***Описано типовий склад ненаселеної буксируваної підводної систем (НБПС) та вказано на переваги застосування такого виду морської техніки для виконання робіт на малих глибинах.***

***Визначено перелік основних режимів функціонування НБПС, які є ключовими для проектних розрахунків системи. Сформовано основні вимоги до проектування та побудови конкурентоздатних мілководних НБПС. До головних вимог віднесено необхідність застосування високопродуктивних підводних технологій, використання сучасних програм комп'ютерного дослідження та проектування. Також вказано на необхідність максимального використання матеріалів, деталей та вузлів, які є доступними на ринку як комплектуючі для складових НБПС.***

***Показано доцільність та можливість застосування методології системного підходу на ранніх стадіях проектування НБПС. У матричній формі сформовано рівняння існування для складових НБПС, які дають змогу вже на стадіях технічної пропозиції та ескізного проектування перевірити технічні рішення на відповідність вимогам технічного завдання. У якості критеріїв відповідності використовуються конструктивні, енергетичні, інформаційні та експлуатаційні характеристики складових НБПС.***

***Послідовність виконання проектних робіт оформлено у вигляді узагальненого алгоритму проектування, який реалізує системний підхід з використанням сучасних комп'ютерних технологій та рівнянь існування НБПС. Розроблений алгоритм дає змогу виконати перевірку вимог технічного завдання вже на ранніх стадіях проектування НБПС та утворює науково обґрунтовану методологічну основу для створення конкурентоспроможних засобів підводної техніки***

***Ключові слова: ненаселена буксирувана підводна система, задачі проектування, системний підхід, рівняння існування***

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# APPLICATION OF SYSTEMS APPROACH AT EARLY STAGES OF DESIGNINNG UNMANNED TOWED UNDERWATER SYSTEMS FOR SHALLOW WATER AREAS

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## 1. Introduction

Unmanned towed underwater systems (UTUS) belong to highly productive underwater robotics and are widely used for searching, nature conservation, mapping and research activities [1]. Such systems are operated from a towing vessel (TV) which houses an energy supply and control system (ESCS) and a cable winch (CW). With the help of CW, length of the slackened off part of tow cable (TC) is changed depending on depth and speed of the TV movement and TC is stored in the inter-operative period. The unmanned towed underwater apparatus (TUA) is launched before towing and raised on board the TV by means of a launch-and-raise device (LRD) after completion of work.

Typical UTUS equipment configuration is shown in Fig. 1.

High performance of the UTUS compared with an unmanned self-propelled fastened apparatus is one of the advantages of its use. Another advantage is the ability to get information about underwater conditions in real time compared with the unmanned autonomous apparatus.

The mentioned advantages of the UTUS are of particular relevance when performing works in shallow marine waters ($H \leq 100$ m) of a large area. Such water areas include, in particular, water areas of sea and river ports, recommended fairways for shipping, open ship anchorages and other water areas of the state maritime complex. Usually, work in such waters is carried out with involvement of small TV, so strict requirements are imposed on the UTUS design for minimizing mass and dimension characteristics of the equipment and power consumption of the system. The latter requirement is particularly relevant when using unmanned TUA having onboard energy sources of a limited capacity.

Today, the unmanned towed underwater systems are designed using the classic procedures elaborated for designing ships: a method of successive approximations in determining all vessel characteristics used to make engineering solutions and a method of optimizing these characteristics. All of this makes it possible to find the best solutions as concerns technical and economic criteria [2, 3]. These methods are used mainly at the stages of draft and engineering design.

Further improvement of the UTUS design methods should raise accuracy of determining characteristics of their components at an early work stage: requirements specification or draft design. Already at these stages, designers must confirm fundamental possibility of creating an UTUS with $S_{UTUS\ TT}$ characteristics specified in the Requirements Specification (RS). As a result of performing these stages, uncertainty of engineering solutions, labor intensiveness and time of execution of the next stages of the UTUS design (engineering design and preparation of design documents) will be significantly reduced. The advantages obtained will ensure competitiveness of the created means of underwater robotics.

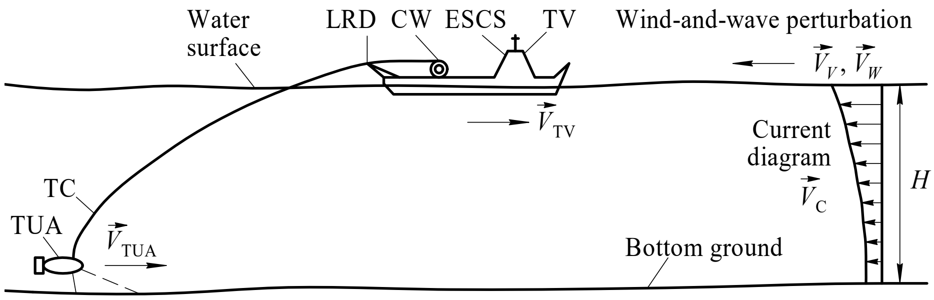


Fig. 1. Typical components of an unmanned towed underwater system

Such improvement can be accomplished through involvement of general principles of the systems approach. Its essence consists in consideration of the design object taking into account interaction of its functional components [4, 5].

## 2. Literature review and problem statement

The problems of the UTUS creation and operation have always been in a center of scientists' attention [6–8]. In the studies of this analysis, the UTUS design is considered as a complex of rigid and flexible bodies moving in the water flow [6] Steady motion of a two-stage towed system and a TC is modeled [7] and dynamics of the TV-TUA system is studied when masses of both components are commensurable [8]. However, these studies were not based on the systems approach and did not use general design techniques for creation of the UTUS in general.

Current state of studies in the field of designing marine towed systems is characterized by elucidation of peculiarities of behavior of the TC and the TUA in a water flow and regularities of controlled movement of the TUA. For example, study [9] proposes mathematical models of the towed systems that take into account dynamics of the TC and the TUA. The problem of controlling spatial position of the TUA during its towing under conditions of external perturbation is considered in [10]. Comprehensive studies of dynamics of the "TC – TUA with moving wings" system were performed in [11] and some performance figures of the system were established. Results of such studies are important for the UTUS designers when assessing concrete modes of operation but they do not contain systematic generalizations concerning organization of the UTUS design process.

A considerable number of studies are devoted to the methods of mathematical modeling for studying controlled dynamics of the TC and the TUA. For example, features of controlling towed underwater apparatuses in shallow waters were established in [12] based on analysis of their most common hydrodynamic shapes for synthesis of automatic control systems. However, there is no systems approach to the design of UTUS in general.

A mathematical model of a towed system in the configuration of semi-submerged TV, TC and TUA was constructed in [13]. The model makes it possible to investigate large displacements and deformations of the TC which is important for extreme UTUS operation modes. However, this model does not make it possible to assess in full the engineering solutions concerning the UTUS components since it does not provide comparison with requirements of the Requirements Specification document.

Influence of the TC whose length is constantly changing on the TUA motion was studied in [14]. A significant influence of towing speed and the TC length on spatial position of the TUA and the forces acting on its structure was established. However, the results obtained are characteristic of just the UTUS deployment mode and are a special case of the designing practice.

Basics of the systems approach were used in [15] in hydrodynamic TC analysis. The authors have studied dependence of towing depth on towing speed depending on the cable diameter and buoyancy based on a number of commercially available tow cables. The generalizations obtained by the authors can be used in the design practice but they do not contain the system generalizations necessary for designing the UTUS in general.

The problems occurring in designing the UTUS for shallow water areas are considered in [16]. The authors of this study focused their attention on the problems of the UTUS control automation. However, issues of the systems approach to the UTUS design processes have generally remained unconsidered. This significantly limits search for the most effective solutions when designing competitive UTUS.

The necessity of introducing the systems approach in the design of underwater robotics was most completely formulated in [17]. In their example of designing unmanned self-propelled attached underwater complexes, the authors considered systematic interaction between the complex components as a decomposition of its basic operations. In this case, it is proposed to design the underwater complex as a sequential execution of the phases of problem statement, creation and engineering. However, practical implementation of the systems approach into the creative phase which, in fact, is the decisive phase remains unresolved since a draft design is performed there.

Thus, the current level of the UTUS design is characterized by well-developed mathematical modeling and design methods for creation of individual components of towed systems. In particular, a broad spectrum of design techniques have been elaborated for towed underwater systems as rigid bodies and their tow cables as flexible bodies in the water flow.

However, the issues of implementing the systems approach at early stages of designing the UTUS for shallow waters have remained unresolved. In particular, the urgent problems include adaptation of principles of the systems approach to the UTUS design and creation of a generalized design methodology based on the relationship between structural, power and information characteristics of the UTUS components. The systems approach is also required in solving a series of problems as components of a generalized UTUS design scheme:

– formulation of current requirements to the design and building of competitive UTUS;

– formalization of the procedure of determining main UTUS operation modes.

Successful solution of these problems will improve reliability of the design solutions at early stages, reduce the time spent at subsequent design stages and raise competitiveness of new underwater equipment.

## 3. The aim and objectives of the study

The study objective is to formulate a generalized procedure of applying the systems approach at early stages of designing unmanned towed underwater systems intended for investigation of shallow waters.

To achieve this goal, the following tasks were set:

– to establish basic UTUS operating modes as key modes for design studies of its components and are necessary for determining technical characteristics of the UTUS components for the most severe operation situations;

– to formulate basic requirements to designing and building competitive UTUS intended for work in shallow waters;

– to adapt principles of the systems approach (taking into account connections between structural, power and information characteristics of the UTUS components) to be applied at early stages of the UTUS design;

– to give an example of using the systems approach at an early stage of designing a UTUS component;

– to develop a generalized UTUS design scheme based on the systems approach taking into account the elaborated basic requirements to the UTUS design and construction.

## 4. Basic modes of operation of an unmanned towed underwater system

Application of the systems approach to creation of the UTUS for shallow waters will be discussed on the example of the Glider Project UTUS developed at Admiral Makarov National University of Shipbuilding, Ukraine.

The design and main elements of the Glider Project TUA and its TC and ESCS are given in Fig. 2.

The UTUS includes the TUA designed according to the hydrodynamic scheme of the flying wing (Fig. 2, *a*). Such TUA has no horizontal tail unit (horizontal steers).

Hydrodynamic spatial position controls (elevons) of such TUA are installed on the rear edges of its bearing surfaces (wings). Their differential deviation changes angular position of the TUA relative to its longitudinal axis (careen of the TUA) and cophasal deviation changes angular position of the TUA relative to its transverse axis (deepening or flotation-up of the TUA).

The UTUS also includes a tow cable and a power supply and control unit (Fig. 2, *b, c*).

Based on the foreign experience [1, 14] and the authors' practical experience in the UTUS design and operation, the following basic UTUS operation modes can be distinguished:

– $R_{Beg}$ mode. Checking operability of all UTUS components: TUA, TC, CW, LRD and ESCS. The most difficult is checking operability of the structural, power and information-and-control equipment of the TUA;

– $R_{Rel}$ mode. Launching the TUA with the help of the LRD at stoppage of the TV in its straight motion at a minimum speed $v_{min}$. The CW releases the tow cable for a preset length for a free TUA transmission overboard the TV;

– $R_I$ mode. Submersion of the TUA to a given depth is performed after the towing vessel has reached working speed $v_j$. The CW releases the tow cable to provide its predetermined length changing during the TUA submersion process;

– $R_{JL}$ mode. This is the mode of rectilinear TV movement on a given course φ at speed $v_J$. The TUA can move in modes of depth stabilization ($R_{JLH}$), height above bottom ($R_{JLA}$) along a flat ($R_{JLP}$) or spatial ($R_{JLS}$) path of motion;

– $R_A$ mode. Flotation of the TUA to the surface is realized by co-phasal deflection of the elevons at a corresponding flotation angle. The CW takes in the cable to prevent its tangling or damage;

– $R_T$ mode. Towing the TUA closer to the TV with the help of the CW during stoppage or slowdown of the TV;

– $R_{Rec}$ mode. The TUA is lifted aboard the TV with the help of the LRD with a simultaneous take in of free TC by the winch;

– $R_{End}$ mode. Checking technical condition of the TUA after completing the submarine mission, for the most part, similar to the $C_1$ mode.

Thus, a task is posed for designers: elaborate design documents for TUA, TC, CW, LRD and ESCS as individual components of the UTUS working in concert across the whole set of modes:

$$R_{UTUS}=\left\{\begin{matrix} R_{Beg};R_{Rel};R_I;R_{JL}\left(R_{JLH},R_{JLA},R_{JLP},R_{JLS}\right); \\ R_A;R_T;R_{Rec};R_{End} \end{matrix}\right\}. \qquad (1)$$

At the next design stage, the most hard $R_{UTUS\,Ext}$ operating modes from the set (1) shall be determined for each component of the UTUS, i. e. TUA, TC, CW, LRD and ESCS. Selection of these modes eliminates the need of design studies of the UTUS components in the entire set of modes (1) and thus reduces the overall design time.

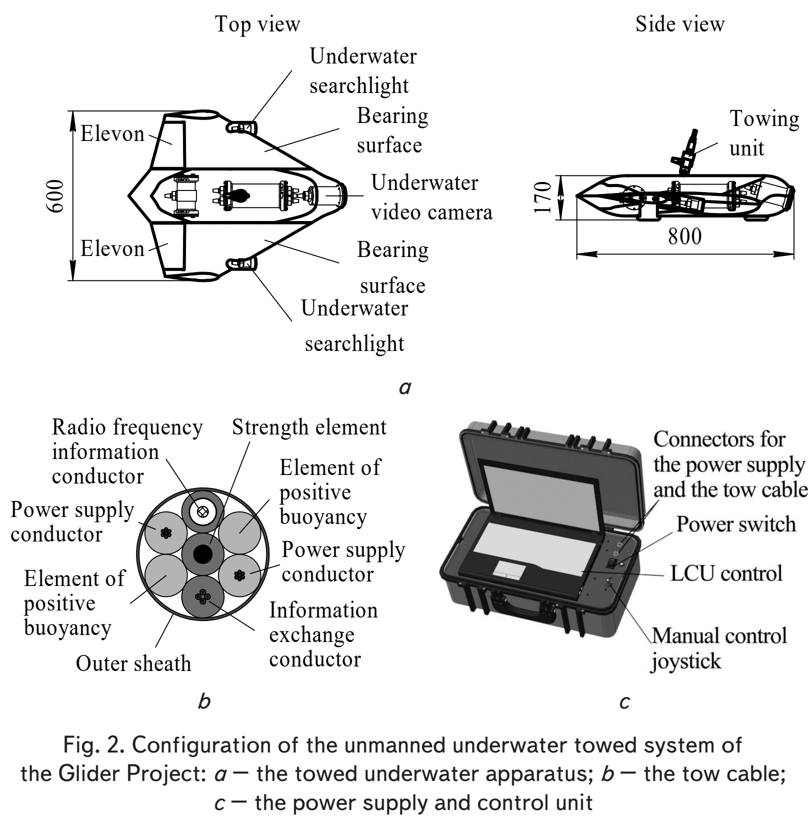


Fig. 2. Configuration of the unmanned underwater towed system of the Glider Project: *a* — the towed underwater apparatus; *b* — the tow cable; *c* — the power supply and control unit

Typically, these are $R_I$, $R_{JL}$ and $R_A$ modes for the TUA and the ESCS; $R_I$, $R_{JL}$ $R_A$ and $R_T$ modes for the TC and the CW and $R_{Rel}$ and $R_{Rec}$ modes for the LRD.

Thus, the set of $R_{UTUS\,Ext}$ modes can be written as follows:

$$R_{UTUS\,Ext}=\{R_{TUV\,Ext}\in R_{UTUS};\ R_{TC\,Ext}\in R_{UTUS};\ R_{CW\,Ext}\in R_{UTUS};\ R_{CD\,Ext}\in R_{UTUS};\ R_{PCS\,Ext}\in R_{UTUS}\}. \quad (2)$$

Let us denote power of the $R_{UTUS\,Ext}$ set as $|R_{UTUS\,Ext}|$ and power of the $R_{UTUS}$ set as $|R_{UTUS}|$. Obviously, the $R_{UTUS\,Ext}$ set contains just those modes from the $R_{UTUS}$ set that are the hardest in the context of operation. Also, there is relation $|R_{UTUS\,Ext}|<<|R_{UTUS}|$ which determines reduction of cost of the project resources (time, manpower involved, etc.) at the early stages of design.

For modes of the set (2), it is necessary to determine draft technical characteristics of the UTUS components (here $S$ means *Specifications* in the publications in English) which ensure operation of individual UTUS components according to the requirements $S_{UTUS\,TT}$ of the RS. Usually, the predefined $S_{UTUS0}$ characteristics are mass-and-size, power and information data on the UTUS components (TUA, TC, CW, LRD and ESCS):

$$S_{UTUS0}=\left\{S_{TUV};S_{TC};S_{CW};S_{CD};S_{PCS}\right\}\Big|_{R_{UTUS\,Ext}}. \quad (3)$$

The resulting set of technical characteristics $S_{UTUS0}$ is the first iteration of the UTUS draft design stage and differs from the characteristics of the $S_{UTUS\,TT}$ set by a greater concretization of engineering solutions. This set forms the basis for further iterations of the draft design of the UTUS components in the hardest operational modes.

## 5. Basic requirements to the design and construction of competitive unmanned towed underwater systems for operation in shallow water areas

The UTUS for shallow waters should be designed in accordance with a number of requirements brought about by the market mechanisms and high competition in the market of marine robotics. The design practice shows that [18–20] can be attributed to the following requirements:

– implementation of high-performance underwater technologies that increase the market value of the UTUS: high level of the UTUS automation, execution of works according to the "all in one dive" SLAM (Simultaneous Location and Mapping) technology, etc. ($S_{MT}$ requirement);

– shortening terms of elaboration of the project documents for designing the UTUS through the use of modern CAD/CAM/CAE technologies ($C_{RT}$ requirement);

– compulsory hydrodynamics check (steady and dynamic motion of the UTUS components) using CFD software packages [19] ($C_{CFD}$ requirement);

– maximum possible use of prefabricated parts and assemblies that are commercially available as the UTUS components ($C_{AP}$ requirement);

– taking into account modern achievements in the fields of materials science, electrical power engineering, electromechanics, automation, electronics, informatics, computer-aided design technologies and their use in the UTUS projects ($S_{MA}$ requirement);

– cutting manufacture costs and providing the possibility of rapid initiation of serial production of the UTUS ($S_{PE}$ requirement) by introduction of the technology of information construction modeling [21].

In addition, requirements are imposed to the TUA and TC as solid and flexible bodies in the water flow to provide them zero or residual positive buoyancy ($C_{ZB}$ requirement). This relates to safe UTUS operation at shallow depths.

Thus, it is possible to formulate the following $C_{UTUS}$ set of current requirements specifications for designing competitive UTUS:

$$C_{UTUS}=\{C_{MT};\ C_{RT};\ C_{CFD};\ C_{AP};\ C_{MA};\ C_{SP};\ C_{ZB}\}. \quad (4)$$

Requirements $C_{MT}$, $C_{RT}$, $C_{CFD}$, $C_{AP}$, $C_{MA}$ and $C_{SP}$ are conventional and equally important for both shallow and deep-sea UTUS. However, the $C_{ZB}$ requirement for shallow UTUS is of an additional relevance because it guarantees safe operation in the event of failure of the power supply and automatic control subsystems of the unmanned towed underwater system.

Taken together, the resulting set of technical characteristics (3) and the set of current requirements (4) form an information basis for development of a generalized scheme of designing the UTUS for shallow water areas.

## 6. Adaptation of the systems approach methodology to early stages of design of an unmanned towed underwater system

The essence of applying the systems approach to the UTUS design consists in applying equations of existence [22] to check feasibility of meeting requirements of the Requirements Specification already at early design stages.

In accordance with this approach, introduce for their consideration the following two sets of matrices for individual component each containing technical characteristics of the UTUS according to the structural ($A$), power ($P$), information ($I$) and operational ($J$) criteria:

– $ET_{UTUS}=\{ET_{TUV};\ ET_{TC};\ ET_{CW};\ ET_{CD};\ ET_{PCS}\}$ is the set of matrices of RS limits for structural, power, information and operational characteristics of the UTUS components;

– $EE_{UTUS}=\{EE_{TUV};\ EE_{TC};\ EE_{CW};\ EE_{CD};\ EE_{PCS}\}$ is the set of matrices of structural, power, information and operational characteristics of the UTUS components obtained at the current design stage.

Each component of the set of the $ET$ matrices is a matrix–column of RS requirements to the structural, power, information and operational characteristics of respective UTUS components:

$$ET_{TUV}=\begin{vmatrix}A_{TUV}\\P_{TUV}\\I_{TUV}\\J_{TUV}\end{vmatrix};\quad ET_{TC}=\begin{vmatrix}A_{TC}\\P_{TC}\\I_{TC}\\J_{TC}\end{vmatrix};\quad ET_{CW}=\begin{vmatrix}A_{CW}\\P_{CW}\\I_{CW}\\J_{CW}\end{vmatrix};$$

$$ET_{CD}=\begin{vmatrix}A_{CD}\\P_{CD}\\I_{CD}\\J_{CD}\end{vmatrix};\quad ET_{PCS}=\begin{vmatrix}A_{PCS}\\P_{PCS}\\I_{PCS}\\J_{PCS}\end{vmatrix}. \quad (5)$$

Each component of the $E_{UTUS}$ set of matrices is a vector of structural, power, information and operational characteristics of the corresponding UTUS components obtained at the *i*-th current iteration of the design calculations:

$$EE_{TUVi}=\begin{vmatrix}A_{TUVi}\\P_{TUVi}\\I_{TUVi}\\J_{TUVi}\end{vmatrix};\ EE_{TCi}=\begin{vmatrix}A_{TCi}\\P_{TCi}\\I_{TCi}\\J_{TCi}\end{vmatrix};\ EE_{CWi}=\begin{vmatrix}A_{CWi}\\P_{CWi}\\I_{CWi}\\J_{CWi}\end{vmatrix};$$

$$EE_{CDi}=\begin{vmatrix}A_{CDi}\\P_{CDi}\\I_{CDi}\\J_{CDi}\end{vmatrix};\ EE_{PCSi}=\begin{vmatrix}A_{PCSi}\\P_{PCSi}\\I_{PCSi}\\J_{PCSi}\end{vmatrix}. \quad (6)$$

It should be noted that each element of the vectors (6) represents the sum of respective structural (*A*), power (*P*), information (*I*) and functional (*J*) characteristics of this or that component of the UTUS.

Pairwise comparison of corresponding elements of the vectors (5) and (6) after each iteration of the design calculations allows the designer to determine level of compliance of current engineering solutions with respect to the UTUS components with RS requirements as to *A, P, I* and *J* criteria.

Note that the above four criteria {*A; P; I; J*} are generalized and can be made up of several local criteria which reveal requirements to the UTUS components in more detail when addressing specific design problems.

For example, in practice, the criterion of structural characteristics (*A*) usually contains at least two local criteria: mass (*M*) and overall dimensions (*K*) or volumes (*V*) of the corresponding UTUS component.

The *P* and *I* criteria make it possible to check whether it is possible to create an UTUS without violation of the RS limits concerning power supply and information equipment of the towed system components.

In addition, of importance is the fourth criterion for existence of *J* which makes it possible to check the possibility of constructing a UTUS with specified operation characteristics [23]. In the first place, these characteristics include the following:

– for the TUA: ability to submerge and move at a working depth ($J_{TUVH}$ local criterion, m) and ensure the LRD efficiency when performing an underwater search mission ($J_{TUVQ}$ local criterion, m/s);

– for the TC: ability to supply the TUA with maximum specified power $P_{TC\max}$ and power quality and provide a two-way information exchange with maximum specified transmission capacity $I_{TC\max}$ of channels of the TC information conductors. Besides, requirements are set for the TC to meet the RS requirements concerning the TC tensile strength *F*, minimum bending radius *D* and maximum rewinding number *N*. Correspondingly, meeting of these requirements is controlled by local criteria $J_{TCP}$ (W), $J_{TCI}$ (bit/s), $J_{TCF}$, $J_{TCD}$ and $J_{TCN}$;

– for the CW: ability to provide linear speed of taking in/loosening the TC in a specified range as determined by the operating modes $R_{UTUS}=\{R_{Rel};R_I;R_{JL};R_A;R_T;R_{Rec}\}$ ($J_{CW\wedge}$ local criterion);

– for the LRD: ability to perform launching and lifting operations with the TUA in a set range of speeds of the load hook as determined by the operating modes $R_{UTUS}=\{R_{Rel};R_{Rec}\}$ ($J_{CD\wedge}$ local criterion);

– for the ESCS: ability to provide power to the TUA, control modes of its operation in accordance with (1) and document the processes and results of the UTUS operation ($J_{PCSE}$, $J_{PCSI}$ and $J_{PCSD}$ local criteria, respectively).

In general, the system of relations (5), (6) forms mathematical basis of a generalized scheme of designing the UTUS based on the systems approach. Description of application of these relationships in the design practice is a trivial engineering problem and a topic for elaboration of a separate design procedure. Let us consider design of one of the UTUS components, the TUA, as an example which demonstrates peculiarities of use of relations (5), (6) at an early stage of the UTUS design.

## 7. An example of using the systems approach at an early stage of designing a component of unmanned towed underwater system

Let us take the Glider Project TUA as a design object and local criteria of mass $M_{TUV}$ and volume $V_{TUV}$, power $P_{TUV}$ and information $I_{TUV}$ as well as local criteria of operation $J_{TUVH}$ and $J_{TUVQ}$ as design criteria.

Let us set up an equation of existence of $EE_{TUV}$ for the TUA, technical and operational characteristics of which are specified in the RS in a form of the $ET_{TUV}$ matrix in accordance with the first constituent sets of matrices (5) and (6).

Then the equations of masses $M_{TUV}$ and volumes $V_{TUV}$ of the TUA can be written as follows:

$$\left.\begin{aligned}M_{TUV}&=M_{TUVK}+M_{TUVP}+M_{TUVI}+M_{TUVG}\le M_{TUV_{TT}},\\V_{TUV}&=V_{TUVK}+V_{TUVP}+V_{TUVI}+V_{TUVG}\le V_{TUV_{TT}},\end{aligned}\right\} \quad (7)$$

where indices *K, P, I* indicate belonging of the mass $M_{TUV}$ or the volume $V_{TUV}$ of the corresponding TUA equipment respectively to the hull-mechanical (*K*), power (*P*), information-control (*I*) groups of the TUA equipment proper.

Index *G* denotes belonging of the TUA equipment to the group of equipment which is additionally mounted on the apparatus to perform underwater works for the intended purpose (e. g. hydroacoustic search devices, instruments for environmental measurements, etc.).

Requirements of comparison of the TUA characteristics obtained at the *i*-th iteration of the design ( $EE_{TUVi}$ matrix) with the RS requirements ($ET_{TUV}$ matrix) are introduced in a form of inequalities into the equations of existence (7) and further in the right parts of the equations of existence.

Equation of the TUA existence according to power and information criteria can be written as follows:

$$\left.\begin{aligned}P_{TUV}&=\left(P_{TUVP}+P_{TUVI}+P_{TUVG}\right)\Big|_{R_{UTUS\,Ext}}\le P_{TUV_{TT}},\\I_{TUV}&=\left(I_{TUVP}+I_{TUVI}+I_{TUVG}\right)\Big|_{R_{UTUS\,Ext}}\le I_{TUV_{TT}},\end{aligned}\right\} \quad (8)$$

where $P_{TUVP}$ is total power consumed by electric equipment of the TUA (power supply unit, video cameras and searchlights, power drives of elevon deflection and other actuators); $P_{TUVG}$ is total power consumed by information and control devices of the TUA (onboard microcontroller, navigation and functional sensors, system of electrical protection, control relays, etc.; $P_{TUVG}$ is total power consumed by mounted electrical equipment of the TUA; $I_{TUVP}$, $I_{TUVI}$, $I_{TUVG}$ are respectively, intensity of information exchange of the power drive control channels, channels of the information and control units of the TUA proper and the control channels of its mounted equipment;

$R_{UTUS\,max}$ is the condition of setting up equations (8) for the most hard mode of the TUA operation in the power or, accordingly, in the information sense which is determined by the set of modes (2).

Equations (7) and (8) are set up based on characteristics of the TUA parts, units and systems incorporated into the project at an early design stage. These units and systems must be produced at a level of recent achievements in the fields of materials science, electrical engineering, automation, electromechanics, electronics, informatics ($C_{MA}$ requirement of the $C_{UTUS}$ set). In addition, these units and systems must be commercially available as the UTUS components ($C_{AP}$ requirement of $C_{UTUS}$ set).

Let us consider the use of equation (7) at an early stage of designing the Glider Project TUA. Taking into account requirements to the TUA (apparatus mass $M_{TUV_{TT}} \le 25$ kg and volume $V_{TUV_{TT}} \le 25{,}5$ l), equations (7) have the following form after entering initial characteristics $S_{TUV} \in S_{UTUS0}$ according to (3) and two iterations for selection of materials and equipment:

$$\left.\begin{aligned} & M_{TUV} = M_{TUVK} + M_{TUVP} + M_{TUVI} + M_{TUVG} = \\ & = 12{,}8 + 7{,}2 + 2{,}75 + 1{,}6 \le 25 \text{ kg}; \\ & V_{TUV} = V_{TUVK} + V_{TUVP} + V_{TUVI} + V_{TUVG} = \\ & = 16{,}1 + 4{,}5 + 2{,}5 + 1{,}5 \le 25 \text{ l}. \end{aligned}\right\}$$

Power and information requirements of the RS to the Glider Project TUA are as follows: maximum power consumed by the TUA electrical equipment is $P_{TUV_{TT}} \le 1$ kVt and maximum intensity of information exchange between the TUA and the ESCS is $I_{TUV_{TT}} \le 500$ Mbit/s. Application of equations of the TUA existence according to power and information criteria (8) produces the following result after introduction of initial characteristics $S_{TUV} \in S_{UTUS0}$ according to (3) and two iterations of equipment choice:

$$\left.\begin{aligned} & P_{TUV} = \left(P_{TUVP} + P_{TUVI} + P_{TUVG}\right)\Big|_{R_{UTUS\,Ext}} \le P_{TUV_{TT}} = \\ & = 0{,}5 + 0{,}15 + 0{,}3 = 0{,}9 \le 1{,}0 \text{ kVt}; \\ & I_{TUV} = \left(I_{TUVP} + I_{TUVI} + I_{TUVG}\right)\Big|_{R_{UTUS\,Ext}} \le I_{TUV_{TT}} = \\ & = 5{,}0 + 100{,}0 + 125 \le 500{,}0 \text{ Mbit/s}. \end{aligned}\right\}$$

Thus, the use of existence equations (7) and (8) at an early stage of the TUA design has made it possible to check and confirm the possibility of creating such an apparatus according to the RS requirements soon after two design iterations. The found variant of the TUA construction using selected structural materials and units of power engineering and informatics ensured a 2.5 times reduction of time spent on development of the contract design. In the future, when designing modifications to the TUA for medium depths (up to 500 meters), it is planned to reduce by 5–7 times the time spent on development of a contract design due to a sharp decrease in the volume of multivariate calculations.

The equation of the TUA existence according to the functional criterion $J_{TUV}$ can be represented as two local criteria, i. e. the possibility of achieving the design working depth of immersion $J_{TUVH}$ and productivity of search operations $J_{TUVQ}$:

$$J_{TUV} = \begin{cases} J_{TUV\,H} \ge H_{TT}; \\ J_{TUV\,Q} \ge Q_{TT}, \end{cases} \qquad (9)$$

where $H_{TT}$, $Q_{TT}$ are maximum values of the working depth of the TUA immersion and its performance in the search, respectively, specified in the RS.

Dependence (9) should be checked with the use of mathematical and computer simulation methods that allow one to study force-and-power, information and operation characteristics of the created TUA ($C_{RT}$ requirement of the $C_{UTUS}$ set) [17, 18].

According to the RS requirements to the Glider Project TUA, maximum working depth $H_{TT}$ is 20 meters and maximum productivity of the search operations $Q_{TT}$=1000 m$^2$/hour. The range of working speeds of towing is 1–6 knots.

Computer simulation of the spatial motion dynamics of the TUA-TC system using a simulation model of [18] has shown that when towed at a speed of 6 knots, the Glider Project TUA reaches a guaranteed depth $H_{TT}$. At the same time, it has been established that width of the instrumental (hydroacoustic) survey must be at least 100 meters in order to achieve required performance of underwater search works $Q_{TT}$=1000 m$^2$/hour. This has necessitated refinement of requirements to the mounted equipment of the TUA, namely devices of hydroacoustic search. This has made it possible to clarify total power consumption $R_{TUVG}$ by the electrical equipment mounted on the TUA and intensity $I_{TUVG}$ of information exchange of this equipment with the RSCS.

Similarly, based on the equations of existence (5), (6), equations of existence of the form (7) to (9) can be obtained for other UTUS components: TC, CW, LRD and ESCS.

## 8. Development of a generalized scheme of the UTUS design based on the systems approach and computer technologies

Let us present the generalized scheme of organization the UTUS design works based on the systems approach with taking into account basic requirements (4) to the design of a competitive UTUS as the following algorithm (Fig. 3).

The following is description of the algorithm blocks in an order of their numbering.

*Block 1.* Analysis of the RS for the UTUS creation and forming draft technical characteristics of its components $S_{UTUS\,TT}$ in a format suitable for further processing in an automatic mode.

*Block 2.* Determining the $R_{UTUS}$ set of significant modes of the UTUS operation and forming the $R_{UTUS\,Ext}$ set of the hardest operation modes for each of its components. The $R_{UTUS\,Ext}$ set modes determine the most intense operating modes in which relevant components of the UTUS must operate.

*Block 3.* Checking conformity of the RS with the current achievements of underwater technologies. The $X_1$ condition has the following predicates:

– $x_{11}$: access to the $Db_{MT}$ database of current underwater technologies;

– $x_{12}$: transition to *Block 4* for development of proposals for the RS correction with the purpose of introduction of current technologies in accordance with the $C_{MT} \in C_{UTUS}$ requirement;

– $x_{13}$: transition to *Block 5* on conditions that current underwater technologies are used in the project.

*Block 5.* Determination of draft technical characteristics $S_{UTUS0}$ of the UTUS components based on the RS requirements.

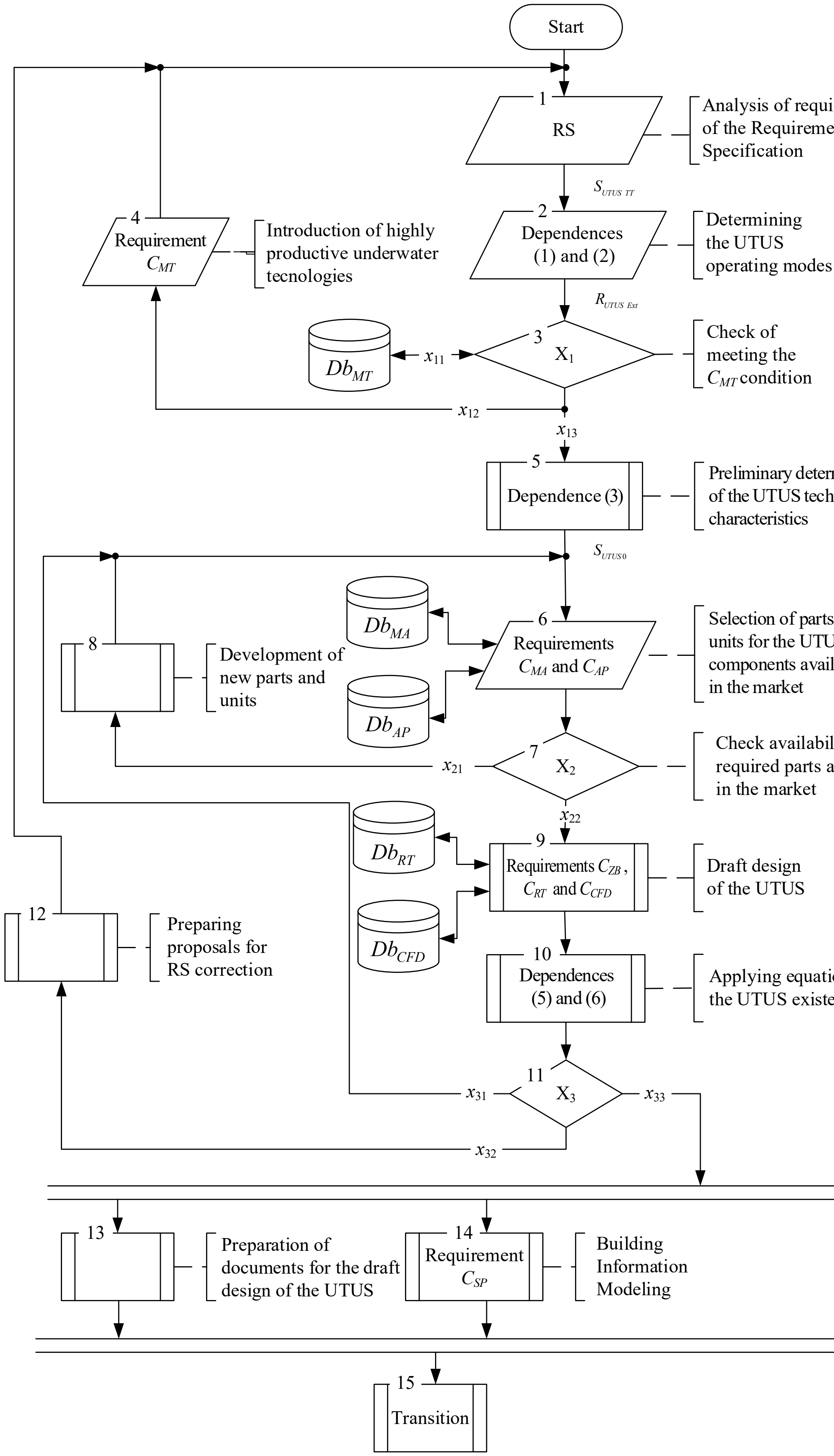


Fig. 3. Generalized algorithm of the UTUS design

*Block 6*. Selection of structural materials, parts and units for the components of the designed UTUS which are available in the $Db_{MA}$ materials database and in the $Db_{AP}$ database of units and underwater robotics systems in accordance with the $C_{MA} \in C_{UTUS}$ and $C_{AP} \in C_{UTUS}$ requirements.

*Block 7.* Checking availability of the necessary structural materials, parts and components in the market of high-tech products. Condition $X_2$ has the following predicates:

– $x_{21}$: transition to *Block 8* of forming an order for development of new materials, parts and units unavailable in the market of such products;

– $x_{22}$: transition to *Block 9* if there is necessary information on selection of structural materials, parts and units for the UTUS design.

*Block 9*. Sketch UTUS design using selected structural materials, parts and units. Of crucial importance here is compulsory use of current CAD/CAM/CAE design technologies ($C_{RT} \in C_{UTUS}$ requirement) and CFD software packages ($C_{RT} \in C_{UTUS}$ requirement) contained in respective $Db_{RT}$ and $Db_{CFD}$ databases. This is due to the availability of reliable data on technical characteristics of the UTUS components at an early design stage including use of dynamic modes. The *Block 9* output is the $S_{UTUSi}$ version of the UTUS sketch design.

*Block 10*. Detecting deviations of structural, power, information and operational characteristics of the respective components of the *i*-th UTUS version from the RS requirements by pairwise comparisons of the vectors (5) and (6).

*Block 11*. Verifying conformity of the design, power, information and operational characteristics of respective components of the *i*-th version of the UTUS $EE_{UTUS}$ with requirements of the RS $ET_{UTUS}$. Condition $X_3$ has the following predicates:

– $x_{31}$: transition to *Block 6* of selecting other materials, parts and units for the UTUS components that would improve design characteristics of the components of the *i*-th version of the towed system;

– $x_{32}$: transition to *Block 12* of formulating proposals for changing the RS requirements because of inability to fulfill its requirements in full;

– $x_{33}$: transition to *Block 13* of preparing documents for the UTUS draft design.

*Block 14*. Creation of an information model of the UTUS design including collection and integrated processing of design, technological and economic data about the created underwater equipment object ($C_{SP}$ requirement). This requirement involves use of the Building Information Modeling technology: modeling the process of UTUS designing as the basis for rapid deployment of mass UTUS manufacture [24].

*Block 15*. Transition to the stage of engineering UTUS design.

Thus, the developed generalized algorithm of designing uses principles of the systems approach in a form of equations of the UTUS existence and provides reliable determination of technical characteristics of the designed system already at early stages of its development.

## 7. Discussion of results obtained in the application of the systems approach to designing unmanned towed underwater systems

The main way to creation of competitive UTUS for shallow water areas is improvement of reliability of engineering solutions at early design stages and reduction of cost of resources, in particular, the design time. Introduction of a systems approach to organization of the UTUS design process forms methodological basis for getting competitive advantages of the created products since it accounts for interaction of main components of the design object in its operation. In addition, the systems approach involves integration of better design technologies which provides high-quality engineering solutions and significantly reduces design time.

Implementation of the systems approach requires solution of a series of applied scientific problems. This can significantly improve efficiency of design works in the process of UTUS creation.

As a result of the study, set (1) of the main UTUS operating modes was identified. These modes are key modes for the design calculation of the system components. Based on analysis of the mentioned modes, those (2) which are the most hard and should form basis of the design calculations for each UTUS component were selected. It is obvious that the set of modes (2) is less powerful, so costs of the project resources get significantly reduced already at the early design stages. Proceeding from the set (2) and the RS requirements, mass, power and information characteristics (3) of the UTUS components (TUA, TC, CW, LRD, ESCS) which are the first iteration of the UTUS sketch design are pre-determined.

Further sketch design of the UTUS should be carried out taking into account current requirements to creation of competitive robotics means intended for work in shallow water areas. Such requirements are formed in a form of the set (4) containing requirements both to the future technologies of application of newly created robotics and application of current design technologies.

The requirements obtained cover the need to design the UTUS for implementation of modern high-performance underwater technologies and use modern computer study and design programs. Besides, requirements are being set to maximize use of materials, units and systems commercially available in the market as accessories for the UTUS components. The above requirements are relevant for creation of any type of technology, however, when supplemented with the requirement of zero or residual positive buoyancy ($C_{ZB}$) they form a complete information basis for development of a generalized scheme of designing the UTUS for shallow water areas.

Theoretical basis of the systems approach to designing shallow water UTUS is formed by the set of matrices (6) of structural, power, information and operational characteristics of the UTUS components obtained at a current design stage. Comparison of elements of the set of matrices with corresponding elements of the set of matrices (5) of the RS limits for the UTUS components allows designers to identify level of compliance of current engineering solutions with the RS requirements as to the selected criteria.

Such verification is first performed for several iterations of the design solutions formed with wide involvement of databases of commercially available materials, units and systems as required by the $C_{AP}$ set (4). In absence of necessary UTUS elements, it is envisaged to formulate technical requirements for them and an order for design, manufacture and delivery.

The UTUS sketch design is completed with preparation of project documents and construction of an information model of designing underwater systems which enables organization of their serial production.

The described UTUS design sequence based on the principles of the systems approach was presented in a form of a generalized algorithm of design works (Fig. 3) which provides a reliable determination of technical characteristics of the designed system at early design stages.

Efficiency of using the systems approach at early stages of UTUS design was confirmed by the example of designing one of the system components, a towed underwater apparatus. It was shown that with the help of equations of TUA existence as to the criteria of mass and volume (7), power and information (8) and functional criterion (9), after just two iterations of the engineering solution, it was found that it satisfies the RS requirements to the towed underwater apparatus. At the same time, due to reduction of the volume of multivariate calculations for the engineering design phase, the time spent on the contract design was reduced by 2.5 times.

Thus, the scientific problem of introduction of the systems approach at early stages of designing the UTUS for operation in shallow water areas was formulated as a result of analysis of published data. Validity of such a conclusion is justified by the fact that the theoretical basis for development of a highly efficient method of designing the UTUS based on the equation of existence of an underwater system as to material, power, information and functional criteria was created. Important components of the created methodology include the approach proposed by the authors to determine main modes of the UTUS operation and formulation of present-day requirements to the design and building of a competitive UTUS. Use of the obtained theoretical results in the design practice has confirmed its effectiveness, in particular, reduction of the time spent at subsequent design stages.

At the same time, it should be noted that in order to maximize effectiveness of the proposed methodology, the following limitations and uncertainties should be overcome:

– develop databases of current underwater technologies, materials, units and systems of underwater robotics, CAD/CAM/CAE design technologies and CFD software packages which will enable quick access to them in the process of automated design;

– establish analytical links between the design parameters and the operational characteristics of the UTUS components to provide a basis for quantitative assessment of the design options for the set of matrices (6) of structural, power, information and performance characteristics of the UTUS.

## 8. Conclusions

1. A set of basic modes of the UTUS operation was formed and the most hard modes for the towed underwater apparatus (tow cable, cable winch, launch-and-lift device and the power supply and control unit as the UTUS components were defined. It was shown that the mass-and-size, power and information characteristics of these components are key characteristics for the design calculations.

2. Basic requirements to designing and building competitive UTUS were formulated. Such requirements include the need to implement modern underwater technologies as a basis for the market value of the UTUS and the use of current databases of existing materials, units and systems for the UTUS. A separate set of requirements are requirements to automation of design processes, use of computer-aided design packages and computational hydrodynamics to test design solutions at the early stages of design.

3. In order to check the possibility of meeting requirements of the Requirements Specification already at early stages of UTUS design, two sets of matrices of UTUS technical characteristics were constructed as to the structural, power, information and operational criteria. These matrices implement the systems approach to UTUS design and represent equation of existence of the UTUS components as to the structural, power, information, and functional criteria. Pairwise comparison of the corresponding elements of the matrices after each iteration of the design calculations allows designers to determine level of conformity of the current engineering solutions as to the UTUS components with requirements of the Requirements Specification.

4. An example of use of the systems approach at an early stage of designing a towed underwater apparatus as a UTUS component was given. Peculiarities of building the matrix of structural, power, information and operational characteristics of the TUA were shown when the criteria of mass and volume, power, information and operational criteria were taken as local criteria. This example confirms the possibility of a 2.5 times reduction of time spent on development of a contract design by reducing amount of multivariate calculations for the engineering design stage.

5. A generalized algorithm of designing the UTUS implements the systems approach to the use of modern computer technologies and equations of existence to verify satisfaction of requirements of the Requirements Specification at early stages of the UTUS design. It features a significant reduction in the cost of design resources, in particular, time for the engineering design by reducing number of options of the engineering solutions under consideration. The developed algorithm forms a scientifically substantiated methodological basis for creation of competitive means of underwater robotics.

References


1. Ikonnikov, I. B., Gavrilov, V. M., Puzyrev, G. V. (1993). Podvodnye buksiruemye sistemy i bui neytral'noy plavuchesti. Sankt-Peterburg: Sudostroenie, 224.
2. Manning, G. C. (2013). The Theory And Technique Of Ship Design: A Study of the Basic Principles and the Processes Employed in the Design of Ships of all Classes. Literary Licensing, LLC, 288.
3. Gaykovich, A. I. (2014). Teoriya proektirovaniya vodoizmeshchayushchih korabley i sudov. Vol. 1. Opisanie sistemy «Korabl'». Vol. 2. Analiz i sintez sistemy «Korabl'». Sankt-Peterburg: Izdatel'stvo «Morinteh», 822, 874.
4. Matousek, R. (1963). Engineering design: A systematic approach. Springer, 264. doi: https://doi.org/10.1007/978-94-010-9306-4
5. Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H. (2007). Engineering Design: A Systematic Approach. Springer. doi: https://doi.org/10.1007/978-1-84628-319-2

6. Korte, H. (2000). Track Control of a Towed Underwater Sensor Carrier. IFAC Proceedings Volumes, 33 (9), 89–94. doi: https://doi.org/10.1016/s1474-6670(17)38129-6
7. Linklater, A. (2005). Design and Simulation of a Towed Underwater Vehicle. Blacksburg, Virginia. Available at: https://vtechworks.lib.vt.edu/bitstream/handle/10919/33622/AmyThesis.pdf?sequence=1&isAllowed=y
8. Buckham, B., Nahon, M., Seto, M., Zhao, X., Lambert, C. (2003). Dynamics and control of a towed underwater vehicle system, part I: model development. Ocean Engineering, 30 (4), 453–470. doi: https://doi.org/10.1016/s0029-8018(02)00029-x
9. Srivastava, V. K., Sanyasiraju, Y., Tamsir, M. (2011). Dynamic Behavior of Underwater Towed-cable in Linear Profile. International Journal of Scientific & Engineering Research, 2 (7). Available at: https://pdfs.semanticscholar.org/fe04/8af7057476a54f47dbd-7c344e6b59d854fcf.pdf
10. Curado Teixeira, F., Pedro Aguiar, A., Pascoal, A. (2010). Nonlinear adaptive control of an underwater towed vehicle. Ocean Engineering, 37 (13), 1193–1220. doi: https://doi.org/10.1016/j.oceaneng.2010.05.010
11. Minowa, A. (2015). System Analyses and Motion Control of a Towed Underwater Vehicle. Tokyo. Available at: https://oacis.repo.nii.ac.jp/?action=repository_action_common_download&item_id=1305&item_no=1&attribute_id=20&file_no=1
12. Blintsov, O., Sokolov, V., Kucenko, P. (2019). Formulation of design tasks of towed underwater vehicles creation for shallow water and automation of their motion control. EUREKA: Physics and Engineering, 2, 30–42. doi: https://doi.org/10.21303/2461-4262.2019.00854
13. Park, J., Kim, N. (2015). Dynamics modeling of a semi-submersible autonomous underwater vehicle with a towfish towed by a cable. International Journal of Naval Architecture and Ocean Engineering, 7 (2), 409–425. doi: https://doi.org/10.1515/ijnaoe-2015-0029
14. Pang, S., Liu, J., Chen, H., Wang, J., Yi, H. (2017). Analysis of motion state of the tow-part underwater towed vehicle system during cable deployment. OCEANS 2017 - Aberdeen. doi: https://doi.org/10.1109/oceanse.2017.8084915
15. Thomas, N., T. Issac, M. (2017). Analysis of Tow Cables. Universal Journal of Mechanical Engineering, 5 (5), 144–149. doi: https://doi.org/10.13189/ujme.2017.050502
16. Williams, K., McGinnis, T., Miller, V., Brand, B., Light, R. (2016). Final Report. Limited Scope Design Study for Multi-Sensor Tow Body. SERDP Project MR-2501. University of Washington. Available at: https://www.serdp-estcp.org/content/download/39999/383953/file/MR-2501%20Final%20Report.pdf
17. Blintsov, V., Klochkov, O. (2019). Generalized method of designing unmanned remotely operated complexes based on the system approach. EUREKA: Physics and Engineering, 2, 43–51. doi: https://doi.org/10.21303/2461-4262.2019.00878
18. Blintsov, O. V., Sokolov, V. V. (2018). Synthesis of a spatial motion dynamics simulating model of an unmanned underwater towed system as an object of control. Shipbuilding & marine infrastructure, 2, 131–143. Available at: http://smi.nuos.mk.ua/archive/2018/2/15.pdf
19. Strasdat, H., Davison, A. J., Montiel, J. M. M., Konolige, K. (2011). Double window optimisation for constant time visual SLAM. 2011 International Conference on Computer Vision. doi: https://doi.org/10.1109/iccv.2011.6126517
20. Van der Auweraer, H., Anthonis, J., De Bruyne, S., Leuridan, J. (2012). Virtual engineering at work: the challenges for designing mechatronic products. Engineering with Computers, 29 (3), 389–408. doi: https://doi.org/10.1007/s00366-012-0286-6
21. Driss, Z., Necib, B., Zhang, H.-C. (Eds.) (2018). CFD Techniques and Energy Applications. Springer. doi: https://doi.org/10.1007/978-3-319-70950-5
22. Blintsov, V., Klochkov, O. (2016). Equations of existence selfpropelled underwater system as assessment of the possibility of its creation. Pidvodni tekhnolohiyi, 3, 25–30.
23. Blintsov, V. S., Klochkov, O. P. (2018). Proektni zadachi stvorennia bezekipazhnoho samokhidnoho pryviaznoho pidvodnoho kompleksu na osnovi systemnoho pidkhodu. Naukovyi visnyk Khersonskoi derzhavnoi morskoi akademiyi, 2 (19), 4–13.
24. Kensek, K. M. (2014). Building Information Modeling. Routledge, 312. doi: https://doi.org/10.4324/9781315797076