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Concept of an Autonomous Underwater Vehicle with Holographic Signal Processing in Shallow Water

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ABSTRACT The design concept for a specialized hybrid autonomous underwater vehicle intended for monitoring in shallow water is presented. In addition to its conventional functions, the proposed configuration of the autonomous vehicle provides the capability to operate in Glider mode for energy-efficient transit to remote monitoring areas. It can also function as a low-noise receiving hydroacoustic station with controlled movement within the water column and switch into radio buoy mode with integrated navigation and communication systems. It is assumed that the vehicle is equipped with a vector-scalar receiver and performs onboard holographic processing of noise signals, enabling real-time detection and localization of low-noise underwater sources based on their acoustic field under conditions of spatial and temporal environmental variability. The potential of such a hybrid vehicle lies in its ability to perform mission-specific tasks in real time onboard. Proposals are formulated for deploying hybrid vehicles as part of a larger group.

INDEX TERMS hybrid autonomous underwater vehicle, noise source, vector-scalar receiver, holographic processing, detection, localization

I. INTRODUCTION

AUTONOMOUS underwater vehicles (AUVs) are being used more and more in various real-world operations and research. They are generally implemented as multipurpose platforms designed for a wide range of tasks, such as the automated search and inspection of the seabed and underwater infrastructure [1]. There is also considerable interest in developing highly specialized underwater vehicles whose onboard instrumentation is tailored to specific critical tasks. One such important task is monitoring the local underwater environment based on acoustic noise analysis. The most effective receiving systems for measuring noise fields generated by moving underwater sound sources, as well as for their detection and identification, are those equipped with combined vector-scalar acoustic receivers (VSRs) [2]–[5]. These VSR receivers can detect underwater sound sources, determine their range and angular position, and monitor their movement trajectory. Among the signal processing methods for VSRs [2], holographic signal processing (HSP) is a particularly promising approach. The theoretical foundations of HSP are presented in [3], [4]. The results of experimental verification are reported in [4], [5].

Since the acoustic field of a moving underwater source is stratified along the depth of the waveguide, especially in shallow waters, informative detection parameters of the moving source are the characteristics of the power flow vector measured using VSRs. The maximum values of these parameters are observed in zones of increased acoustic illumination whose positions change dynamically as the noise source moves. These zones of increased illumination in the acoustic field can be found by tracking the sound field's dynamics using a VSR-based receiving system mounted on a silent, moving underwater platform, which could be an AUV.

Using AUVs to monitor the underwater environment and detect and localize low-noise underwater sources based on their noise fields, especially in the context of spatial-temporal environmental variability, is currently of great importance [6], [7]. This issue is particularly pertinent in shallow waters, where reliable seabed data is lacking and non-stationary processes in the water column can result in substantial hydrological variability. To enable the effective use of acoustic receivers, AUVs designed to perform such tasks must meet additional requirements. These requirements include minimizing self-noise and enabling controlled movement in the work area in order to search for zones of increased illumination in the monitored acoustic field. One way to reconfigure an AUV with standard onboard systems into a weak signal receiving station capable of silent, controlled movement is to use a hybrid AUV (HAUV) [8], [9].

Several spatially distributed platforms equipped with VSRs are employed to fulfill the intended functions. Each carrier processes the energy characteristics of the acoustic field to generate onboard informational parameters. These parameters are then transmitted to a control station via a HAUV relay command and processed. Using the calculated bearings and known coordinates of the platforms, the location of the noisy object is estimated. Groups of underwater vehicles implementing such scenarios must meet requirements for enhanced robustness in hydroacoustic data processing and low sensitivity to changing environmental conditions. Additionally, the group receives navigational and informational support through radio and hydroacoustic communication channels between the control station, the command HAUV, and each AUV. These objectives are achieved by reconfiguring the AUV into a HAUV. The HAUV is a multifunctional platform that can operate in active mode, like a conventional AUV, with thrusters engaged, or in passive mode, like an underwater glider, with thrusters disengaged and using onboard buoyancy and stability control systems. It is equipped with a receiving hydroacoustic system (HAS) based on VSRs with modules for processing noise vector-scalar fields. HAUVs are currently among the most promising mobile technical tools for covertly monitoring the underwater environment. They achieve this through their low noise signature and ability to carry a wide array of equipment while dynamically adjusting their movement program and location [10], [11]. In the near future, it is expected that HAUVs equipped with VSR modules and robust noise signal processing software will significantly change the nature of, and increase the efficiency with which, low-noise underwater vehicles are detected and localized by their noise fields. HAUVs are particularly irreplaceable in under-ice operations.

Our paper presents a design concept for a specialized HAUV intended for shallow-water monitoring. A model of a hybrid platform combining the capabilities of a transport vehicle and a low-noise underwater receiving station is developed. Solutions for the development of onboard equipment for weak acoustic signal reception based on HSP methods for VSRs are proposed, providing high noise immunity and low sensitivity to medium inhomogeneities in underwater noise source detection and localization.

II. HAUV APPLICATION MODEL

Within the HAUV application model, the vehicle intended for monitoring underwater noise in controlled areas over specified periods is considered as an underwater robot that fulfills its assigned tasks by automatically switching between functional modes. Two primary functions are distinguished. The first function enables HAUV to serve as a transport platform and carrier of equipment for receiving and processing acoustic noise signals. The second function enables the HAUV to operate as a silent underwater station for receiving and processing the acquired acoustic noise fields with controlled movement along the water column. The HAUV must also be equipped with radio and satellite communication and navigation systems and have the capability to periodically or emergency surface. During these periods, the results of the acoustic field monitoring are transmitted via radio to the control center.

During patrol operations within the designated water area, the HAUV periodically moves its receiving system vertically, from the surface to the seabed and back, while monitoring acoustic field levels. At depths corresponding to elevated signal levels, the HAUV maintains a hovering mode for acoustic data acquisition. Accurate knowledge of the current HAUV position is essential for the detection and localization of noise sources.

Considering the above recommendations for receiving acoustic data, the operational model of a HAUV includes the following stages: moving to reach the initial operating point, receiving signals during underwater noise monitoring, and delivering data, during which the monitoring results are transmitted to the control center. The procedure for switching between these functional modes is explained further below.

A. MODEL OF HAUV IN VSR TRANSPORT MODE

When traveling to the operation's designated geographic starting point, it is advisable for the HAUV to travel on the sea surface or underwater in AUV mode, or underwater in Glider mode. In AUV mode, the vehicle is launched from a carrier or coastal base and uses its standard propulsion system. It is also guided by satellite navigation data. While moving underwater, the vehicle descends to a predefined depth. Dead-reckoning coordinates are then calculated using data from the heading and ground-relative speed sensors. Once the target location is reached, the vehicle surfaces to refine its geographic coordinates. At this stage, accumulated dead reckoning errors can be corrected through surface maneuvering.

This method is recommended when the deployment area is within a few kilometers of the carrier or base. However, if the deployment area is tens of kilometers away, it is most energy-efficient for the vehicle to travel through the water column in underwater Glider mode without using thrusters.

Fig. 1 shows a model of HAUV operation in a in VSR transport mode for delivering the HAS from the base point to the assigned location and back after completing underwater noise field monitoring.

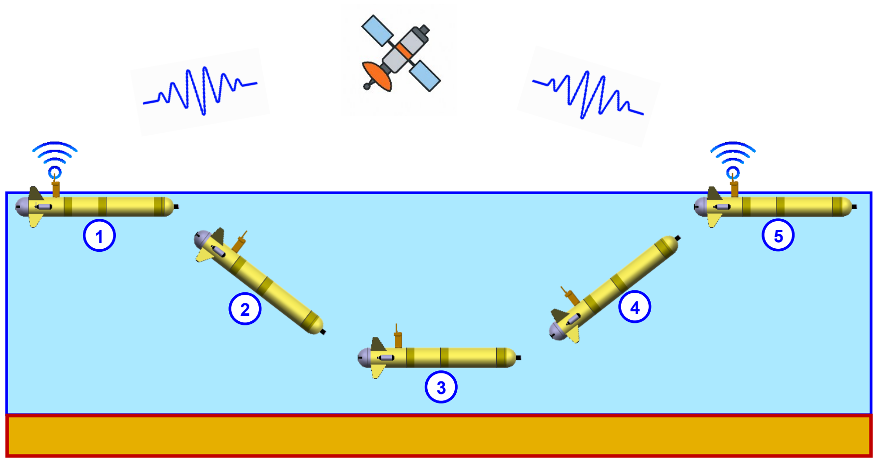

FIGURE 1. Model for the Deployment of HAUV in VSR Transport Mode.

The HAUV's safe movement is ensured by underwater navigation with periodic surfacing. During these surfacings, the HAUV's coordinates are corrected using satellite navigation systems and course adjustments are made.

Initially (Fig. 1, pos. 1), the HAUV travels on the surface from its base location. After determining its geographic coordinates, it dives to a specified depth using the main tilting thrusters, which generate the necessary forward thrust and pitching moment (Fig. 1, pos. 2). Once the target depth is reached, the HAUV moves through the water column toward the monitoring point. It maintains a stable speed, depth, and heading with the help of control forces and moments generated by the thrusters (Fig. 1, pos. 3). While underwater, the HAUV's coordinates are estimated using the heading angle and predefined travel speed. Upon reaching the designated monitoring point, the HAUV surfaces (Fig. 1, pos. 4) to refine its geographic coordinates (Fig. 1, pos. 5). Any accumulated dead reckoning error is compensated for by performing surface maneuvers based on satellite navigation corrections.

B. MODEL OF HAUV IN VSR OPERATION MODE

In VSR operation mode (HAS mode), the HAUV operation model involves positioning the vehicle vertically at a specified distance from the seabed with minimal deviation from the designated monitoring point. Then, the HAUV returns to the surface.

The noise environment is monitored using a HAUV operating as a HAS. This is implemented through the following sequence of maneuvers (see Fig. 2):

- Initial position of the HAUV on the surface upon arrival at the monitoring point (Fig. 2, pos. 1).
- Transition to a vertical orientation after refining geographic coordinates on the surface (Fig. 2, pos. 2).
- Vertical descent with a $+90^\circ$ pitch angle (stern-first) under main thrusters to a predefined depth of 5–10 meters above the seabed (Fig. 2, pos. 3).
- Active stabilization of the HAUV in the vertical position at 10 meters above the seabed, based on targeting data from the aft echo sounder (Fig. 2, pos. 4).
- Anchor deployment with a 10-meter line and shutdown of thrusters, transitioning into a low-noise vertical hovering mode for recording vector-scalar noise fields. The HAUV is held in place by negative net buoyancy with the anchor, while maintaining positive buoyancy of the HAUV itself (Fig. 2, pos. 5).
- Activation of the main thrusters for vertical stabilization at 10 meters above the seabed and release of the anchor line (Fig. 2, pos. 6).
- Vertical ascent to the surface under thruster power (Fig. 2, pos. 7–8) to transmit monitoring results to the data collection center and refine geographic coordinates.
- Transition to horizontal orientation and determination of geographic coordinates (Fig. 2, pos. 9–10).

III. FUNCTIONAL SYSTEMS MODEL OF HAUV

Let us consider functional systems of HUAV. Fig. 3 shows a functional systems model of HAUV, illustrating the composition and interaction of its onboard systems.

As described in Section II, the HAUV application model assumes the use of the HAUV in two operating modes: VSR transport mode and VSR operation mode. In VSR transport mode, the HAUV is ballasted as a self-propelled vehicle with zero pitch and slight positive buoyancy. Upon receiving a mission assignment, the vehicle is launched from a carrier vessel and proceeds to the designated coordinate point. In the VSR transport mode, the following functional systems are assumed to operate (see Fig. 3):

- Energy Supply System.
- Propulsion–Steering System.
- Control and Navigation Software System.
- Hydroacoustic Navigation and Communication System.

Once the assigned coordinates are reached, transition mode is activated, refining the geographic coordinates at the

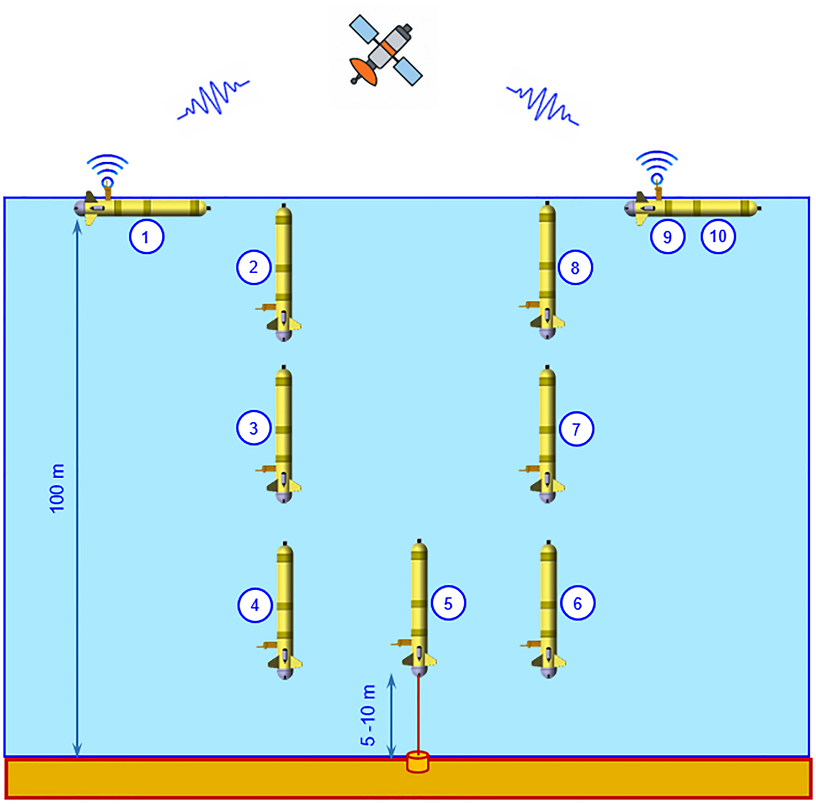

FIGURE 2. Model for the Deployment of HAUV in VSR Operation Mode.

surface and converting the self-propelled HAUV into a silent underwater Glider. To do so, Propulsion - Steering System is deactivated. In HAUV transition mode, the following functional systems are assumed to activate (see Fig. 3):

- Radio Communication System.
- Buoyancy Control System.
- Stability Moment Control System.
- Hydroacoustic System.
- Anchoring Parking System.

These functional systems are then commanded to provide a stern-down pitch angle of 90 degrees and slightly negative buoyancy. The HAUV then begins a slow descent while receiving and processing data. After completion of the descent, the anchoring system is deployed, after which the HAUV transitions to the VSR Operation Mode.

The proposed model for implementing the core functions of the HAUV implies significant differences between the equipment of a HAUV and that of a conventional AUV. The standard configuration of a conventional AUV includes a rigid hull structure with a power supply system, a propulsion and steering system, onboard control and navigation systems, as well as hydroacoustic navigation and communication systems. In the case of the HAUV, the conventional AUV configuration must be supplemented with functional systems that provide additional operational capabilities. These include a buoyancy control system, a stability moment adjustment system, an anchoring and parking system, a radio communication module, as well as structural modifications for Glider mode operation. The HAUV's payload is a hydroacoustic station based on VSR.

We will describe the main functional systems of HAUV that determine its design for underwater monitoring.

A. BUOYANCY CONTROL SYSTEM

This system generates control forces and moments that act on the vehicle during low-noise operation. When used in VSR transport mode, it must ensure symmetrical control of residual buoyancy and a zero static trim angle. When used in VSR operation mode, it must provide maximum positive buoyancy and an additional righting moment to maintain a vertical position. The system can be integrated into the hull with two variable-volume modules (see [1], [12]). The bow and stern modules are located symmetrically relative to the center of buoyancy and are attached to the flanges of the bow and stern compartments. Each module contains a hydraulic pump with a variable-speed electric drive and a solenoid valve mounted on a connection plate. The equipment is housed in a pressure-resistant container filled with hydraulic fluid. A variable-volume membrane connected to the pump outlet is regulated by the solenoid valve.

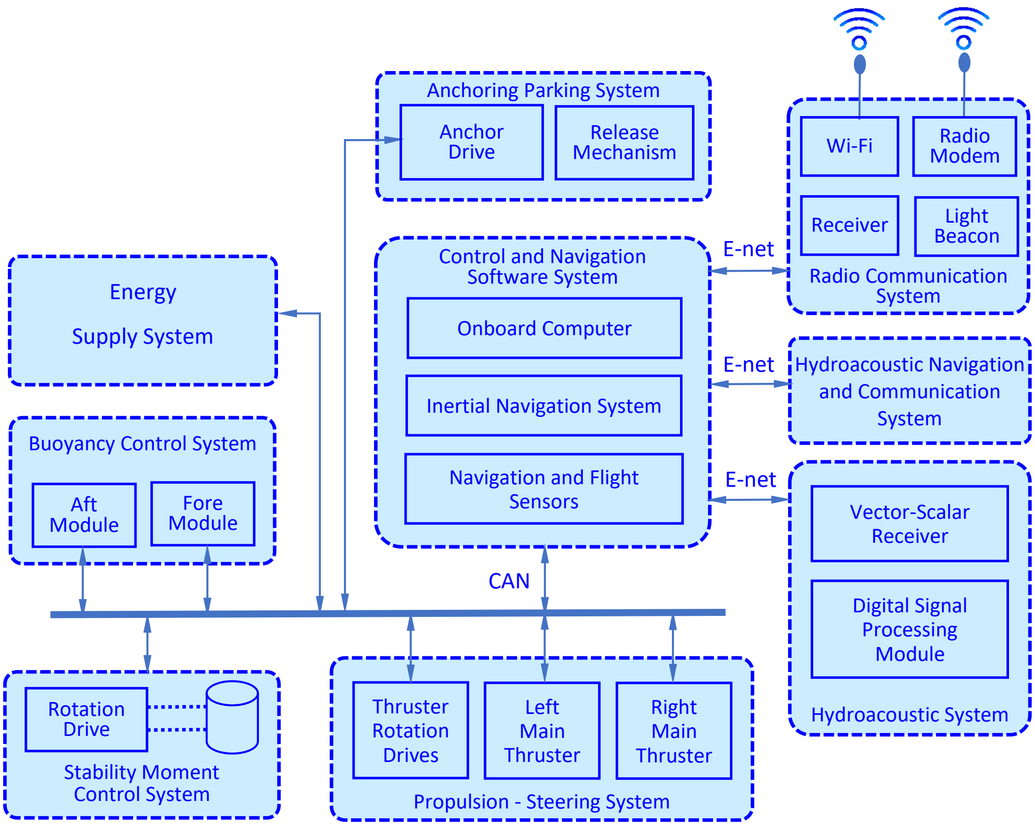

FIGURE 3. Functional Systems Model of HAUV.

B. STABILITY MOMENT CONTROL SYSTEM

It is designed for low-noise, energy-efficient stabilization of the vehicle in a vertical position when the trim angle is +90 degrees toward the stern. This is accomplished by shifting the vehicle's center of mass to two positions: one in the negative region of the vertical axis and the other in the negative region of the longitudinal axis. This setup also enables adjustment of the static trim angle from 0 to +90 degrees (see [9]).

C. ANCHOR PARKING SYSTEM

This system keeps the vehicle anchored to the seabed in VSR operation mode. It ensures the anchor is reliably fixed in all motion modes, and allows for the anchor to be released and separated from the vehicle under its own weight to a fixed cable length of 5-10 m. It also allows for the cable reel to be released, which maintains the connection between the vehicle and the anchor. A structural implementation of the Anchoring Parking System is shown in Fig. 5.

D. CONTROL AND NAVIGATION SOFTWARE SYSTEM

This system provides the control logic necessary to automate the mission by changing the current functions of the HAUV. It implements two operational modes: HAUV in VSR transport mode, in which the vehicle travels autonomously to the patrol area; and HAUV in VSR operation mode, in which propulsion is disabled and the vehicle moves vertically at designated coordinates while maintaining the vertical orientation of its body axis in order to receive acoustic signals from the environment. The system also manages buoyancy, enabling the vehicle to periodically surface. During this time, monitoring results are transmitted via radio to the control center (Radio Communication System).

E. HYDROACOUSTIC NAVIGATION AND COMMUNICATION SYSTEM

This system uses an underwater acoustic communication channel to transmit acoustic monitoring data and control commands between the HAUV and the control station in the form of brief, formalized messages. After deployment at the designated coordinates, it also supports position refinement for the HAUV and other units in the group.

For HAUV to be effective in monitoring the underwater environment, it must be able to detect and localize low-noise underwater vehicles in real time and transmit this information to a control unit. Onboard data processing must generate monitoring results in the form of detection events, the angular position of the noise source, and the spectral composition of the acoustic signal. This significantly reduces the frequency of communication sessions and the amount of data that needs to be transmitted to the control center.

F. HYDROACOUSTIC SYSTEM

To achieve this, the onboard HAS equipment and the system's operational conditions must meet several requirements. When the vehicle moves using its standard propulsion system, considerable self-noise is produced by the HAUV due to the propellers, vibrations, and hydrodynamic flow around the hull in the frequency range of the receiver system [13]. Therefore, measures must be taken to reduce this noise. Another important requirement concerns the influence of hull structures on the directivity pattern of the receiving system, which increases bearing measurement errors.

To meet these requirements, HAUV is reconfigured into a low-noise receiving station with a vertical orientation of the vehicle's longitudinal axis in its standard signal reception mode. In this configuration, the HAUV equipment is located in the bow of the vehicle and the VSR is mounted on a gimbal inside a spherical, water-filled, acoustically transparent dome. This allows the VSR to remain horizontal regardless of the receiving module's inclination (which may occur due to water currents in the operational area).

The top section of the HAS module houses the navigation and communication antennas, which exchange data with the control center when the vehicle is on the surface of the sea. The lower section contains a sealed compartment with electronic functional units that operate the receiving system. The HAS is fully integrated with HAUV for power supply, data exchange, and synchronization through a unified time system.

The input data for the HAS are signals from the VSR, and the outputs are the results of processing the vector-scalar noise fields. The HAS equipment includes the VSR, as well as electronic modules that perform the necessary signal conversions. These include analog filtering of received signals, adjustment of their amplitude to optimal levels for digital conversion through automatic gain control. Within the framework of the proposed HAUV model, it is assumed that the processing of VSR hydroacoustic signals is based on HSP methods (see Section V). HSP methods enable relatively simple onboard algorithmic implementation on HAUV and make it possible to minimize the amount of information transmitted from HAUV.

The equipment also performs analog-to-digital conversion of the VSR signals and interfaces the digitized data via a serial interface to the digital signal processing module. It generates a high-stability reference frequency for synchronization and supplies necessary voltages to all electronic components. The HAS software package processes the received VSR signals in real time, generating periodic messages that are transmitted via communication channels to the data collection center. These messages contain information on the monitored noise fields.

IV. HAUV STRUCTURE MODEL

Let us consider structure systems of HUAV.

Figs 4 and 5 show the structural design of the proposed HANPA model. Structural model of HAUV in VSR transport mode is presented in Fig. 4. Structural model of HANPA in VSR transport mode consists of the following elements:

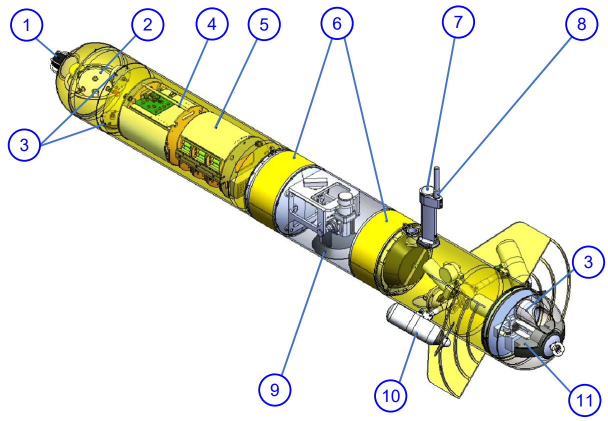

FIGURE 4. Structural Model of HAUV in VSR Transport Mode.

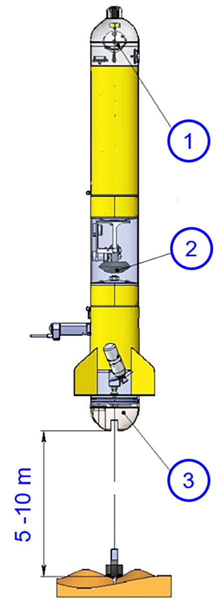

FIGURE 5. Structural Model of HAUV in VSR Operation Mode.

- Antenna of Acoustic Navigation and Communication System (Fig. 4, pos. 1).
- Vector-Scalar Receiver of Hydroacoustic System (Fig. 4, pos. 2).
- Antennas of Echo-Sounding System: forward – downward – aft (Fig. 4, pos. 3).
- Control System Electronics Unit (Fig. 4, pos. 4).
- Battery Module of Energy Supply System (Fig. 4, pos. 5).
- Buoyancy Control System (Fig. 4, pos. 6).
- Receiver of Satellite Navigation (Fig. 4, pos. 7).
- Antenna of Radio Communication System (Fig. 4, pos. 8).
- Stability Moment Control System (Fig. 4, pos. 9).
- Main Thruster of Propulsion - Steering System (Fig. 4,

pos. 10).
– Anchoring Parking System (Fig. 4, pos. 11).

Structural model of HAUV in VSR operation mode is presented in Fig. 5. Structural model of HANPA in VSR operation mode consists of the following elements:

– Vector-Scalar Receiver of Hydroacoustic System (Fig. 5, pos. 1).
– Stability Moment Control System (Fig. 5, pos. 2).
– Anchoring Parking System (Fig. 5, pos. 3).

This structural design enables monitoring of the underwater environment based on the operational HAUV model presented and the technical solutions of its systems when functioning in both VSR transport and VSR operation modes.

The parameters of the HAUV model are defined by its intended application conditions. Model calculations indicate the feasibility of developing a vehicle with the parameters presented in Table 1, assuming a maximum diving depth of 500 meters and autonomous Glider mode operation for up to two months.

TABLE 1. Parameters of HANPA Model

Parameter	Value
Maximum Air Weight (kg)	100
Dimensions: Length, Width, Height, (m)	not more than: 2.3, 1.7, 0.4
Capacity of the Energy Supply System (kWh)	2
Maximum Speed in VSR Transport Mode (m/s)	not less than: 2
Maximum Range in VSR Transport Mode (km)	not less than: 10
Movement Speed in VSR Operation Mode (m/s)	0.01–0.03
Maximum Speed in Glider Mode (m/s)	0.35

V. HOLOGRAPHIC SIGNAL PROCESSING MODEL

Within the framework of the designed HAUV Model, signal processing in the HAS is based on HSP methods for detecting and localizing underwater noise sources. These methods rely on the stable structural features of the interference pattern, or interferogram $I(f,t)$, generated by a noise source in the frequency–time domain [3]–[5], [14]–[16]. The configuration of the localized fringes in the interferogram $I(f,t)$ depends on the frequency range, observation time, shallow-water environment parameters, and the speed and trajectory of the source. However, along these fringes, the phase shift remains nearly constant. This allows the source interferogram $I(f,t)$ to be treated as a universal deterministic mathematical model of the noise signal and the propagation environment. A hologram $F(\tau,\nu)$ of an underwater signal source is obtained by applying a two-dimensional Fourier transform (2D-FT) to the source spectral density accumulated in the interferogram domain over the observation period. The signal emitted by the underwater source accumulates quasi-coherently along the localized fringes of the interferogram $I(f,t)$, whereas background noise accumulates incoherently. At the output of the 2D-FT, that is, in the source hologram $F(\tau,\nu)$, the source signal spectral density is concentrated in a narrow region, whereas the noise is spread across the entire hologram domain.

Within this HSP framework, the relationship has been established between the characteristics of the source signal spectral density in the hologram $F(\tau,\nu)$ and source parameters (bearing, range, radial velocity and depth). The output signal-to-noise ratio (SNR) has been determined; it defines the limiting detection range of an underwater source based on its sound field. The relationship between the input and output SNRs has also been determined. An algorithm for resolving multiple sources has been developed. HSP methods for detecting and localizing sources have been successfully validated in a number of full-scale and computational experiments [3]–[5], [14]–[16]. Localization of the spectral density in the hologram $F(\tau,\nu)$ represents focusing of the field of a moving source. Its focusing factor [14] exceeds the focusing factor achieved by wavefront reversal and by time reversal of the wave to the location of the primary wave source [17]. Unlike these types of focusing, the spectral density of a moving source is automatically localized at the receiving point.

A. HSP ALGORITHM

The distance between the source and the receiver varies over time and can be expressed as follows

$$r(t) = r_0 - vt, \tag{1}$$

where r_0 is the initial position of the source at $t_0 = 0$, t is the current observation time, and v denotes the constant velocity of the moving source.

Source Interferogram. The two-dimensional interferogram $I(f,t)$ describes the distribution of the received acoustic intensity in the joint frequency-time domain (f,t) and is initially expressed as

$$I(f,t) = |S_r(f,t)|^2. \tag{2}$$

where where $S_r(f)$ is received spectrum of source. This representation can be further written in terms of the power spectrum of the transmitted waveform and the channel response:

$$I(f,t) = |S_s(f)|^2\,|H(f,t)|^2. \tag{3}$$

here $S_s(f)$ is transmitted spectrum of source. In turn, the transfer function of the shallow-water waveguide $H(f,t)$ is expressed, in terms of the normal modes of the environment:

$$H(f,t) = \sum_{m=1}^{M} H_m(f,t)\,\exp\{\mathrm{i}h_m\,(r_0 - vt)\}, \tag{4}$$

where $H_m(f,t)$ is individual mode contribution and h_m is represent the modal horizontal wavenumber.

Source Hologram. To extract the holographic features from the measured acoustic field, we apply 2D-FT to the interferogram $I(f,t)$. This transformation maps the signal from the frequency-time domain (f,t) into the hologram domain (τ,ν), producing the function $F(\tau,\nu)$ that can be written as

$$F(\tau,\nu) = \int_0^{\Delta t}\int_{f_1}^{f_2} I(f,t)\,\exp\bigl[\mathrm{i}(2\pi\nu t - 2\pi f\tau)\bigr]\,dt\,df,$$

where τ is the time-lag variable, and ν is the frequency in the hologram plane. The integration over f extends across the signal band, from $f_1 = f_0 - \Delta f/2$ to $f_2 = f_0 + \Delta f/2$, where Δf is the bandwidth of the transmitted waveform, f_0 is the central frequency, and Δt is the total observation time.

The location of the focal spot closest to the origin in the hologram plane yields direct estimates of the kinematic parameters of the source, namely, its radial velocity and initial position. Following [3]–[5], these estimates are obtained from

$$\dot{v} = -k_v\nu_1, \qquad \dot{r}_0 = k_r\tau_1, \tag{5}$$

where the proportionality coefficients are defined as

$$k_v = (M-1)\bigl(h_{1M}(f_0)\bigr)^{-1}, k_r = (M-1)\left(\frac{dh_{1M}(f_0)}{df}\right)^{-1}.$$

Here, the overdot notation indicates that the values are not the exact source parameters, but rather their estimates obtained by means of HSP.

The HSP algorithm operates as follows. The spatial-spectral structure of the hologram $F(\tau,\nu)$ is markedly different from that of the original interferogram $I(f,t)$, the relationship between them is strictly bijective. In other words, the hologram provides a complete and unique representation of the interferogram. Consequently, applying the inverse 2D-FT to $F(\tau,\nu)$ fully reconstructs the original interferogram $I(f,t)$, thus ensuring that no information about the propagation channel or modal interference pattern is lost.

B. HSP NOISE IMMUNITY

The noise immunity of the processing (for a given noise level) is determined by the number of independent frequency-time noise realizations accumulated during the observation period within the specified frequency range. The noise immunity, defined as the ratio of the output signal-to-noise ratio (SNR) to the input SNR of VSR, is estimated as $\theta = J\gamma$, where J is the number of noise realizations accumulated over the observation period Δt, and γ is the concentration coefficient, equal to the ratio of the areas on the hologram occupied by the noise and signal spectral densities. According to empirical and numerical experiments in the frequency range $f = 0.1 - 1$ kHz, the concentration coefficient γ is estimated to be between 6 and 10. Assuming $\Delta t = 30$ seconds and $J = 20$, the resulting noise immunity using VSR is $(\theta = 120 - 200)$.

C. HSP ROBUSTNESS

HSP is robust with respect to spatial-temporal variability in the propagation medium. On the hologram $F(\tau,\nu)$, the spectral densities of the signal and the perturbed field occupy non-overlapping regions, which allows for effective filtering. Spectral densities caused by slow environmental fluctuations appear as narrow bands stretched along the frequency axis. In contrast, the spectral density of the source signal is concentrated in a narrow band aligned either at an angle to the time axis (for a moving source) or along the time axis (for a stationary source) [18], [19].

D. HSP ADAPTIVE APPROACH

These refer to algorithms that can estimate the parameters of a underwater source without requiring prior knowledge of the shallow water. HSP adaptive algorithms use at least two VSRs that are positioned in the horizontal plane and are spatially separated. These algorithms rely on measurements of the detection function's characteristics. The detection function is defined as the angular distribution of the spectral density on the hologram [20].

E. HSP METHOD OF SOURCES RESOLUTION

The HSP method sources resolution of is based on the principle that the interferograms $I(f,t) = \sum_k I_k(f,t)$ and holograms $F(\tau,\nu) = \sum_k F_k(\tau,\nu)$ resulting from multiple sources are a linear superposition of the individual interferogram $I_k(f,t)$ and hologram $F_k(\tau,\nu)$ of those sources. In such cases, the spectral densities of the different sources on the holograms $F_k(\tau,\nu)$ do not fully overlap [21].

VI. CONCLUSION

This paper has presented the concept and model of a specialized HAUV intended for shallow water acoustic monitoring in passive mode. The proposed HAUV combines the functions of a VSR Transport, an Glider, a low-noise VSR Operation, and a Surface Radio Buoy. Such a configuration enables the HAUV to autonomously reach a designated monitoring shallow water, reconfigure itself into a low-noise vertical receiving mode, acquire VSR acoustic data, and transmit compact monitoring data to a control center.

A functional and structural model of the HAUV has been developed. The model includes the main onboard systems required for mission execution, namely the Energy Supply System, Propulsion and Steering System, Buoyancy and Stability Moment Control Systems, Anchoring and Parking System, Hydroacoustic Navigation and Communication System, Radio Communication System, and Hydroacoustic System based on a VSR. The proposed operating scenario allows the HAUV to reduce self-noise during acoustic measurements by disabling the Propulsion and Steering System and maintaining a stabilized vertical position near the seabed. This makes the platform suitable for detecting weak acoustic signatures in shallow water environments, where spatial and temporal variability of the propagation medium significantly affects conventional monitoring methods.

The paper also describes the use of HSP as the core method for onboard analysis of vector-scalar noise fields. By transforming the accumulated frequency-time interferogram $I(f,t)$ into the hologram $F(\tau,\nu)$ domain, the proposed approach concentrates the spectral density of the source signal in a localized region while distributing background noise over the hologram $F(\tau,\nu)$ domain. This provides enhanced noise immunity and enables the estimation of source parameters, including bearing, range, radial velocity, and depth. The considered HSP framework also supports robustness with respect to environmental variability, adaptive localization without complete prior knowledge of the shallow water waveguide, and resolution of multiple sources.

The obtained estimates show that, for typical shallow-water conditions and an observation interval of 30 s, the HSP gain can provide a substantial improvement in the output SNR. This confirms the feasibility of using the proposed HAUV as a mobile receiving system for the detection and localization of low-noise underwater sources. Furthermore, a group of such HAUVs can form a rapidly deployable distributed receiving array over an extended shallow water area, thereby increasing the spatial coverage and reliability of underwater monitoring.

Future work will focus on detailed numerical modeling of HAUV motion and stabilization in realistic hydrological conditions, experimental validation of the hydroacoustic station and vector-scalar receiver configuration, and full-scale testing of onboard HSP algorithms. Further development will also include cooperative operation of multiple HAUVs, optimization of inter-vehicle communication protocols, and integration of adaptive HSP algorithms for real-time monitoring in nonstationary shallow-water environments.

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