Improvement of Technological Equipment Drone for Water Sampling: Design and Modeling

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One of the modern problems in the field of ecology is the creation of environmentally friendly equipment for monitoring the state of various reservoirs by taking water for further laboratory analysis. Water quality monitoring is needed to record changes in water quality over time, as well as to detect contamination from storm water runoff, which may contain microorganisms, minerals, debris, and fuel residues. One of the promising ways to solve this problem is using drones to collect hydro-chemical data on the spot and take water samples from freshwater environments. This approach makes it possible to perform the aspects of biological and physical-chemical water sampling that are necessary for implementing large-scale water sampling programs and makes these programs more efficient, safe, and economically profitable. However, in modern times, the use of drones for water quality monitoring is held back by a number of important limitations, namely the low level of objective sampling and the relatively small volume of water samples.

The article proposes a fundamentally new design of the technological equipment of a drone for taking water samples, namely a new design of a bathometer – a device for taking water samples and installing them on the Cardan suspension. These structural differences ensure the orientation of the bathometer only under the influence of gravitational force, which in turn significantly increases the objectivity of water sampling. The article also provides kinematic and dynamic models of the bathometer's movement on the Cardan suspension rings. It presents the modeling results in the form of graphical and analytical dependencies of kinematic analysis, which constitutes the scientific aspect of the problem. The main motivation of the conducted research is the creation of environmentally friendly equipment in the form of an unmanned aerial vehicle, which is designed to increase the objectivity of water sampling.

Keywords*: drone platforms, quadcopter, water sampling devices, water monitoring, bathometers*

1. INTRODUCTION

In the last decade, unmanned aerial vehicles have been quite successfully used to monitor the environment, including water resources of rivers, lakes, and other bodies of water. Qualities such as the possibility of remote control and maneuverability allow this type of drone in the form of quadcopters and multicopters to survey large water areas and quickly carry out sampling of survey objects for further laboratory analysis. However, the technological equipment of these devices needs improvement and further development. This is confirmed by the fact that water sampling in accordance with national standards must be carried out at different depths of rivers and lakes. For the objectivity of taking water samples, it is not enough to use only containers that are equipped with drives for lowering and raising the so-called bathometers for taking water samples. It is necessary to ensure the measurement accuracy of the bathometer's immersion depth, as well as to exclude turbulence when taking water into the bathometer. The last negative quality is a consequence of the fact that modern designs of bathometers involve manual control of the locking elements by a person in the boat. In addition, for the objectivity of water sampling, it is necessary that the gravitational force of its weight determines the position of the bathometer and does not depend on the position of the winch cable, which is used on drones to lower the bathometer into the water.

The article proposes a fundamentally new design of a device for taking water samples, which is installed on a Cardan suspension with three degrees of freedom. This difference allows you to determine the position of the bathometer only by the gravitational force of its weight. It thus eliminates the negative influence on the position of the bathometer of the cable on which the

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Received: Decembar 2023, Accepted: February 2024
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doi: 10.5937/fme2402237P

bathometer is lowered into the reservoir. In addition, a new design of the closing covers of the bathometer with an electromagnetic drive of the closing valves is proposed, which provides the possibility of remote control of the position of the valves and also ensures a laminar mode of water flow when it is taken into the bathometer. Another advantage of the new design of the technological equipment of the drone is the increased accuracy of measuring the depth of the immersion of the bathometer into the water body. This property is ensured by installing an encoder on the drive of the cable winch for accurate calculation of the cable length that lowers the bathometer into the water.

2. PREREQUISITES AND MEANS FOR SOLVING THE PROBLEM

First, we will consider the most promising technical solutions for drone prototypes, which are designed for water sampling in various water areas. The paper [1] describes the achievements in the collection of water samples using drones that monitor water quality in various reservoirs. Here, water quality monitoring refers to the identification of specific water quality problems. The phenomenon of pollution from storm water is studied in [2], which notes that the specified water pollution can contain microorganisms, garbage, fuel, and minerals. However, both studies do not provide specific drone designs of the specified type. The results of laboratory and field experiments are presented in [3], which describes an experimental drone in the form of a quadcopter equipped with a video camera that transmits images in real time. These studies are devoted to water turbidity measurements with a portable, so-called turbodimeter at a vertical distance of 5 meters between the drone and the water surface.

However, the use of drones for water quality monitoring is currently hampered by a number of important limitations identified in the study [4], namely the low success rate of sampling and the differences between water chemistry parameters when using a drone and samples collected from a boat. In [5], a data processing workflow based on an integrated cloud solution is presented, which solves the complex tasks of monitoring water surfaces and provides data on water reflectance and water quality products, such as turbidity and a (Chl-a) concentration. Moreover, the proposed Map Water system supports common camera types and performs geometric and radiometric correction followed by conversion into water reflectance data. However, these works do not propose constructive solutions for water sampling devices. In contrast to previous studies, technical solutions for water sampling devices, which have drives for lowering and raising containers with water, are proposed in the works [6, 7]. However, in both cases, the amount of movement of the specified containers is limited, which does not allow taking water samples at greater depths, for example, in the range (10...30) m. The unique Aquatic Micro Air Vehicle drone is proposed in [8], which can move both in air and underwater space. It can solve the task of collecting data on water resources, as well as reduce the costs of monitoring the state of the seas and oceans.

In the article [9], it is noted that the American company Reign Maker has developed a nozzle for drones that simplifies the collection of water samples in rivers and reservoirs. This nozzle is a long holder for an open bottle that is lowered into the water by the drone. However, it should be noted that water sampling with a bottle is accompanied by a turbulent flow of water, which negatively affects the objectivity of water sampling. Studies [10, 11] illustrate the compilation of bathymetric maps of monitoring areas and statistical experimental plans when taking water samples, which is a methodological approach to solving the problem under consideration.

A unique Drone system (DOWSE) for water sampling from the surface of various reservoirs is proposed in [12]. The DOWSE system included sampling devices printed on a 3D printer and attached to the drone. To inspect samples in hard-to-reach or dangerous places, a drone [13] was developed, which is equipped with a sampler for thin-film microscopic solid phase extraction (TF-SPME). This solution allows the water sampler to protect the sorbent phase from external contamination. The drone flight heuristic algorithm [14] can not only quickly solve the large-scale joint optimization problem but also rationally use the total energy consumption of the water sampling equipment. Article [15] illustrates the possibility of combining the functions of a multipurpose flying drone and a floating mechanism for water quality monitoring, and the study [16] confirms the feasibility of using drones to collect hydro-chemical data from freshwater environments for biological and physicochemical water sampling. In the work [17], an orthogonal mosaic, which is created by an unmanned aerial vehicle, is proposed to estimate the amount of collected rainwater. In studies [18], it is proposed to use drones to monitor the quality of water in irrigation channels in order to improve the quality of water for agriculture. However, in these studies, there are no proposals for improving the designs of the drones themselves. A promising direction in solving the problem of quality monitoring of water resources can be the use of anthropomorphic designs of robots, which are proposed in studies [19, 20, 21], but this is possible if these robots are equipped with technological devices for analyzing water samples. Studies [22, 23] confirm the need to improve equipment for monitoring and assessing water resources despite the existing examples of successful use of drones. The quadcopter robot [24], as well as the drone [25], which was created for environmental monitoring in natural disasters, can be adapted for monitoring water resources. However, these drones require an addition in the form of special technological equipment for water intake.

Based on the above research analysis, it can be stated that the task of increasing the objectivity of water sampling for monitoring the state of reservoirs remains relevant.

3. FORMULATION OF THE PROBLEM

Until now, there is no technological equipment for water sampling drones that ensures the objectivity of water sampling, namely, determining the position of the bathometer by the gravitational force of its weight while simultaneously increasing the accuracy of measurement of the immersion of the bathometer in the reservoir. This problem can be solved by placing the bathometer on the Cardan suspension and studying the kinematics and dynamics of its movement, which is proposed below.

4. SOLUTION OF THE PROBLEM UNDER CONSIDERATION

The above analysis of publications indicates a lack of research on the technological equipment of drones. Therefore, in this article, the engineering object of engineering novelty is a fundamentally new design of technological equipment [26] of a drone for taking water samples, namely a new design of a bathometer installed on a Cardan suspension. The scientific aspect of solving the problem consists of kinematic and dynamic models of the movement of the bathometer on the rings of the Cardan suspension, and the results of modeling are given in the form of analytical dependencies of kinematic analysis.

4.1 Drone construction

Figure 1 shows the first version of the drone, created by the authors and tested at the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" at the Department of Information Systems and Technologies. This drone was successfully demonstrated at Web Summit, Lisbon (November 13-16, 2023). However, installing the bathometer of this drone directly on its body did not allow for taking water samples at various depths of reservoirs. Therefore, as a result of further research, new technological equipment was created for the drone by installing a bathometer on the Cardan gimbal, as shown in Figure 2.

Figure 1. Prototype drone for water sampling

A winch is installed on the lower part of the quadcopter, which has a drive in the form of an electric motor with an encoder for calculating the number of revolutions of the winch, which means the depth of the bathometer for water sampling. In order for the orientation of the bathometer to be determined by the gravitational load from the force of its weight, the bathometer is installed on a Cardan suspension, which is fixed on the winch cable.

Figure 3 shows the longitudinal section of the bathometer, which, according to the new solution, consists of two coaxial hermetic cylinders, namely the outer and inner cylinders, which are closed with hermetic covers. The holes for water intake in the lids are opened and closed by cone valves with an electromagnetic drive in the form of solenoids. The inner sealed cylinder also houses the power supply and remote control units.

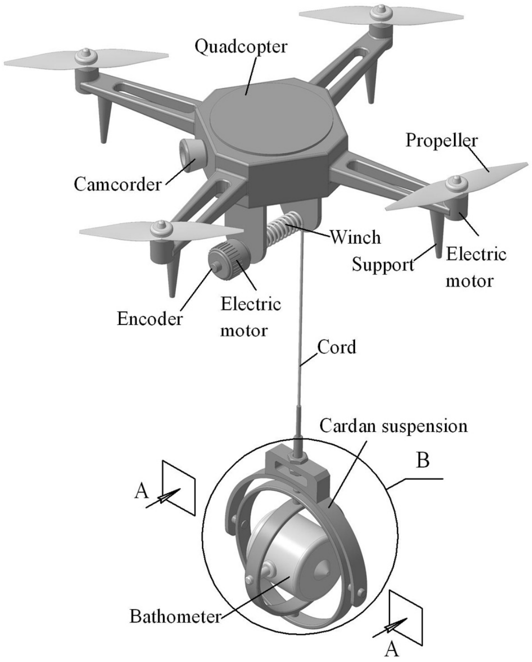


Figure 2. Improved drone design for water sampling

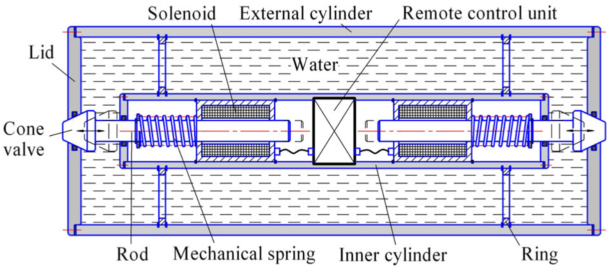


Figure 3. Longitudinal section of the bathometer (See also A–A Figure 2)

The drone works as follows. According to the coordinates set by the operator, the drone flies to the water sampling point and hovers over the surface of the reservoir at a certain height, H. After that, the winch drum (Figure 2) unwinds the cable under the action of the engine. One revolution of the drum of the cable winch covers a distance equal to the length of the coil $l=\sqrt{s^2+(\pi d)^2}$ (where: s is the pitch of winding the cable coil; d is the diameter along the axis of the cable coil).

For each revolution of the winch drum, there is a certain number of encoder pulses depending on its bit rate, which allows you to set the depth of the bathometer in the water with high accuracy because the depth h of the bathometer will be equal to: $h=n\sqrt{s^2+(\pi d)^2}+R$ (where: n is the number of revolutions of the winch drum, R is the distance from the axis of the bathometer to the point of attachment of the gimbal to the cable). The indoor length L of the unwound cable will equal $L = H + h = H + n\sqrt{s^2+(\pi d)^2} + R$ (H is the drone's height above the water surface). Since the bathometer is installed on the rings of the gimbal, which rotate by Euler angles, its position will be determined only by the action of gravity load from the weight of the bathometer and will not depend on such negative phenomena as twisting of the cable or arbitrary tilting of the drone due to the wind or other influences. After the bathometer is immersed to a given depth, the operator sends a signal to the solenoids (See Figure 3), which retract the rods and open the conical valves, i.e., holes in the end caps of the outer cylinder. During the regulated time, the bathometer is filled with water to a volume determined by the volume of the water sample. Next, the electromagnetic drives are turned off, and under the action of the springs, the valves close the holes in the bathometer covers. After that, the reverse of the motor of the winch drum is turned on, and after the cable is completely wound on the gimbal drum, the suspension is pressed against the lower part of the drone, which the operator returns to the base to deliver another water sample. Then, the cycle repeats.

5. SIMULATION OF THE FUNCTIONING

To determine the orientation of the bathometer, which is installed on the Cardan suspension, it is necessary to perform a kinematic and dynamic analysis of the move–ment of the Cardan suspension while obtaining analy–tical dependencies of the rotation angles of the thrust generator suspension and its speeds. We will remind you that the gimbal itself, as shown in Figure 2, is installed on the winch cable in such a way that the centers of rotation of its rings coincide with the center of mass of the bathometer.

5.1 Kinematic analysis of the movement of the Cardan suspension

The Cardan suspension includes a fixed half-ring (Fig. 4) and two rotating rings – the outer and inner rings, which are installed on their respective axes. A batho–meter for water sampling is attached to the inner ring.

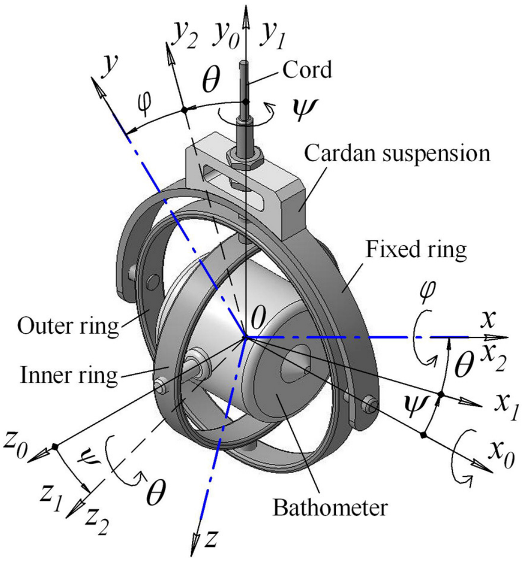


Figure 4. Cardan suspension with three degrees of freedom in the form of rotation angles *ψ*, *θ*, and *φ* (See also element "B" Figure 2)

Let's choose the point O (the fixed point of the gimbal) as the beginning of the fixed coordinate system $Ox_0y_0z_0$. Let's also choose at point O the beginning of the moving coordinate system $Oxyz$, which is perma–nently attached to the body of the bathometer and moves with it. The bathometer has three degrees of freedom, and to describe its movement, it is convenient to use the Euler-Krylov angles (ψ, θ, φ), which make it possible to obtain the required position of $Oxyz$, which is permanently attached to the bathometer, by making three turns to the specified angles. The first turn by the angle ψ, which is called the precession angle, is made around the Oy_0 axis. At the same time, we get the coordinate system $Ox_1y_1z_1$ attached to the body, which characterizes the position of the bathometer after the first turn. The direction cosines of the received axes relative to the previous coordinate system $Ox_oy_oz_o$ can be written in the form of matrix B_1, the columns of which are the direction cosines of the axes $Ox_1y_1z_1$, respectively

$$B_1 = \begin{pmatrix} cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -sin\psi & 0 & cos\psi \end{pmatrix}. \tag{1}$$

The second rotation to the angle θ, which is called the nutation angle, is carried out around the Oz_1 axis, and we get a coordinate system $Ox_2y_2z_2$ rigidly attached to the body of the bathometer. The direction cosines of the received axes relative to the previous coordinate system Ox_1,y_1,z_1 can be written in the form of matrix B_2, the columns of which are the direction cosines of the axes $Ox_2y_2z_2$, respectively, we get the matrix (2). The third turn, by the angle φ, the angle of the bathometer's own rotation, is performed around the axis Ox_2.

$$B_2 = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

As a result, we get the final position of the bathometer, which is characterized by the $Oxyz$ coor–dinate system $Ox_2y_2z_2$. The direction cosines of the received axes relative to the previous coordinate system can be written in the form of the B_3 matrix, the columns of which are the direction cosines of the Ox, Oy, Oz axes, respectively

$$B_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix}. \tag{3}$$

After multiplying the matrices B_1, B_2, and B_3, we obtain the matrix B, the columns of which are the direction cosines of the Ox, Oy, Oz axes relative to the fixed coordinate system $Ox_oy_oz_o$:

$$B = B_1B_2B_3 = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \tag{4}$$

where indicated:

$$a_{11}=\cos\theta\cos\psi;\;\; a_{13}=\sin\psi\cos\varphi+\sin\varphi\cos\psi\sin\theta;$$
$$a_{21}=\sin\theta;\;\; a_{22}=\cos\theta\cos\varphi;$$
$$a_{23}=-\sin\varphi\cos\theta;\;\; a_{31}=-\sin\psi\cos\theta;$$
$$a_{32}=\sin\varphi\cos\psi+\sin\psi\cos\varphi\sin\theta\,;$$
$$a_{33}=\cos\psi\cos\varphi-\sin\varphi\sin\psi\sin\theta\,.$$

Each rotation angle ψ, θ, φ corresponds to an angular velocity vector.

$$\vec{\omega}_1=\vec{j}_o\frac{d\psi}{dt}=\dot{\psi}\vec{j}_o;\;\; \vec{\omega}_2=\vec{k}_1\frac{d\theta}{dt}=\dot{\theta}\vec{k}_1;$$
$$\vec{\omega}_3=\vec{i}\,\frac{d\varphi}{dt}=\dot{\varphi}\vec{i}, \tag{5}$$

where $\vec{j}_o,\vec{k}_1,\vec{i}$ are the unit vectors directed along the coordinate axes Oy_o, Oz_1, Ox respectively. Then the total angular velocity is equal to the geometric sum of the specified angular velocity vectors

$$\vec{\omega}=\vec{\omega}_1+\vec{\omega}_2+\vec{\omega}_3=\dot{\psi}\vec{j}_o+\dot{\theta}\vec{k}_1+\dot{\varphi}\vec{i}\;. \tag{6}$$

Let us express the unit vectors $\vec{j}_o$, $\vec{k}_1$, in terms of the unit vectors of the moving coordinate system $\vec{i}$, $\vec{j}$, $\vec{k}$

$$\vec{k}_1=(\vec{k}\cos\varphi+\vec{j}\sin\varphi);$$
$$\vec{j}_o=\vec{i}\sin\theta+\cos\theta(\vec{j}\cos\varphi-\vec{k}\sin\varphi). \tag{7}$$

Substituting (7) into expression (6), we find the projections of the angular velocity on the axis of the moving coordinate system

$$\omega_x=\dot{\phi}+\dot{\psi}\sin\theta;\;\; \omega_y=\dot{\theta}\sin\varphi+\dot{\psi}\cos\theta\cos\phi;$$
$$\omega_z=\dot{\theta}\cos\varphi-\dot{\psi}\cos\theta\sin\phi. \tag{8}$$

Similarly, if you express the unit vectors $\vec{k}_1,\vec{i}$, through the unit vectors of the fixed coordinate system $\vec{i}_0$, $\vec{j}_0$, $\vec{k}_0$ $\vec{k}_1=(\vec{k}_o\cos\theta+\vec{i}_o\sin\theta)$; $\vec{i}=\vec{j}_o\sin\theta+\cos\theta$ $(\vec{i}_o\cos\psi+\vec{k}_o\sin\psi)$ then you can find the projections of the angular velocity on the axis of the fixed coordinate system

$$\omega_{x_o}=\dot{\theta}\sin\psi+\dot{\varphi}\cos\theta\cos\psi;\;\; \omega_{y_o}=\dot{\psi}+\dot{\varphi}\sin\theta;$$
$$\omega_{z_o}=\dot{\theta}\cos\psi-\dot{\varphi}\cos\theta\sin\psi. \tag{9}$$

Next, we find the angular acceleration vector of the bathometer body

$$\vec{\varepsilon}=\frac{d\vec{\omega}}{dt}=\varepsilon_x\vec{i}+\varepsilon_y\vec{j}+\varepsilon_z\vec{k}\;.$$

Then, we calculate the projections of the angular acceleration vector on the axis of the moving coordinate system using the formulas:

$$\varepsilon_x=\frac{d\omega_x}{dt}=\ddot{\varphi}+\ddot{\psi}\sin\theta+\dot{\psi}\dot{\theta}\cos\theta;$$
$$\varepsilon_y=\frac{d\omega_y}{dt}=\ddot{\theta}\sin\varphi+\ddot{\psi}\cos\theta\cos\varphi+$$
$$+\dot{\theta}\dot{\varphi}\cos\varphi-\dot{\psi}\dot{\theta}s\sin\theta\cos\varphi-\dot{\psi}\dot{\varphi}\cos\theta\sin\varphi; \tag{10}$$
$$\varepsilon_z=\frac{d\omega_z}{dt}=\ddot{\theta}\cos\varphi-\ddot{\psi}\cos\theta\sin\varphi-$$
$$-\dot{\theta}\dot{\varphi}\sin\varphi+\dot{\psi}\dot{\theta}\sin\theta\sin\varphi-\dot{\psi}\dot{\varphi}\cos\theta\cos\varphi.$$

Thus, the position of the bathometer for water sampling is completely determined in the space of arbitrary orientation.

5.2 Dynamic model of bathometer movement

To study the dynamics of the movement of a given mechanical system, that is, a bathometer on a gimbal, we will use the Lagrange equations of the 2nd kind, which have a standard form

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}=Q_i;\quad i=1,2,\ldots n\,, \tag{11}$$

where q_i are the generalized coordinates; $\dot{q}_i$ – generalized speeds; Q_i – the generalized force corresponding to the generalized coordinate q_i; $T=T(q_i,\dot{q}_i,t)$ is an expression of the kinetic energy of a mechanical system. Since in our case $q_1=\psi$; $q_2=\theta$; $q_3=\varphi$, the system of equations (11) will have the form

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\psi}}\right)-\frac{\partial T}{\partial \psi}=Q_\psi;$$
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\theta}}\right)-\frac{\partial T}{\partial \theta}=Q_\theta; \tag{12}$$
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}}\right)-\frac{\partial T}{\partial \varphi}=Q_\varphi.$$

The given mechanical system consists of three rigid bodies. Body 1 is an inner circular ring with a diameter of d_b and a mass of m_b (See also Figure 4). This body has two degrees of freedom, and the angles completely determine its position ψ and θ and the instantaneous angular velocity vector is calculated by the formula

$$\vec{\omega}=\vec{\omega}_1+\vec{\omega}_2=\dot{\psi}\vec{j}_o+\dot{\theta}\vec{k}_1\,. \tag{13}$$

The projections of this angular velocity on the axis Ox_2,y_2,z_2, which are invariably attached to the ring mentioned above of the Cardan suspension, are equal to

$$\omega_{x2}=\dot{\psi}\sin\theta;\quad \omega_{y2}=\dot{\psi}\cos\theta;\quad \omega_{z2}=\dot{\theta}\,. \tag{14}$$

Since the axes of the coordinate system Ox_2,y_2,z_2 are the main axes of inertia for the ring, the expression for calculating the kinetic energy of this ring will have the form

$$T_1=\frac{1}{2}((\omega_{x2})^2I_{x2}+(\omega_{y2})^2I_{y2}+(\omega_{z2})^2I_{z2})\,. \tag{15}$$

Let's calculate the axial moments of inertia of the ring:

$$I_{y2}=\iint((x_2)^2+(z_2)^2)dm=\left(\frac{d_b}{2}\right)^2\iint dm=\frac{m_b d_b^2}{4};$$
$$I_{x2}=\iint((y_2)^2+(z_2)^2)dm=\frac{1}{2}I_{y2}=\frac{m_b d_b^2}{8}; \tag{16}$$
$$I_{z2}=\iint((y_2)^2+(x_2)^2)dm=\frac{1}{2}I_{y2}=\frac{m_b d_b^2}{8}.$$

(for the ring, the coordinate is y_2=0).

Substitute expressions (14) and (16) into formula (15) and get the expression for kinetic energy

$$T_1 = \frac{m_b d_b^2}{16}((\dot{\psi})^2(1+\cos^2\theta)+(\dot{\theta})^2)\,. \qquad (17)$$

Body 2, that is, the bathometer, has three degrees of freedom, and its position in space is completely determined by the angles ψ, θ, φ, and the projections of the angular velocity vector are described by formulas (8). Then, for a bathometer, the expression of kinetic energy can be written as for a body in spherical motion

$$T_2 = \frac{1}{2}(\omega_x^2 I_x + \omega_y^2 I_y + \omega_z^2 I_z - \\ -2\omega_x\omega_y I_{xy} - 2\omega_x\omega_z I_{xz} - 2\omega_y\omega_z I_{yz}), \qquad (18)$$

where I_x, I_y, I_z are the axial moments of inertia of the bathometer relative to the axes of the reference system attached to the bathometer I_{xy}, I_{xz}, I_{yz}– centripetal moments of inertia of the bathometer?

Body 3 is the outer ring of the Cardan suspension (See Figure 4), the diameter of which is d_3 and the mass is m_3. This ring has one degree of freedom; it rotates around a fixed axis, and its position completely determines the angle ψ. The kinetic energy of this ring is equal to

$$T_3 = \frac{1}{2}(\dot{\psi})^2 I_3 = \frac{m_3 d_3^2}{16}(\dot{\psi})^2\,. \qquad (19)$$

Therefore, the total kinetic energy of the bathometer - gimbal system is equal to the sum of the found kinetic energies of the individual bodies of this system:

$$T = \frac{m_b d_b^2}{16}((\dot{\psi})^2(1+\cos^2\theta)+(\dot{\theta})^2) + \frac{m_3 d_3^2}{16}(\dot{\psi})^2 + \\ + \frac{1}{2}(\omega_x^2 I_x + \omega_y^2 I_y + \omega_z^2 I_z - 2\omega_x\omega_y I_{xy} - \\ -2\omega_x\omega_z I_{xz} - 2\omega_y\omega_z I_{yz}). \qquad (20)$$

Next, suppose we find the partial derivatives included in equation (12) and the projection of the weight of the bathometer on the axis of the fixed coordinate system, as well as give the rotation angles of the gimbal rings a possible movement δ_ψ with the calculation of elementary work according to the classical method (which is known). In that case, the problem is reduced to the solution of the system of differential equations:

$$\begin{cases} \dfrac{dv_1}{dt} = c_{11}D_1 + c_{12}D_2 + c_{13}D_3; \\ \dfrac{dv_2}{dt} = c_{21}D_1 + c_{22}D_2 + c_{23}D_3; \\ \dfrac{dv_3}{dt} = c_{31}D_1 + c_{32}D_2 + c_{33}D_3; \end{cases} \begin{cases} \dfrac{d\psi}{dt} = v_1; \\ \dfrac{d\theta}{dt} = v_2; \\ \dfrac{d\varphi}{dt} = v_3. \end{cases} \qquad (21)$$

It is marked here:

$$D_1 = Q_\psi - F_1 + \frac{\partial T}{\partial \psi};\; D_2 = Q_\theta - F_2 + \frac{\partial T}{\partial \theta};$$

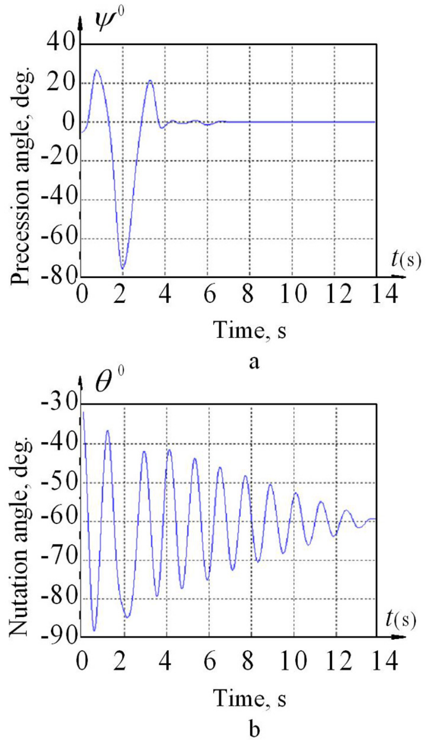
$$D_3 = Q_\varphi - F_3 + \frac{\partial T}{\partial \varphi};\; \dot{\psi} = v_1;\; \dot{\theta} = v_2;\; \dot{\varphi} = v_3;$$

$F_{1,2,3}$ – expression of fractions of derivatives by angles of rotation of suspension rings taking into account moments of forces Q_ψ, Q_θ, Q_φ.

The system of differential equations (21) is solved by numerical methods, in particular, by the Runge-Kutt method of the fourth order of accuracy at given initial values of the Euler-Krylov angles (See Figure 4) and their time derivatives. Based on this solution, the graphs of changes in time of the angles ψ, θ rotation of the gimbal rings, which are provided below, were constructed.

6. ANALYSIS OF SIMULATION RESULTS

The results of modeling in Figure 5 (a, b) of the rotation process to the angles ψ, θ of the rings of the Cardan suspension show the presence of oscillations due to the small moment of rolling friction forces in the supports of the rings. Moreover, dampers are installed in the supports of the ring, which rotates through the first precession angle ψ. Therefore, the damping period of the ring oscillations does not exceed 4 seconds, as seen in Figure 5 (a). There are no dampers in the supports of the ring, which rotates through the second nutation angle θ, so the damping period of the ring oscillations is much longer and reaches values of up to 14 seconds (Figure 5, b). This effect clearly indicates the need to use dampers to dampen vibrations.



a

b

Figure 5. Changes in the rotation angles *ψ, θ* of the gimbal rings with a bathometer (a – with dampers; b – without dampers)

Hydraulic dampers, which convert vibration energy into liquid friction forces, are mass-produced by the industry as components and can be used to reduce the amplitude of vibration of suspension rings. Figure 6 shows that the angle γ between the vertical and the radius vector: the center of the suspension → the center of mass of the bathometer gradually decreases, and the bathometer takes a position along the line of gravity load, which had to be proved by installing the bathometer on the gimbal.

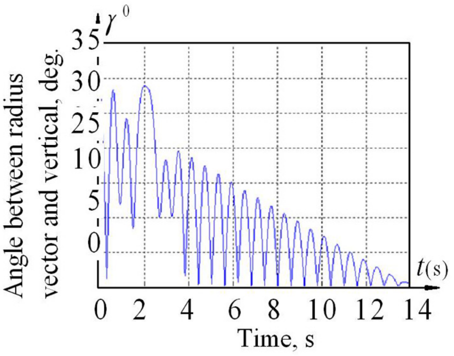


Figure 6. Changes in the rotation angles γ of the gimbal ring with a bathometer

Figure 7 shows the graphs of changes in angular velocities of the rings (blue line – angular velocity $\dot{\psi} = \frac{d\psi}{dt}$, with dampers; red line – angular velocity $\dot{\theta} = \frac{d\theta}{dt}$, in the absence of dampers), which confirm the feasibility of using dampers to dampen vibrations.

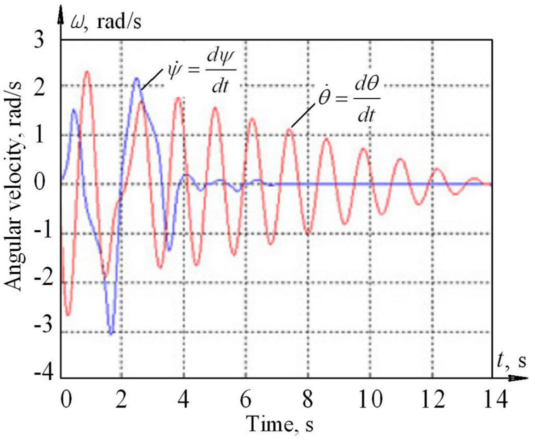


Figure 7. Change in time of angular velocities of the Cardan suspension rings with a barometer ($\dot{\psi} = d\psi/dt$ with dampers; $\dot{\theta} = d\theta/dt$ without dampers)

Reduction of oscillations can also be achieved by increasing the coefficient of friction and replacing the rolling supports with sliding supports, which will result in an increase in the moment of rolling friction forces in the ring supports. In addition, it is possible to operate the bathometer on the rings of the Cardan suspension with two degrees of freedom; that is, it can be assumed that there is no actual rotation of the bathometer, for example, in the absence of current in a body of water such as a lake. In this case, we should put in the above formulas $\varphi = 0$; $\dot{\varphi} = 0$, and then they are greatly simplified. That is, with 2 degrees of freedom, the elements of matrix B (4) will have the form:

$$\begin{aligned} &a_{11} = \cos\theta\cos\psi; \quad a_{12} = -\cos\psi\sin\theta; \quad a_{13} = \sin\psi; \\ &a_{21} = \sin\theta; \quad a_{22} = \cos\theta; \quad a_{23} = 0; \\ &a_{31} = -\sin\psi cos\theta; \quad a_{32} = \sin\psi\sin\theta; \quad a_{33} = \cos\psi. \end{aligned} \tag{22}$$

Then, unlike statement (21), the problem is reduced to the solution of a system of four (not six) linear differential equations

$$\begin{cases} \frac{dv_1}{dt} = c_{11}D_1 + c_{12}D_2 \\ \frac{dv_2}{dt} = c_{21}D_1 + c_{22}D_2 \\ \frac{d\psi}{dt} = v_1 \\ \frac{d\theta}{dt} = v_2 \end{cases} \tag{23}$$

where indicated:

$$D_1 = Q_{\psi} - F_1 + \frac{\partial T}{\partial \psi}; \; D_2 = Q_{\theta} - F_2 + \frac{\partial T}{\partial \theta}.$$

Similarly to case (21), the differential equations (23) system is solved by numerical methods, particularly by the Runge-Kutt method of the fourth order of accuracy at given initial values of the Euler-Krylov angles.

7. DISCUSSION

In contrast to technical solutions [6, 7], in order to ensure the objectivity of water sampling, this work proposes to install a suitable device, namely a bathometer, on a gimbal. This way of placing the bathometer makes it possible to avoid the influence of twisting the drone winch cable on its position. In addition, in contrast to the project [9], the presence of a winch with a cable on which a bathometer is installed makes it possible to take water samples at different depths of reservoirs and to equip the winch drive with an encoder, i.e., a device for converting the values of the rotation angles of the winch drum into electrical signals, significantly increases the accuracy of measurement of the depth of the bathometer in the reservoir. According to the recommendations [22, 23], the equipment for monitoring the quality of water resources was improved.

If there is a rigid connection between the drone and the bathometer, as is the case in the considered known technical solutions, additional external disturbances may occur, for example, loads from wind or water flow. Therefore, to reduce such disturbances, this article proposes connecting the bathometer to the drone cable by means of a gimbal joint suspension, which has three degrees of freedom. As a result of the proposed solution, the bathometer is only under the influence of gravity from its own weight, which contributes to the objectivity of water sampling.

The simulation results showed the presence of bathometer oscillations with a certain damping period, which can be significantly reduced by using hydraulic dampers that convert the energy of oscillations into fluid friction forces and can be used to reduce the amplitude of oscillations of suspension rings. Moreover, the graphs in Figure 6 prove that the angle between the vertical and the radius vector of the center of mass of the bathometer suspension gradually decreases, and the bathometer takes a position along the line of gravity load, which was to be proved by installing the bathometer on the Cardan suspension.

8. CONCLUSION

In this article, the authors proposed a fundamentally new design of the technological equipment of a drone for taking water samples for the purpose of further laboratory analysis. Installing a device for taking water samples on the gimbal suspension allows the orientation of the position of the bathometer under the influence of the gravitational load of its weight, i.e., the position of the bathometer does not depend on such a negative phenomenon as possible twisting of the drone's winch cable.

Equipping the bathometer with valves with an electromagnetic drive allows not only remote control of the opening and closing of the water intake holes but also to avoid the turbulence of the flow of water entering the bathometer and bringing the flow of water taken into the bathometer closer to a state close to laminar flow.

In the end, the application of the developed technological equipment and recommendations provided as a result of modeling the operation of the bathometer provides an opportunity to significantly increase the objectivity of water sampling in various reservoirs with the help of drones, which contributes to ensuring the environmental cleanliness of equipment for monitoring the quality of water resources.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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УНАПРЕЂЕЊЕ ТЕХНОЛОШКЕ ОПРЕМЕ ДРОНА ЗА УЗОРКОВАЊЕ ВОДЕ: ПРОЈЕКТОВАЊЕ И МОДЕЛОВАЊЕ

М. Полишчук, О. Ролик

Један од савремених проблема у области екологије је стварање еколошки прихватљиве опреме за праћење стања различитих резервоара узимањем воде за даљу лабораторијску анализу. Праћење квалитета воде је потребно да би се забележиле промене у квалитету воде током времена, као и да би се открила контаминација услед отицања атмосферских вода, које могу садржати микроорганизме, минерале, остатке и остатке горива. Један од обећавајућих начина за решавање овог проблема је коришћење дронова за прикупљање хидрохемијских података на лицу места и узимање узорака воде из слатководних средина. Овакав приступ омогућава извођење аспеката биолошког и физичко-хемијског узорковања воде који су неопходни за реализацију великих програма узорковања воде и чини ове програме ефикаснијим, сигурнијим и економски исплативијим. Међутим, у модерним временима, коришћење дронова за праћење квалитета воде спутава низ важних ограничења, односно низак ниво објективног узорковања и релативно мала запремина узорака воде.

У чланку се предлаже принципијелно нови дизајн технолошке опреме дрона за узимање узорака воде, односно нови дизајн батометра – уређаја за узимање узорака воде и њихово постављање на кардан суспензију. Ове структурне разлике обезбеђују оријентацију батометра само под утицајем гравитационе силе, што заузврат значајно повећава објективност узорковања воде. У чланку су дати и кинематичке и динамичке моделе кретања батометра на карданским прстеновима. Резултате моделовања представља у виду графичких и аналитичких зависности кинематичке анализе, што чини научни аспект проблема. Основна мотивација спроведеног истраживања је стварање еколошки прихватљиве опреме у виду беспилотне летелице, која је пројектована да повећа објективност узорковања воде.