The Compact Remotely Operated Underwater Vehicle with the Variable Restoring Moment

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Abstract. This paper presents the development of the new small-sized high-maneuverable remotely operated vehicle. The main scope of the vehicle is survey of shipwrecks. The main feature of the vehicle is variable restoring moment achieved by the rotated ring with the ballast in the transverse plane of the vehicle. This feature augmented with low value of own restoring moment and the overactuated propulsion system consisting of four vehicle and four horizontal thrusters allows high range of maneuverability to be achieved. The vehicle is equipped with the built-in lithium-ion battery. This feature reduces tether weight and allows automatic emergency return functions of the vehicle to the coast station in the case of cable damage to be implemented. The design rationale of the vehicle and the systems integration diagram are presented in the article. The design rationale of the variable restoring moment mechanism is described. The software based on modern development of Institute of Marine Technology problem FEB RAS and Far Eastern Federal University are presented.

1. Introduction

Every shipwreck sweeps away many lives. Therefore, it’s extremely important to determine the reason of the incident to thwart future recurrences of such tragedies. Currently, the most affordable way to study shipwrecks is the use of remotely operated underwater vehicles (ROVs). So, for instance, the tandem of two ROVs, Jake and Elwood, were used for survey of the interior part of the Titanic [1]. Another vehicle of ROV class JASON [2] also was used for survey the famous German flagship Bismarck that was sunk 1941. So, due to need to investigate the causes of shipwrecks and need to prevent potential technogenic catastrophes near the wreckage in the case of a fuel tank leakage the shipwrecks survey by a ROV is remain actual today.

The modern experience obtained during the development of underwater oil fields and underwater gas and optical pipelines, has proved to be useful in the field of underwater survey and inspection of shipwrecks [3]. Progress in ever-smaller electronic components and significantly increasing the accuracy of navigation equipment [4] [5] allows the compact and cheap survey class vehicles to be designed and implemented to perform high-precision and qualitative survey of shipwrecks [6] [7] [8] [9], especially in comparison to large vehicles used previously [10]. At the same time, significant progress of the software development allows even autonomous underwater vehicles to be used for these purposes [11]. But despite the increasing development and intellectualization of underwater vehicles, most of the work for visual inspection of shipwrecks is carried out by ROVs [12] [13].

The survey of shipwrecks through cracks in the hull or other holes of ships (for example, door or porthole) is the quite complicated task due to lack of maneuverability of common underwater vehicles.
That is due in part to the elongated form of the cracks and their random orientation in space. Therefore, the shape and dimensions of the survey vehicle, its maneuverability and payloads placing must ensure possibility the vehicle operating at arbitrary angles. Due to special conditions of the work inside the shipwrecks, the problem of design of the small-sized high-maneuverable remotely operated vehicle that meets the specified requirements seems to be actual.

2. Design rationale
The development the vehicle for the shipwreck survey is the specific task facing the developers of remotely operated underwater vehicles. The vehicle must meet the following list of requirements:
- the compact design - the most important criterion that ensures that the vehicle can enter the living and technical compartments of a sunken ship;
- wide-angle camera with a light-sensitive matrix for the qualitative visual survey of the ship’s condition;
- high maneuverability of the vehicle. This ensures the vehicle work in narrow technical tunnels of ships and aircrafts.

To obtain the vehicle with improved technical characteristics we propose to place the power supply on board of ROV and to provide data exchange between the ROV operator and the vehicle through an optical fiber communication cable. The risks of equipment loss and short-circuits are significantly reduced with build-in power supply. It also allows algorithms for autonomous leaving the sunken ships and returning to the base to be implemented. The article [16] shows the implementation of automatic return the autonomous vehicle to the base for recharging.

The main idea of the proposed vehicle consists in depart from the principles of the classical design of the underwater vehicle, where high stability and controllability are ensured. Similar attempts were made earlier during the development the Ocean Module V8 [14]. The points of gravity and buoyancy forces of this vehicle are coincided, this allows the arbitrary orientation of the vehicle in space to be controlled.

The proposed vehicle is made with the own restoring force close to zero and it is additionally equipped with the mechanism for changing one. The mechanism allows the angle of the vehicle’s roll to be passively set. The similar orientation control system is used in the Deep Trekker DTG2 [15], where the system of variable pitch angle of the vehicle was implemented by free movement of the electronics unit of the vehicle within the sealed enclosure around its transverse axis.

3. Vehicle overview
The frame of the ROV (signed as 1 at the Figure 1) is the monolithic polypropylene brace. The placing of the autopilot (2), the rotary camera (3) and the battery pack (4) in the single housing (5) allows the mass and dimensions of the vehicle to be minimized. The sealed transparent housing is made of acrylic. One of housing ends is the flat plastic cover with nine hermetic connectors, the second end is made in the form of a hemisphere for the camera placing.

The vehicle propulsion system (figure 1b) consists with eight thrusters (6). The propulsion system layout is accorded to the traditional vectorized scheme, ensuring the controllability of the vehicle for all degrees of freedom. The thrusters are maximally spaced from the center of the vehicle to maximize the propulsion system torque. Each thruster provides thrust within the range from -6 to 9 N.
3.1. Electronic unit

The vehicle autopilot is based on the single-board computer Raspberry Pi 3 B+ (figure 2). This computer is taken due to its wide availability and the ability to run the Ubuntu 16.04, on which our control system is based. Another important feature of this computer is the presence of the CSI-2 connector.

This interface allows an external digital camera to connected and high-definition video bypassing the CPU to be received followed by publishing it to the operator’s console. This interface greatly offloads the main CPU and allows the video stream to be broadcasted and vehicle motion to be controlled independently at the same time. The wide-angle camera with a light-sensitive matrix OV5647 designed for night vision has been selected for this vehicle. Two EMAX servo motors were used to implement the two-axis control of the camera’s rotation. This provides rotation in the range of 180 degrees for each of the controlled camera axes.

Current orientation and the angular velocities of the vehicle are handled by the IMU Xsens MTi 710 sensor. It provides the high-precision determination of the vehicle orientation both in the Euler angles and in quaternions, which is important for building the control system.

The conversion of data between optical cable and Ethernet is carried out by physical layer converter SNR-CVT-100A-V3. The chip PCA9685PW with 16 independent PWM channels was used to implement the PWM driver for the slave devices control. The control of the driver is done through Raspberry build-in I2C protocol.

![Figure 2. The functional diagram of the electronic unit.](image)

3.2. Control system

The control system of the vehicle represents a set of functionally separated modules. Each module is the separate application written in high-level language C++. For inter process communication the special IPC library developed by institute of Marine Technology Problems FEB RAS was used [17]. The software was developed within Qt Creator environment with the qmake compiler. All modules are divided into two groups. First group consists platform-independent modules. These modules can be started and debugged on any computer and operating system. Second group consists modules that depend on the platform. These modules require specialized equipment (in our case Raspberry Pi 3 B+ and its peripheral library). The second group is needed for high-level abstract of all other control modules with the possibility of their separate startup and debugging.

The development of control allocation algorithms for the overactuated propulsion system is based on solving quadratic optimization problems [18] [19].

3.3. Power system

During the designing we considered several battery types (The problem of the batteries arrangement is considered commonly during the designing the AUV power supply system, for instance in the paper [20]). To achieve the minimum vehicle dimensions lithium-ion batteries were chosen due to the best energy density (Table 1). The 4s5p battery scheme was chosen. This scheme provides 15V voltage and 18Ah capacity with 60A peak current and total 1.1 kg weight. Such battery characteristics were chosen to provide power for thrusters without additional transducers.
4. Mechanism for variable restoring moment

The rotation mechanism proposed for the ROV is shown in Figure 3a, b. It consists of the stepper motor 1, the gear train with internal gearing (pinion 2 and 3), the floating element 4, the weight 5 and elements for attaching the mechanism to the ROV frame. Toothed cylindrical gears 2 and 3 are made of polypropylene. The weight 4 represents the set of lead plates. Floating element 4 is the bar of high-density foam (density 200 kg/m³). Further, in calculations, the mass of the floating element and the volume of the lead load are neglected because of their smallness.

The vehicle designed so that the gravity G and the buoyancy force V were coincided at the point O (Figure 4a) without the weight 4 and the floating element 5. The point O is the center of the reference frame Oxyz. This reference frame is connected to the vehicle, so the longitudinal axis of the vehicle coincides with the axis Oy and the axis Oz is coincided with normal axis of the vehicle as shown in Fig. 1.

The additional advantage of the design is convenience for roll angle ballasting. The vehicle can be ballasted by placing weights on the gear 3 similarly to the balancing process of car wheels.

During the development of the mechanism for variable restoring moment, the glider development experience was used. The method for glider’s pitch control is based on changing the relationship between the buoyancy and the gravity force [21-24].

5. Results

During the development of the vehicle, the hydrodynamic characteristics were calculated by the FlowWorks program. Fig. 4 shows the results of modeling the vehicle motion along the longitudinal axis. According to the results, the vehicle velocities along longitudinal and normal motion are in the range from -1 to 1 meter per second and from -0.75 to 0.75 meters per second respectively. Figure 5 shows the result of simulating the vehicle motion along the longitudinal axis within the laminar flow.

| Parameters                  | Lead-acid | NiCd | NiMH | Li-ion | LiPo |
|-----------------------------|-----------|------|------|--------|------|
| Energy density, W*h/kg      | 42-55     | 70-84| 60-120| 130-170| 120-150|
| Charging time, h            | 8-16      | 1    | 2.4  | 1      | 1    |
| Element voltage, V          | 2         | 1.2  | 1.2  | 3.6    | 3.8  |
| Peak current, A             | 1.75      | 1    | 2.5-3| 10     | 30   |
| Charging temperature, C     | -20-50    | -20-65| -10-60| 0 - 45 | 0 - 45|
6. Conclusions
During the research, the small-sized high-maneuverable remotely operated vehicle with autonomous power supply for survey shipwreck was proposed. A new mechanism for vehicle control is presented. Hydrodynamic calculations of the vehicle have been carried out, the range of possible motion velocities been clarified. The choice of build-in vehicle battery is substantiated.

7. Future work
One of the perspective ways to improve the vehicle is to implement the active surface float buoy for following the vehicle on the water surface and providing the wireless connection between the vehicle and the ROV operator. This approach will significantly reduce the cable length required for operation.

The additional way to improve the quality of vehicle control and visual survey is to use a VR head-mounted display. This innovation will significantly improve the quality of visual inspection of the underwater situation by the teleoperator.

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