficult to calculate the arrival time of the signal from the source to the receiver. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex relief of the bottom and that the sound wave, moving along the trajectory of its own movement, changes the speed of movement. The measured distance errors by acoustic methods, depending on the trajectories along which the acoustic signal propagates, and on changes in the speed of sound along the specified trajectories, can be up to 3 ± 0.3%.

Thus, it can be stated that some problems of underwater communication are solved by technical means, some are taken into account by mathematical modeling. Some problems have not been solved and there are limitations in the propagation of an acoustic signal under water. Such limitations are determined by determining the bit error rate (BER).

Fig. 7.12 shows that the determination of the range of the communication relay station is calculated by determining the intersection of the actual constant BER value with a threshold value of BER of 2%.

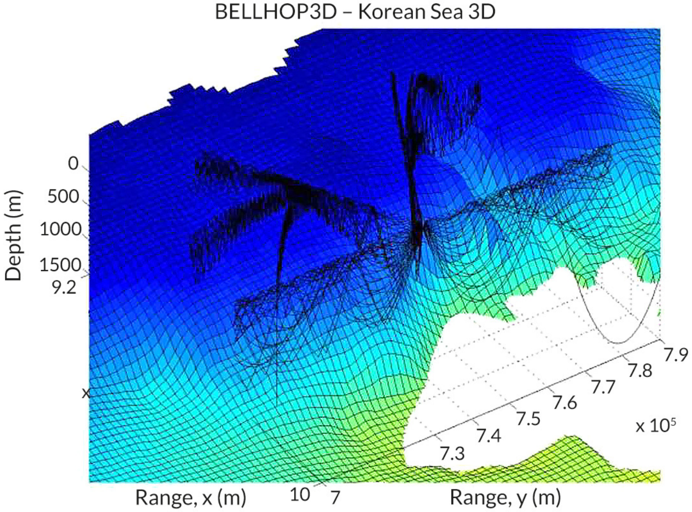

Fig. 7.9 Scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope

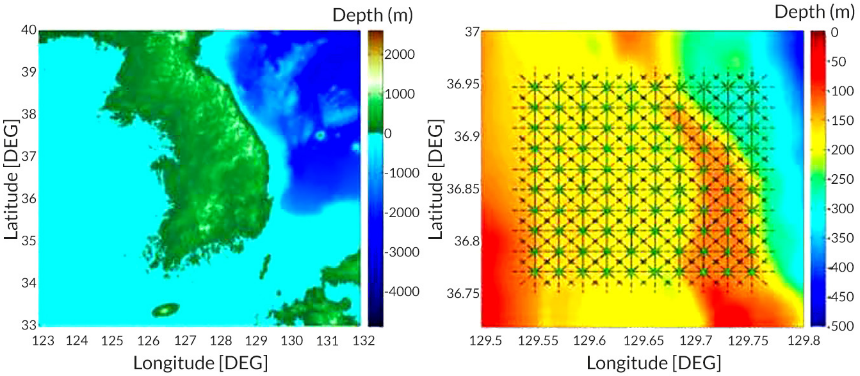

Fig. 7.10 The map and scheme of the acoustic relay network of underwater communication, as the basis of mathematical modeling

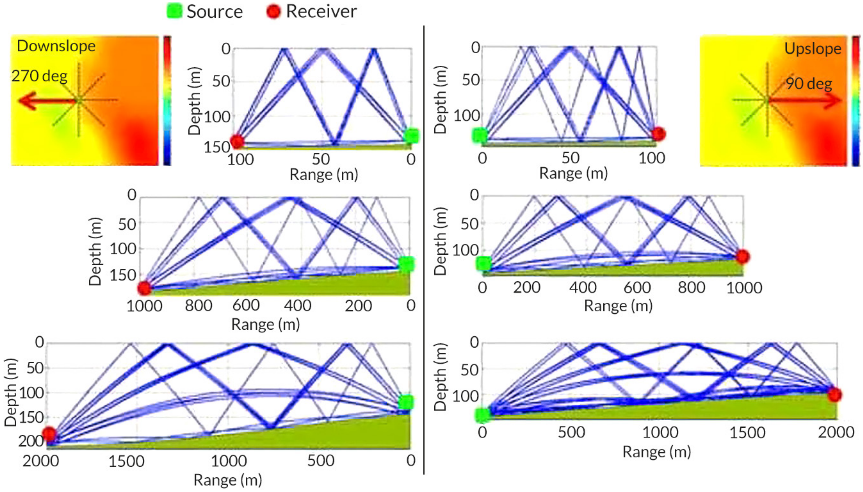

Fig. 7.11 Results of calculations of acoustic ray trajectories for azimuthal angles 270° and 90°

A reliable data exchange system requires real-time communication with high data rates and low error rates. **Fig. 7.13** shows the simulation results of the optimal deployment of the underwater data exchange network for two different seasons. Certain quantitative characteristics are defined. The distance between each sensor node and its neighboring sensor nodes corresponds to the minimum communication threshold. The level of communication coverage for February was estimated at 85.2%, which is higher than in August (estimated at 80.6%).

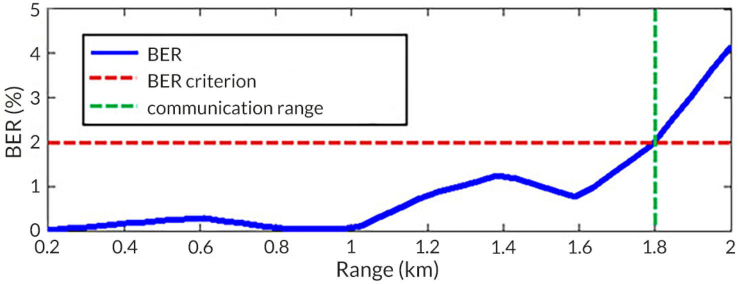

Fig. 7.12 Example of BER variation as a function of range

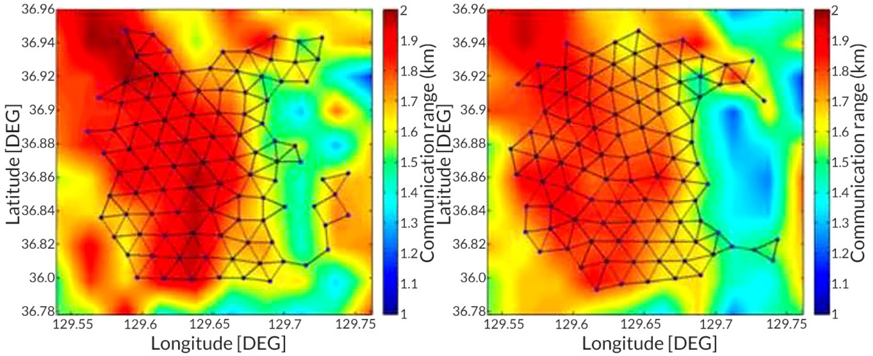

Fig. 7.13 Simulation results of the optimal deployment of an underwater data exchange network using 100 sensor nodes

Prospects for the creation of hybrid acoustic and electromagnetic systems are considered in the work [15]. In principle, data exchange in the interests of ship control and positioning can be carried out by acoustic (mechanical) waves in the sound frequency range, lasers (coherent electromagnetic waves) in the optical wavelength range of 400−600 nm, and radio waves at frequencies of 30−300 MHz. The results of the comparison of the specified underwater communication technologies are given in the **Table 7.1**.

The best underwater data exchange in terms of speed and volume of transmitted information is provided by laser methods. In second place is radio communication in the microwave range and in third place is the hydroacoustic communication channel.

The advantage of data transmission in the radio range is that, unlike laser and acoustic methods, radio waves propagate freely through the interface between the ocean and the atmosphere [16].

Table 7.1 The results of the comparison of the specified underwater communication technologies

Parameter	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1–4 dB/km)	Frequency and conductivity dependent (3.5–5 dB/m)	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	1500 ms^{-1}	2.3×10^8 ms^{-1}	2.3×10^8 ms^{-1}
Data rate	kbps	Mbps	Gbps
Latency	High	Moderate	Low
Distance	More than 100 km	< 10 m	10–150 m (500 m potential)
Bandwidth	1–100 kHz	MHz	150 MHz
Frequency band	10–15 kHz	30–300 MHz	5×10^{14} Hz
Transmission Power	10 W	mW–W	mW–W

As an example of the prospect of combining military and civilian technologies, it is possible to cite a possible prospective hybrid of military communication systems "Tactical Underwater Network Architecture" [17], and civil underwater acoustic communication systems [18] and systems of hydroacoustic automatic identification of the movement of underwater targets [11].

The first system, which is an alternative to unreliable hydroacoustic underwater communication, involves the installation of autonomous surface buoys with radio receivers and radio transmitters (surface buoys under water connected by a fiber optic cable) solves the problem of reliable data transmission (traffic control). The second system provides for the installation of sonar devices on surface buoys, which provides protection of the surface system from saboteurs to the underwater vehicle and simplified underwater positioning. The third system involves retrofitting surface buoys with an acoustic vertical antenna array to provide additional underwater hydroacoustic communication of an underwater vehicle with surface radio communication buoys. The fourth system involves the additional use of an antenna array as a noise deflector. the noise direction finder is used as an element of underwater AIS to passively track the trajectory of an underwater vehicle equipped with a hydroacoustic emitter with an individual acoustic signature.

7.5 Conclusions

A new architecture has been proposed for the control system of an autonomous underwater vehicle, which incorporates both hierarchical and behavioral control structures. This significantly expands the capabilities of the AUV, allowing it to solve tasks of various classes under the constraints of limited computational resources of the onboard computing network.

Within the proposed architecture, a behavioral approach is applied at different levels of the functional three-tier control system architecture. The control structures at the executive level have a fixed composition, while variable structures are formed at the tactical level based on a developed library of agents.

An approach to building the tactical-level agent library is justified based on the functional decomposition of the target class of tasks. The robot's actions are formulated in terms of agents that form the library, which provides a foundation for creating declarative missions. The agent structure has been developed and studied, including a local environment model, tools for action planning based on this model, and analysis of the utilized information to assess the agent's operability.

This gives reason to believe that sea transportation of cargo under water will become a reality in the near future. An underwater transport fleet will be built just as quickly. Unlike conventional ships, which are difficult to design, designing a fleet of unmanned underwater vehicles will not take much time, because simplified technologies for the construction of military submarines and LDUUVs will be involved. The experience of creating bottom network bottom positioning and communication systems based on the hydroacoustic principle of action should be applied in combination with systems operating on other physical principles. Microwave radio communication directly between an underwater vehicle in an underwater position and satellite means of communication certainly has prospects. There are prospects for laser communication, which is unsurpassed in the speed and volume of information transmission and the real time scale.

Research has demonstrated the necessity to improve the control systems of autonomous underwater vehicles as more complex tasks beyond simple search and survey operations are undertaken. There is a pressing need to expand the range of solvable task classes.

Accordingly, in the course of further scientific investigations, the author is prepared to focus efforts on the recognition and classification of search objects and situations occurring in the underwater environment, detection of emerging trends in the operational situation, and modeling the behavior of certain objects that may pose danger or threat.

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