Alternative Ways for Deep Sea Research and Improving Methods for Automatic Control Systems of Underwater Robotics

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Abstract. The report examines deep-sea inhabited and uninhabited underwater vehicles and robotic systems (RSSs), which already allow the deployment of near-bottom autonomous and remotely controlled technical means for long-term and planned oceanological, geophysical, biological and many other studies. Ways and methods of increasing the accuracy of launching autonomous RSSs into a given area of work and finding the most interesting anomalous research objects are considered. The analysis is based on half a century of experience in the creation and use of autonomous and remotely controlled underwater robots at the IMTP FEB RAS.

1. Introduction
The ocean is the cradle of humanity. Born in a hydrothermal abyss and living on the shore, a person knows perhaps less about the deep-sea areas of the seabed than about the surface of the far side of the Moon, and the biological diversity of the Ocean, according to marine biologists, has been studied only by five percent [1]. To date, the depths of the ocean have been explored and explored worse than the atmosphere and near-earth space. It has become banal to say that the ocean occupies more than two-thirds of the surface of our planet, and the volume of oceanic water masses is 18 times greater than the volume of continents located above sea level. The vast resources of the oceans are used by mankind hardly by a few percent. Only in the last half of the last century did man from time to time begin to look timidly into the vast world stretching under the surface of the seas and oceans. Inhabited and uninhabited underwater vehicles, especially deep-water vehicles, which, undoubtedly, will be of decisive importance in the upcoming development of the Ocean, greatly helped in understanding what they saw.

2. Deep-sea inhabited vehicles
The first among the inhabited deep-sea vehicle (DSV) was the unique bathyscaphe "Trieste". Back in 1961, the Swiss father Auguste and son Jacques Picard, competing with the French, created the Trieste bathyscaphe.

After numerous upgrades, Jacques Piccard and Don Walsh dived in it into the Mariana Trench to a depth (according to the instruments of that time) - 10919 m. The third person to hit the bottom of the Mariana Trench in Challenger's Abyss (on the “Deep Sea Challenger”) was American director James Cameron. The seven-hour dive took place on March 25, 2012 on the Deep Sea Challenger. It reached the Challenger Abyss, a section of a depression at a depth of 10898 m.
The fourth person who reached near the extreme depths of the Ocean was Victor Vesekovo. In 2019, a unique commercial reusable two-seater “Triton 36000/2” was created, working with the “Landers” seabed station. “Triton 36000/2” is the third vehicle to visit the Mariana Abyss. In May last year (2019), a world diving record was set - 10927 meters. Equipping the reusable “Triton - 36000/2” with deep-sea two-link remote-controlled system will significantly expand the range of research tasks and underwater technical work.

3. Deep-sea robotic systems

The rapid development of underwater robotics over the past decades suggests that the main role in the exploration, development and protection of the resources of the World Ocean will be played by underwater robotic systems. One of the elements of which may be AUVs, inhabited underwater vehicles, normobaric underwater laboratories and stationary normobaric inhabited underwater structures.

The first all-deep remote-controlled towed-tethered robotic complex was the Japanese system “Kaiko - 11 000”, created by the Japanese Japan Agency for Marine Earth Science and Technology (JAMSTEC) in 1995. “Kaiko” made many discoveries in marine biology, collecting samples of benthos previously unknown to science, and made a significant contribution to the understanding of the processes of spiding and subduction. The loss of Kaiko on May 31, 2003 was a tragedy for the global oceanographic community. The $ 15 million complex was lost in the Ocean off the coast of Japan when a typhoon approached the coast due to snagging and breaking of the secondary cable connecting the towed module with the tethered one. Let us note that the ideology of building the “Kaiko” system and some “know how” were borrowed from the FEPI (see the project “Lortodromia-RVO”) and developed by our Japanese colleagues.

The unique two-link towed-tethered bottom system ROV "ABISMO" (Automatic Bottom Inspection and Sampling Mobile) has become the second all-deep robotic complex [1,2]. It was established at JAMSTEC for sediment sampling and oceanographic research. Its development began in April 2005, and in the fall of 2007 it reached 9760 m in the Izu-Ogasawara Trench.

Already the first few attempts to penetrate the abyssal depths have shown the unreliability of tethered underwater technical means. There was an accident (cable break) during tests in the Atlantic of the harness module of the project FEPI “Lortodromiya – RVO”. An inhabited DSV turned out to be more reliable. We can say that progress towards autonomy is predetermined by the laws of physics. The success of autonomous inhabited vehicles and almost half a century of research by the Institute for Marine Technology Problems of the Far East Branch of the Russian Academy of Sciences (IMTP FEB RAS) in the field of autonomous technologies allow us to consider that the most promising means of studying the ocean depths will be precisely the AUV as part of the RSs.

A representative commission of the US World Center for the Development of Advanced Technologies (WTEC), authorized by the Office of Naval Research (ONR) and the National Science Foundation (NSF), worked in Vladivostok. According to the official conclusions of the commission: “IMTP has more experience in the practical application of AUV than all the programs of the United States combined.”

The accumulated experience in the creation and use of deep-sea AUVs allowed IMTP to create one of the most advanced and most demanded devices in the conditions of an academic institute, and then the “Klavesin” series put into service. For a number of the most important characteristics “Klavesin” surpasses well-known foreign analogues.

In recent years, the activity of the Central Design Bureau “Rubin” in the development of marine robotics has noticeably increased. Taking into account the operating experience and practically all the “know how” of the IMTP, “Rubin” in a short time (after 20 years of work by the IMTP) built and on May 8 tested at a depth of more than 10 km a demonstration version of the all-deep AUV “Vityaz-D”. Not everything worked out. But there is every reason to believe that for the first time a domestic AUV has reached a record depth in its class, Russian deep-sea autonomous technologies as part of the RS will successfully develop on an industrial basis and will become the driver of our progress.
4. Automatic control theory methods for improving automatic control systems

Many (if not most) research, survey and search DSV missions can be reduced to bringing it to a “target point” (area) [6] and finding the extrema (anomalies) of the natural physicochemical ocean fields (PCOF) or induced by man-made objects.

The first step in solving this problem is the creation of a deep-sea robotic complex (DSRC) with a Lender-controlled stationary bottom station (SBS). [6]

At the second stage, the same methods can be applied to the control of the AUV itself. Unguided Lenders have already been used in deep-sea inhabited dives of the “Deep Sea Challenger” and “Triton 36000/2”.

As one of the examples of the application of the above methods, we can consider the problem of bringing the DSRC (Fig. 1) to a given area [6] and finding the deepest place in it at great and extreme depths in conditions of insufficient range and reliability of the available hydroacoustic equipment and other sensors. It is proposed to use at the beginning terminal methods [4, 5] to bring the DSRC into a given area, and then, using the known methods of extreme guidance, find and descend to the maximum depth or target the extremum of PCOF.

![Figure 1. Scheme of DSRC interaction (IMTP project): 1 - Carrier vessel (ship control equipment); 2 - Ship towed antenna; 3 - Lander; 4 - Ship direction finder; 5 - AUV; 6 - Measuring probe.](image1)

![Figure 2. Lander (IMTP project): 1 - Aft compartment; 2 - Navigation-communication and research equipment compartment; 3 - Anchor-fairing compartment; 4 - Cable-rope; 5 - Float module of search equipment; 6 - Aft fairing; 7 - Power engineering equipment.](image2)

However, currents and other disturbances can displace the uncontrolled Lander a considerable distance from the proposed research site. For example, you might not even get into the Mariana Trench. Thus, we come to the conclusion that it is advisable to control Lander. Arguing further, we can assume the feasibility of creating a DSRC from two AUVs, different both in configuration and in equipment.

When creating a controlled Lender, it is necessary to improve the mathematical model of the process of its immersion and interaction with the environment and flow. The flow must be taken into account not just kinematically, but as an external dynamic disturbing effect. For this purpose, in our opinion, it is advisable to introduce into the right-hand side of the equations of dynamics a certain “virtual flow force” equal (with the hypothesis of laminar flow) to the product of the flow velocity and the hydrodynamic resistance along the corresponding connected axis. This “force” can be viewed as an unknown harmful effect. But it can also be measured, taking into account the difference between the dynamics of the control object (Lender or the AUV itself) and the flow sensor located on it. On the other hand, you can use a Doppler meter relative to the speed or determine the overall, total, disturbing
effect by methods of functional diagnostics. Then it is possible to use the advantages of the combined control principle, well known from the theory of automatic control.

5. Determination of unknown disturbances by diagnostic methods
One of the ways to improve the efficiency of the AUV control system is the construction of robust systems, i.e. systems insensitive to directly not measurable external disturbances. The most significant such impacts are changes in buoyancy depth (due to compression of the AUV hull and changes in the density of the medium), as well as variable currents. They can change both in time and space. If we assume that buoyancy is regulated during the mission, then, apparently, the main component of the unknown disturbance will be the dynamic component of the current.

Let us consider this problem using a simple example of AUV motion in the vertical plane, which in the state space is described by a model:

\[
\begin{align*}
\dot{x}_1(t) &= x_1(t), \\
\dot{x}_2(t) &= \frac{1}{Ta} (Ka(x_3(t) + F_{rev}(t) + \beta) - x_2(t)), \\
\dot{x}_3(t) &= \frac{1}{Td} (Kd(Ky(h_s - x_1(t)) - K_{oc}^e x_2(t)) - x_3(t)),
\end{align*}
\]  

(1)

where \(x_1\) – dive depth, \(x_2\) – dive speed.

It is assumed that the measured variables are \(x_1\) and \(x_2\), i.e.:

\[
y_1(t) = x_1(t), \quad y_2(t) = x_2(t).
\]

To solve the problem of determining the flow value, we use a reduced model of the original model (1), i.e. a low-dimensional model, on the basis of which a sliding observer is further built, which estimates the flow value. In the case under consideration, the reduced model has the form:

\[
\begin{align*}
\dot{x}_{1e}(t) &= \frac{1}{Ta} (Ka(x_{2e}(t) + F_{rev}(t) + \beta) - y_2(t)), \\
\dot{x}_{2e}(t) &= \frac{1}{Td} (Kd(Ky(h_s - y_1(t)) - K_{oc}^e y_2(t)) - x_2(t)),
\end{align*}
\]  

(2)

where \(x_{1e} = x_2\), \(x_{2e} = x_3\).

A sliding observer is built on the basis of this model and has the form [7-9]:

\[
\begin{align*}
\dot{z}_1(t) &= \frac{1}{Ta} (Ka(z_2(t) + \beta) - y_2(t)) + \frac{Ka}{Ta} v(t) - ke(t), \\
\dot{z}_2(t) &= \frac{1}{Td} (Kd(Ky(h_s - y_1(t)) - K_{oc}^e y_2(t)) - z_2(t)),
\end{align*}
\]  

(3)

where \(e_1(t) = z_1(t) - x_{1e}(t) = z_1(t) - y_2(t)\), the coefficient \(k > 0\) is selected to ensure the required quality of the transient process, the discontinuous function \(v(t)\) has the form:

\[
v(t) = g \frac{e(t)}{|e(t)| + \delta}, \quad g > |F_{rev}(t)|.
\]

It is easy to see that the errors \(e_1(t)\) и \(e_2(t) = z_2(t) - x_2(t)\) satisfy the equations:

\[
\begin{align*}
\dot{e}_1(t) &= \frac{Ka}{Ta} e_2(t) - ke_1(t) + \frac{Ka}{Ta} (v(t) - F_{rev}(t)), \\
\dot{e}_2(t) &= -\frac{Kd}{Td} e_2(t)
\end{align*}
\]
where $e_2(t) \to 0$, and in the sliding mode $\dot{e}_1(t) = 0$ and $e_1(t) = 0$ [8], this implies the relation for estimating the value of the current velocity:

$$\hat{F}_{\text{res}}(t) = g \frac{e(t)}{|e(t)| + \delta}.$$  

(6)

$\delta$ - small positive number.

6. Modeling

The simulation of the AUV motion in the vertical plane under the action of the flow is implemented in the MATLAB SIMULINK package (Fig. 3), the control object is compiled according to the notation of the modeling package according to formulas (1), the sliding observer - according to the formulas (3), the estimate of the flow velocity - according to the formula (6). The speed and dynamics of the change in the flow in the process of AUV motion modeling were set in different ways. The result of estimating the value of the flow velocity was obtained close to the one specified on the model.

Figure 3. SIMULINK diagram and simulation results.

7. References

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