Architectural and structural type of self-propelled tethered underwater vehicles with improved maneuverability

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Summary. The modern underwater complexes with umbilical tethers development trends overview and their underwater vehicles as technological equipment carriers peculiarities are given. The main disturbances that influence an underwater vehicle motion within underwater complex with umbilical tethers and the quality of work that it performs are described.

The constructive elements layout basic concept of an underwater vehicle as a part of an underwater complex with umbilical tethers is analyzed. The propulsive complexes typical configurations are overviewed.

The underwater vehicle progressive and rotary spatial motions separation concept is proposed. The concept makes it possible to design underwater vehicles with minimal disturbances influence while moving or positioning at six degrees of freedom and thus provide control quality enhancement of technological equipment installed on an underwater vehicle.

The theoretical basis of a new architectural-and-structural type of a self-propelled tethered underwater vehicle consisting of rotary and progressive motion platforms is developed.

The possible self-propelled tethered underwater vehicle design of the new architectural-and-structural type consisting of three propulsive devices and three rotary drives for processing equipment six freedom degrees motion is proposed

Key words: underwater vehicle, architectural-and-structural type.

INTRODUCTION

The trends in the development of underwater complexes with umbilical tethers and, in particular, of tethered underwater remotely operated vehicles (ROVs) progress towards designing them as all-purpose technical devices for implementing a wide range of underwater technologies [3, 4, 13, 23]. Thus, due to the use of the principle of modular design and the centralized digital information exchange system, the ROV turns from a specialized device into an all-purpose carrier of specialized equipment that could be called underwater platform [10]. So its main function is the positioning at a given point or motion along a given trajectory and the objective of its operation is the positioning or transportation of technological equipment.

The technological equipment can be generally divided into devices of passive (photo, video, hydroacoustic survey) and active interaction with the environment and underwater objects (manipulators, cutters, illuminating equipment, active sonar devices, etc.). Different categories of the technological equipment are characterized by different requirements for their movement in the water space. Thereat, both progressive and rotary motions of the “platform – equipment” system should be considered. The integration of the properties of the platform and technological equipment forms the ROV for the given purpose:

- the high-velocity platform and the hydroacoustic complex form a scout or searching ROV;
- the maneuverable platform with a videocomplex and a set of specialized sensors form an observation or inspection ROV;
- the maneuverable platform with a videocomplex and a system of manipulation devices form a work class ROV;
- the platform with satisfactory velocity and maneuverability characteristics combined with a set of attached various purposes equipment form a multi-purpose ROV.

Usually the technological equipment is located in the bow or keel part of the ROV and the umbilical tether is fastened to the top or to the stern of the ROV. At the cruise motion the tether remains above or behind and does not interrupt the equipment while operating.

PROBLEM STATEMENT

The main disturbances that affect the maneuverability of the ROV in the water space are:

- the force and moment vectors of the tether, which is an integral element of the ROV working within an underwater complex with umbilical tethers [5, 16, 22];
- the hydrodynamic force and moment vectors originating from the ROV motion relative to the water (e.g. currents) [15, 21].

The force disturbances caused by the technological equipment operation also affect the ROV. They can be considered as values of the second order of smallness in comparison to the basic ones and can be ignored.

Placing the mounting point of the tether runnig end at the ROV mass center is ideal. In this case, the tether creates almost no moments and the propulsion system (PS) has to compensate only the disturbing forces of the tether. However, to keep the tether moment equal to zero when the ROV rotational coordinates change (e.g. course), it is necessary to ensure structurally the free motion of the tether within a certain sector, or else the tether will touch other ROV elements, which will cause tether force application points appearance that are distant from the ROV mass center and, consequently, the emergence of disturbing moments.

The tether running end, i.e. its input node (IN), is typically mounted on the transverse axis in the ROV diametrical plane ensuring its free motion in the range of 20...90°. Thereat, it is not always possible to place the mounting axis in the center of mass; designers are forced to shift it towards the stern [7]. Such mounting creates a small ROV pitching moment, which usually does affect much the maneuverability, but the moment occurring when changing the ROV course or moving it away from the diametrical plane of the carrier vessel still has a significant impact. Because of this the ROV pilot is forced to direct it mainly with its nose against the incoming water flow, which leaves no possibility to survey or approach underwater objects from desired directions, so the ROV angular position is chosen due to operational conditions including the direction of the current [6].

Apart from initialization of disturbances by the tether, the change of the ROV course also leads to occurrence of disturbing forces and moments as a result of impact of the so-called "oblique" water flow. At such flow-around the ROV pilot finds it difficult to adapt into conditions of the dynamically changing flow, resulting in worse control quality. These reasons necessitate the synthesis of complex automatic control systems [14, 20], which provide a satisfactory control quality only in certain motion modes of the ROV.

LATEST RESEARCH AND PUBLICATIONS ANALYSIS

The basic principles of assembling the elements of the ROV design are as follows. The structure of the ROV is divided into three areas: bow, middle and stern. In the bow area the technological equipment is located. In the rear area the power control module, main propulsion and steering complex are located and the tether IN is mounted. The steering assisting devices are located at different places along the casing, depending on the maneuverability requirements. The rest of the equipment is located mainly in the middle area of the ROV. The elements with a large mass are typically located in its bottom part [24].

The configuration of the ROV PS determines the possible controlled motions of the technological equipment. Modern ROVs are characterized by a wide variety of PS configurations and technological capabilities [2, 8, 17]. The three-propulsion PS structure is typical for many ROVs: two cruise propulsion devices are located in the horizontal plane of the ROV at its left and right sides and provide longitudinal progressive motion and yawing, one vertical propulsion device provides vertical progressive motion. Such ROV is able to perform controlled motion by two progressive and one rotary degree of freedom. The disadvantage of this structure is the inability to perform lateral motion and to change the pitch and roll of the ROV. Considering this, the ROVs are additionally equipped with lateral steering assisting devices and drives for technological equipment rotation (e.g. video cameras) in the vertical plane.

The small-sized ROV for inspecting underwater objects and collecting underwater samples that is able to move and position itself in the underwater space in six degrees of freedom is known [25]. The vehicle comprises eight propulsion devices: four vertical and four horizontal ones. The main disadvantage of such design is the difficulty of turning and keeping a specified angular position of the ROV at motion in a water flow or positioning in a current under the influence of disturbing forces and moments.

Similar limitations are typical for the ROV with improved maneuverability, that provides motion and positioning of the technological equipment in underwater space in six degrees of freedom, and its PS consists of twelve propulsion devices [12]. In addition, the PS complexity leads to engaging more pilots and/or to synthesis of complex multidimensional and multiloop regulators for controlling its spatial motion.

ARTICLE PURPOSE

The article purpose is development of a new architectural and structural type of self-propelled tethered underwater vehicle as a carrier of technological equipment, which ensures minimal disturbing influences on it during spatial motion and positioning in six degrees of freedom, and thus improves the control quality of its technological equipment.

PRINCIPLE OF SEPARATING PROGRESSIVE AND ROTARY MOTIONS

Any ROV as a physical body moving in three-dimensional space has six degrees of freedom: three progressive and three rotary. For carrying out the full range of tasks, the ROV controlled motion should be performed in all six degrees of freedom.

The theoretical basis of the suggested architectural and structural ROV type is formed by the separation of its structure into two parts, each of which performs a specific task and moves in its own degrees of freedom:

- progressive motion platform (PMP);
- rotary motion platform (RMP).

The PMP main elements are the bearing frame, the tether IN mounting element and the propulsion system, which makes it possible for the ROV to move in progressive degrees of freedom in any direction. Such PS should generate the forces, the resultant of which will always go through the ROV center of mass regardless of the value of each force, so the resultant of the control moments will always be equal to zero (ideally) or minimal.

The ROV elements, orientation in space of which is not essential, should also be included to the PMP structure, i.e. rigidly mounted on the frame. They are the buoyancy blocks, balance weights, navigation system, strong casings with an onboard computer, information exchange system, power electronics and more.

All the equipment sensitive not only to progressive, but also to rotary coordinates (first of all, the technological equipment) should be located on the RMP, which is attached to the PMP and has its own rotary drives that provide change of the rotary coordinates of the technological equipment. The RMP implementation options depend on the particular equipment, which is planned to be installed on the ROV. For example, rotary motion in the RMP horizontal plane can be common for all pieces of equipment, and the rest of rotary degrees of freedom can be implemented by the RMP with a separate drives for each piece of equipment. It is possible to place several RMPs on the PMP.

The main disturbances that influence the ROV are the vectors of the tether tension force and moment. To minimize the influence of disturbing moments, the tether IN mounting point should be placed in the ROV mass center. If the tether is not flexible enough, the IN should be mounted on pin joints that will provide the specified angles of its free motion. In general, the tether free motion should be provided within the horizontal cone, the apex of which coincides with the ROV center of mass and IN mounting point, and the cone angle should be sufficient to ensure the specified range of the tether free motion.

The progressive motion of the ROV built on the principle of separating progressive and rotary motion (SPRM) can be freely performed in any direction, provided the length of the released part of the tether and the PS power capacity are sufficient. At that, the control conditions close to ideal will be provided: the bow of such ROV will be oriented against the oncoming water flow, and the tether will be located behind the ROV stern, which is its natural location at even a minimum water flowing. This is the way to solve the problem of the ROV controlled progressive motion at a given spatial trajectory under the disturbing influence of the tether.

The effective angular coordinates range variation of the RMP technological equipment is restricted by the presence of the PMP elements and the tether in the ROV stern. Yet, particular rotary trajectories realized by the corresponding RMP drives are sufficient to solve most of underwater tasks, as they are usually carried out either in the lower or in the upper hemisphere of the water space relative to the ROV.

To carry out such kind of work, it is proposed to implement the SPRM principle according to the draft drawing shown in Fig. 1.

The buoyancy block is located on the upper level. The PS is located and the tether IN is

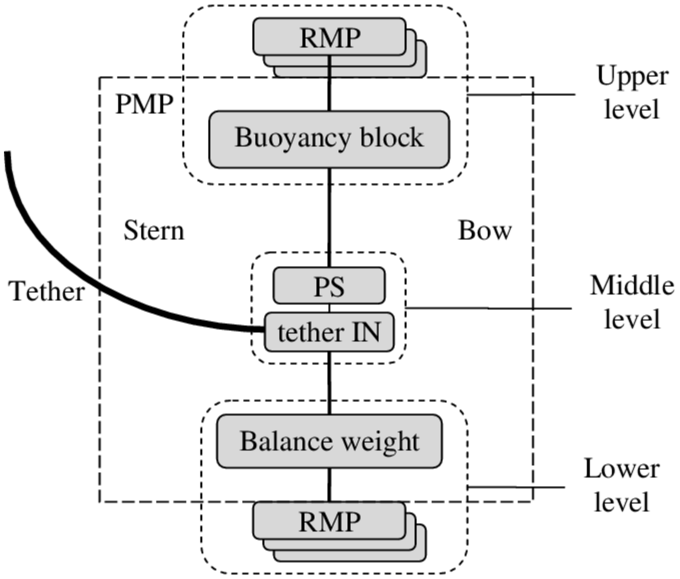


Fig. 1. ROV architecture

mounted on the middle level. The PS propulsion devices are oriented in such a way that the direction of PS force vector always passes through the ROV mass center. The balance weights and other heavy equipment are located on the lower level. Depending on the nature of the performed tasks, the RMP is located on the upper, lower or both of the levels.

At the ROV progressive motion, the disturbing influences of the water flow will create the force and the moment of resistance. The force of the resistance will be compensated with the PS propellers. The moment of resistance will cause the change of the ROV angular coordinates (pitch and roll). There are two ways to reduce the disturbed ROV angular coordinates zero: a passive method and an active method. The passive method implies locating the buoyancy block at the top of the ROV and the balance weights at its bottom. The active method implies the usage of the pitch-and-roll control system and is implemented if the passive method is not sufficient. If there remains any non-zero pitch and roll, the RMP can work them out so that they would not affect the angular orientation of the technological equipment. The RPM will also compensate the change of technological equipment horizontal angular coordinate.

NEW ARCHITECTURAL AND STRUCTURAL TYPE UNDERWATER VEHICLE VARIANT OF REALIZATION

When developing the ROV configuration according to the SPRM principle, the major importance has the location of the PS propellers, mounting points of the tether IN, and the RMP proper.

To provide the self-propelled ROV progressive motion in three degrees of freedom, at least three reverse propelling devices are required. At that, their placement should meet two requirements: first, the vectors of their force should pass through the ROV mass center in order not to create moments; second, they should be linearly independent, so that the control force vector could be directed arbitrarily.

If the scalar value of the thrust of each propelling device is designated as F_1, F_2 та F_3, then the ROV propulsive force $\vec{F}$ is determined by the following expression:

$$\vec{F} = \vec{a}_1 F_1 + \vec{a}_2 F_2 + \vec{a}_3 F_3,$$

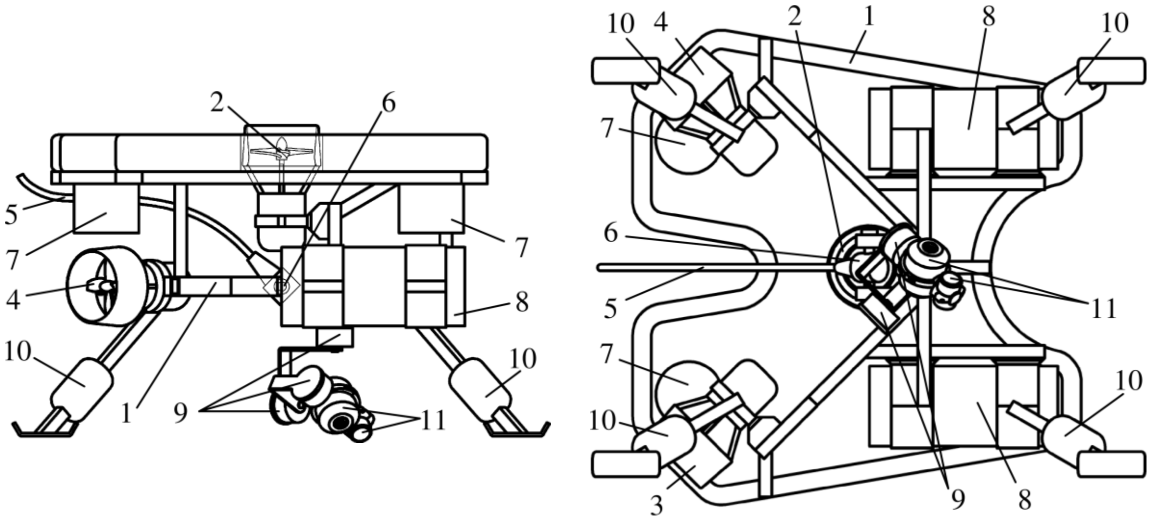
where $\vec{a}_{1,2,3}$ are unit vectors which form the basis of the PS affine coordinate system.

If the propelling devices are located perpendicular to each other, the vectors $\vec{a}_{1,2,3}$ will form the orthonormal basis of the PS orthogonal coordinate system.

The variant of the ROV design which has been developed with the use of the SPRM principle and is equipped with three propelling devices arranged perpendicular to each other is shown in Fig. 2 [9]. The Figure indications are following: *1* – the frame, *2* – the vertical propelling device, *3* – the horizontal left propelling device, *4* – the horizontal right propelling device, *5* – the tether, *6* – the tether input node, *7* – the pitch-and-roll control system, *8* – the strong shells of the electronic blocks, *9* – the RMP drives, *10* – the balance weight, *11* – the technological equipment.

The vertical propeller is directed upwards; the left and right horizontal (cruise) propellers are directed at the angle of 45° to the ROV diametral plane, with the horizontal left propeller being directed forward and to the right and the horizontal right propeller directed forward and to the left. The propelling devices placement allows mounting the tether IN in the ROV mass center.

The RMP is placed at the bottom of the ROV; it is a rotating device with three degrees of freedom, and the technological equipment is mounted on it (the camera and the LED-light in this example). The three RMP drives are fixed according to the gimbals suspension principle; their rotary axes have a common intersection point. This RMP configuration provides arbitrary angular orientation of the technological equipment installed on it using the minimum number of rotary drives.



а *б*

Fig. 2. ROV design drawing: *a* – right-side view, *b* – bottom view

The rotary motion restrictions will be formed by the wired connections which could be eliminated with the use of the electrical current transition modules.

Disturbing moments can occur on the ROV elements due to the influence of the oblique liquid flow. Such disturbances are compensated by the passive effect of the buoyancy block and balance weights, as well as by the active effect of the pitch-and-roll control system.

The free tether motion in the diametral plane is provided in the range of approximately ±45°. The length of the released part of the tether when operating is chosen as such that its free motion is sufficient for the tether not to create the pitching moment.

In the horizontal plane, the free tether motion is provided within several degrees so the tether can create the moment turning the ROV around its vertical axis. Yet, the rotating devices of RMP will compensate the ROV yaw and will provide a constant value of the angular orientation of the technological equipment. Thus, there is no need in the ROV controlled rotary motion.

The ROV control system generates two groups of control signals:

- the PMP control vector $\vec{u}_p = \{u_1, u_2, u_3\}$, where $u_{1,2,3}$ are the control actions of the propulsion devices;

- the RMP control vector $\vec{u}_r = \left\{u_\alpha, u_\beta, u_\gamma\right\}$, where $u_{\alpha,\beta,\gamma}$ are the control actions of the rotary drives.

To study the ROV operational motion, the ROV-fixed coordinate system (FCS) and basic coordinate system (BCS) are usually used. The BCS is suggested to be stationary, and the ROV motion is considered relative to it [19]. The FCS center coincides with the ROV mass center, its abscissa and ordinate axes are orthogonal and lie in the ROV diametral plane. The former is directed to the bow, and the latter is oriented vertically upwards. The applicate axis forms the right-hand coordinate system with them; it lies in the ROV horizontal plane with the abscissa axis and in the ROV transverse plane with the ordinate axis.

Regardless of whether the basis $\vec{a}_1$, $\vec{a}_2$, $\vec{a}_3$ is orthonormal, the control force $\vec{F}$ can be presented in projections both on the BCS and FCS axes:

$$\vec{F} = \vec{i}_b F_{xb} + \vec{j}_b F_{yb} + \vec{k}_b F_{zb} = \\ = \vec{i}_a F_{xa} + \vec{j}_a F_{ya} + \vec{k}_a F_{za},$$

where $\vec{i}_b$, $\vec{j}_b$, $\vec{k}_b$ are the BCS unit basis vectors, $\vec{i}_a$, $\vec{j}_a$, $\vec{k}_a$ are the FCS unit basis vectors.

If the coordinates of the FCS basis vectors are set in the BCS:

$$\vec{i}_a = i_x \vec{i}_b + i_y \vec{j}_b + i_z \vec{k}_b; \\ \vec{j}_a = j_x \vec{i}_b + j_y \vec{j}_b + j_z \vec{k}_b; \\ \vec{k}_a = k_x \vec{i}_b + k_y \vec{j}_b + k_z \vec{k}_b,$$

then the correlation between the $\vec{F}$ vector projections on the BCS and FCS axes is determined by the following matrix equations [11]:

$$\begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix} = A \begin{bmatrix} F_{xa} \\ F_{ya} \\ F_{za} \end{bmatrix}; \quad \begin{bmatrix} F_{xa} \\ F_{ya} \\ F_{za} \end{bmatrix} = A^{-1} \begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix};$$

$$A = \begin{bmatrix} i_x & j_x & k_x \\ i_y & j_y & k_y \\ i_z & j_z & k_z \end{bmatrix}.$$

The correlation between the $\vec{F}$ vector projections on the FCS axes and the PS coordinate system is determined likewise.

If the coordinates of the $\vec{a}_1$, $\vec{a}_2$, $\vec{a}_3$ vectors in the FCS basis are known (they determine the direction of the ROV propelling devices operation and are known from its design characteristics):

$$\vec{a}_1 = a_{1x} \vec{i}_a + a_{1y} \vec{j}_a + a_{1z} \vec{k}_a; \\ \vec{a}_2 = a_{2x} \vec{i}_a + a_{2y} \vec{j}_a + a_{2z} \vec{k}_a; \\ \vec{a}_3 = a_{3x} \vec{i}_a + a_{3y} \vec{j}_a + a_{3z} \vec{k}_a,$$

then the correlation between the $\vec{F}$ vector projections on the FCS axes and the PS coordinate system is determined according to the following matrix equations:

$$\begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix} = AA' \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}; \quad \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \left(AA'\right)^{-1} \begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix};$$

$$A' = \begin{bmatrix} a_{1x} & a_{2x} & a_{3x} \\ a_{1y} & a_{2y} & a_{3y} \\ a_{1z} & a_{2z} & a_{3z} \end{bmatrix}.$$

For the control problems, the determination of the control signals u_1, u_2, u_3 in particular, the determination of the F_1, F_2, F_3 values by given F_{xb}, F_{yb}, F_{zb} is of special importance, since the latter determine the direction of the ROV progressive motion.

To control the angular coordinates of the technological equipment their various geometric representations and transformations could be used [1, 18]. If stepper electric motors are used as the RMP drives, and the angular orientation of the technological equipment is set by Euler angles θ, φ and ψ, then the RMP control actions can be determined as a vector function of a given angular orientation of the technological equipment $\vec{u}_r = \vec{f}\left(\theta, \varphi, \psi\right)$, which may vary for specific RMP configurations.

As a result, there could be the ROV designed in accordance with the SPRM principle, which consists of the PMP and the RMP. Moving and positioning of the technological equipment in three progressive degrees of freedom is performed by means of the PMP with the use of the PS comprising three propelling devices. Moving and positioning of the technological equipment in the rotary degrees of freedom is carried out by means of the RMP with the three-stage rotating device. At that, the controlled ROV motion and positioning in three rotary degrees of freedom is not realized, which significantly eliminates the unpredictable changes of hydrodynamic effects on its hull, reduces the number of the propelling devices and simplifies the process of their control. Mounting the tether IN at the center of mass of the ROV also considerably reduces the disturbing moments, which makes the process of the ROV control easier.

CONCLUSIONS

1. On the basis of the proposed principle of separating rotary and progressive three-dimensional motion, the theoretical basis of design of the new self-propelled tethered underwater vehicles architectural and structural type comprising two platforms was developed, according to which:

- the resultant propulsive force of the progressive motion platform passes through the center of mass of the vehicle; its absolute value and direction are controlled values, which provides the motion in progressive degrees of freedom along an arbitrary trajectory under the disturbing influences of the tether and the water flow;
- the controlled rotary motion of the technological equipment is performed by the rotary motion platform relative to the progressive motion platform; the latter provides the technological equipment insensitivity to major disturbing influences.

2. The possible design variant of the new architectural and structural type self-propelled tethered underwater vehicle is proposed, which comprises the propulsion system consisting of three propelling devices for performing the progressive motion of the underwater vehicle in any direction, and a rotating device with three drives for performing the rotary motion of the technological equipment along any trajectory; at that, the required number of the installed drives is minimal, which simplifies the process of the underwater vehicle control.

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Архітектурно-конструктивний тип самохідних прив’язних підводних апаратів з удосконаленою керованістю

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Анотація. Розглянуто тенденції розвитку сучасних підводних комплексів з гнучкими зв’язками та особливості їх підводних апаратів як носіїв технологічного обладнання. Наведено відомості щодо основних збурень, які впливають на рух підводного апарата у складі підводного комплексу з гнучкими зв’язками, та на якість виконуваної ним роботи.

Проаналізовано основні принципи компоновки елементів конструкції підводного апарата як складової підводного комплексу з гнучкими зв’язками. Розглянуто типові конфігурації рушійних комплексів підводних апаратів.

Запропоновано принцип відокремлення обертового та поступального тривимірних рухів підводного апарата, застосування якого при проектуванні підводних апаратів дає змогу забезпечити мінімальні збурюючі впливи при їх русі та позиціонуванні за шістьма ступенями свободи, і тим самим покращити якість керування технологічним обладнанням, встановленим на підводних апаратах.

Розроблено теоретичні основи побудови нового архітектурно-конструктивного типу самохідних прив’язних підводних апаратів у складі платформ обертового та поступального руху.

Запропоновано один з можливих варіантів конструкції самохідного прив’язного підводного апарата нового архітектурно-конструктивного типу у складі рушійного комплексу з трьома рушійними пристроями та обертового пристрою з трьома приводами для здійснення поступального та обертового рухів технологічного обладнання за шістьма ступенями свободи.

Ключові слова: підводний апарат, архітектурно-конструктивний тип.