Simulation and control of biomimetic underwater vehicle with undulating propulsion

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Abstract: - In recent times, we may notice some new designs of underwater vehicles, which imitate living underwater organisms, e.g. a fish. These vehicles are called biomimetic. They are driven by undulating propulsion, imitating wavy motion of fins. In the paper, problem of mathematical modeling of underwater vehicle with undulating propulsion is undertaken. This model can be used, e.g. for initial tuning of control system of new underwater vehicles.

Key-Words: - mathematical model, underwater vehicle, undulating propulsion

1 Introduction

In the recent years, a dynamical development of underwater robotics has been noticed. One of the latest innovative constructions in this field are autonomous biomimetic underwater vehicles (BUVs) [1][4]. They imitate underwater living organisms, e.g. fishes, marine mammals, etc. They can imitate both the construction and kinematics of motion. BUVs are driven by undulating propulsion imitating real fins, e.g. of a fish – Fig. 1.

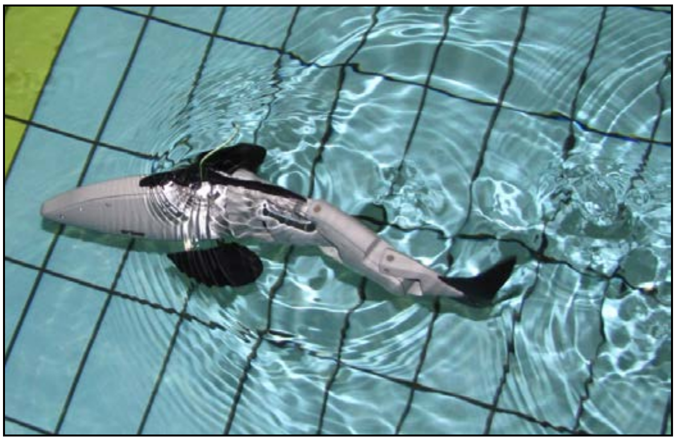

Fig. 1. BUV CyberFish ver. 3 in a swimming pool

Such vehicles have the following features crucial from the point of a view of military applications: (1) their propulsion is more energy efficient and (2) more silent [3] than classical propulsion based on screw propellers (based on initial research carried out in Polish Naval Academy), (3) they are very difficult to differentiate from the real inhabitants of underwater environment (larger secrecy and potential range of operation – Fig. 1).

Fig. 2. BUV CyberFish ver. 5 in silicon coating [5]

The paper includes results of the research on BUVs carried out within two projects. The projects were preceded by the works on technology demonstrators of BUVs called CyberFishes (Fig. 1 and Fig. 2). The first of mentioned above projects is carried out in Poland by the consortium consisted of the following scientific and industrial partners: Polish Naval Academy PNA – the leader, Cracow University of Technology CUT, Industrial Institute of Automatics and Measurement PIAP and Forkos Company [7]. The main objective of the proposed project is to build heterogeneous torpedo-shaped BUVs with undulating propulsion for selected scenarios of underwater ISR. The second project was started in connection with Unmanned Maritime Systems Programme in European Defense Agency [8]. The project is carried out by the consortium consisted of the mentioned above Polish partners and also Bundeswehr Technical Center for Ships and Naval Weapons WTD 71 in Eckernförde, Germany. The main objective of the project is to build BUVs similar to real inhabitants of underwater environment, prepared for their swarm operation.

As it was showed above, the research on BUVs are consistent and are developing in the direction of autonomous vehicles cooperating in a swarm. This development requires many different research focused on control algorithms, starting with low-level control and providing to semi– or fully–autonomous behaviors at the end of the research. Low-level control system is understood as a set of controllers of motion parameters of BUV, e.g. of course, depth, etc. Therefore, this paper undertakes the problem of selection of controllers for the specific new type of underwater control object, i.e. the biomimetic underwater vehicle. The research described in this paper were preceded by the research on modelling motion of BUV inter alia for selecting proper behavior for the course change. In the vehicles with undulating propulsion, the change of course can be achieved in different way by using tail and/or side fins. The results of the research are described in detail in [10].

In the works [1][4], the biomimetic designs based on the study of undulating fin propulsion mechanisms are considered. Moreover, extensive study of biomimetic locomotion with mathematical description is described.

In this paper, mathematical model of biomimetic underwater vehicle is described based on classical Fossen model of motion of marine vehicle [2] with some improvements taking into account the new undulating propulsion system. This model is described in details in the next section. Then, in the third section the measurement of thrust generated by the artificial fin is presented. In the next fourth section, BUV controllers are presented. In the fifth section, the results of operation of BUV controllers are presented in the form of control along desired trajectory. In the last section, the conclusions are formulated. At the end, the acknowledgment and references are inserted.

2 Mathematical Model of BUM Motion

Usually, an underwater vehicle is considered as a rigid body with the following features:

- it has three planes of symmetry,
- it moves in six degrees of freedom,
- it moves at a low speed in a viscous fluid.

Motion of the vehicle is described by means of two reference systems: (1) the movable coordinate system associated with the vehicle $x_oy_oz_o$ and (2) the immovable coordinate system associated with the Earth xyz.

The origin of the movable coordinate system O responds to the center of gravity of the vehicle, while its axes are defined as: (1) x_o is a longitudinal axis directed from the stern to the bow, (2) y_o is a transverse axis directed to the starboard, and (3) z_o is a perpendicular axis directed from the top to the bottom. Changes of the position of the movable coordinate system $x_oy_oz_o$ are described with respect to coordinate system xyz associated with the Earth. Due to the fact that the vehicle moves at a relatively low speed, acceleration of points on the Earth's surface is ignored and the coordinate system xyz is considered as a stationary. Therefore, the centrifugal and centripetal forces and moments of force caused by the spin of the Earth may be neglected.

Taking into account mentioned above assumptions, to simulate motion of BUV, a nonlinear model of underwater vehicle in 6 degrees of freedom [2] was used. The motion of the vehicle is described by 6 differential equations, very often presented in the compact matrix form:

$$\mathrm{M}\dot{\nu} + \mathrm{D}(\nu)\nu + \mathrm{g}(\eta) = \tau \qquad (1)$$

here:

ν – vector of linear and angular velocities in the movable system,

η – vector of vehicle position coordinates and its Euler angles in the immovable system,

M – matrix of inertia (the sum of the matrices of the rigid body and the accompanying masses),

$D(\nu)$ – hydrodynamic damping matrix,

$g(\eta)$ – vector of restoring forces and moments of forces of (gravity and buoyancy),

τ – vector of control signals (the sum of vector of forces and moments of force generated by propulsion system τp and by environmental disturbances τd).

The left side of the equation (1) includes forces and moments of force caused by the following physical phenomenas: an inertia of the body of the vehicle and inertia of the accompanying masses of a viscous liquid, a hydrodynamic dumping of water environment, a balance of a gravity and a buoyancy. While the right side of the equation (1) represents the vector of forces and moments of force acting on the vehicle generated by a propulsion system and additional environmental disturbances (under surface of water especially a sea current). The parameters of the matrices included in the left side of equation (1) were calculated based on the dependencies included in [2]. The problem undertaken in this paper is to calculate the vector of forces and moments of force τ_p generated by the new type of propulsion system, which is an undulating propulsion imitating operation of real fish fins:

$$\tau_p = [X, Y, Z, K, M, N] \tag{2}$$

here:

X, Y, Z – the forces acting respectively in longitudinal, transverse and vertical axes of symmetry,

K, M, N – the moments of force acting relative to respectively longitudinal, transverse and vertical axes of symmetry

The calculation of the vector of force and moments of force generated by propulsion should take into consideration specific configuration of the considered undulating propulsion. In the Fig. 3, the 3D design of BUV with specific undulating propulsion is illustrated. In this case, the propulsion system consists of pivoted module of tail ended with movable tail fin and two independently driven side fins.

The thrust generated by the each fin should be referenced to the origin of gravity O (Fig. 3) using simple dependencies on the vector transformation:

$$X = X_t + X_l + X_r - X_d \tag{3}$$

$$Y = Y_t \tag{4}$$

$$Z = Z_l + Z_r \tag{5}$$

$$K = 0 \tag{6}$$

$$M = M_l + M_r \tag{7}$$

$$N = N_t + N_l - N_r - N_d \tag{8}$$

here:

lower indexes t, l and r refer respectively to tail, left side and right side fins operation,

lower index d refers to damping caused by left or right side fin working as stern (the surface of fin set perpendicularly to the longitudinal axis of symmetry).

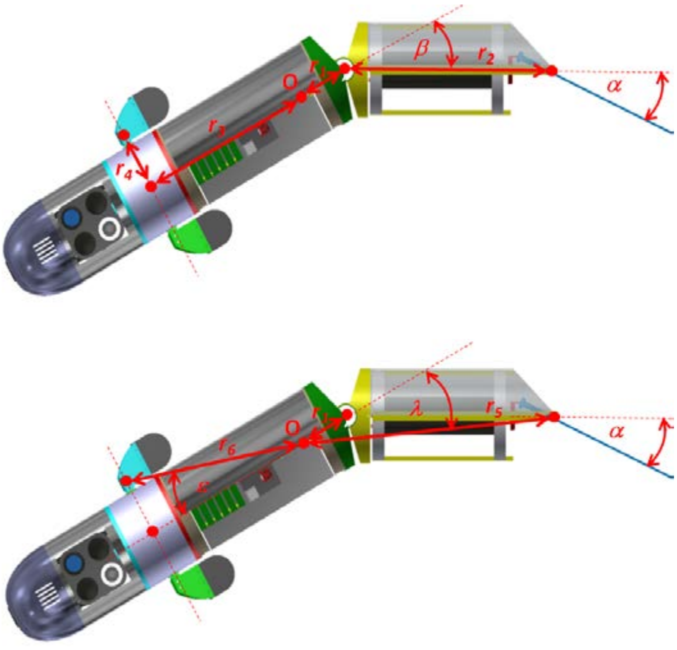

Fig. 3. BUV No. 2 designed within Polish project (top view) [7]

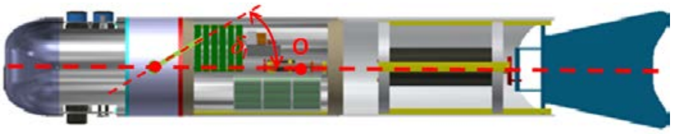

Fig. 4. BUV No. 2 designed within Polish project (side view) [7]

The vector components (e.g. X_t, Y_t, N_t) are calculated taking into consideration localization of fins relative to the gravity origin using the following formulas:

$$X_t = \cos\beta \cdot T_t \quad (9)$$

$$Y_t = \sin\beta \cdot T_t \quad (10)$$

$$N_t = -\cos\lambda \cdot r_5 \cdot Y_t \quad (11)$$

$$X_l = \cos\delta_l \cdot T_l \quad (12)$$

$$Z_l = \sin\delta_l \cdot T_l \quad (13)$$

$$N_l = r_4 \cdot X_l \quad (14)$$

$$M_l = r_3 \cdot Z_l \quad (15)$$

$$N_d = \cos(90-\varepsilon) \cdot r_6 \cdot X_d \quad (16)$$

here:

Tt, Tl, Tr – the thrusts generated respectively by tail, left and right side fins,

β, λ, δl, ε – the angles illustrated in the Fig. 3 and 4,

r1 – the distance between the gravity origin and the center of rotation of the tail module,

r_2 – the distance between the center of rotation of the tail module and the center of rotation of the tail fin,

r_3 – the distance between the gravity origin and the center of rotation of the side fins,

r_4 – the distance between the center of rotation of the side fins and center of rotation of the left of right fin (it is a distance between the center of rotation of each side fin and the longitudinal axis of symmetry),

r_5 – the distance between the gravity origin and the center of rotation of the tail fin,

r_6 – the distance between the gravity origin and the center of rotation of the left or right side fin.

The vector components for right side fin X_r, Y_r, N_r, M_r can be calculated using formulas for left side fin (12-15) inserting instead of the angle δ_l proper angle for right side fin δ_r. The hydrodynamic dumping generated by left or right side fin X_d (set in position perpendicular to the longitudinal axis of symmetry) can be determinated using dependencies included in [2].

Each fin generates a thrust with the value changing in time depending on the control parameters of the fin, especially amplitude and frequency of the fin oscillation [5]. The thrust generated by the fin depends also on the type of used fin (stiffness of the fin membrane, shape and dimensions of the fin, etc.).

In the paper, the thrusts T_t, T_l, T_r were determinated in empirical way by measurement of the different fins using laboratory stand described in details in the next section.

3 Measurement of thrust generated by FIN

In Fig. 5, the laboratory stand for measurement of the thrust generated by an underwater vehicle, e.g. BUV, designed and built in Polish Naval Academy is illustrated.

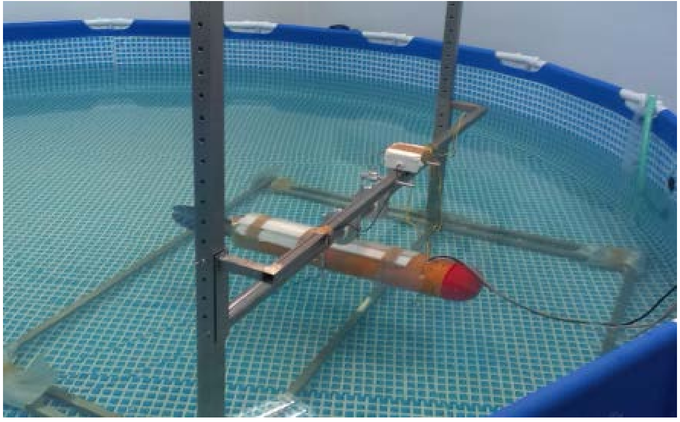

Fig. 5. The laboratory stand for measurement of the thrust generated by an underwater vehicle built in Polish Naval Academy [9]

The stand for measurement of the thrust consists of the following components:

1) the frame for mounting the measurement system with height-adjustable mounting point of the measurement system,
2) the set of two strain gauges with the transmission of power via a lever with unequal arms (the arms are attached to both sides of the underwater vehicle),

3) the microprocessor system for the thrust measurement, processing the data from the strain gauges to the proper format of data transmitted by a serial link,
4) the PC with software for control, registration, visualization and archivisation of motion parameters of the physical model of an undulating propulsion.

The measurement of the thrust measurement is carried out by microprocessor system, which register the output voltages of the two strain gauge beams and then process these voltages on the respective forces and send the values of the forces to the host computer via serial connection [9]. In Fig. 6, selected results of the forces *X* and moment of force *N* for the physical model of undulating propulsion with trapezoidal tail fin are presented. During the measurement the rotational speed of the tail fin motor was increased by 300 r/min per every 10 seconds. In the 60th second of test the rotational speed was equal to 1500 r/min what corresponds to approx. 2 Hz of the fin oscillation. Therefore, the changes of force *X* and moment of force *N* observed in the Fig. 6 were received for increasing frequency of the fin oscillation from 0 to 2 Hz and constant amplitude of the deflection of the caudal fin (equal to 20°). The force and moment of force mentioned above decide about motion of the underwater vehicle in the horizontal plane, especially advance velocity and an oscillation of motion.

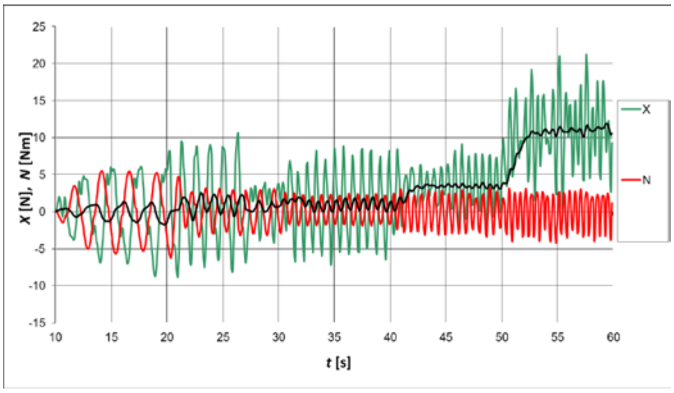

Fig 6. Changes of force X and moment of force N for the model of undulating propulsion with increasing frequency from 0 to 2 Hz and constant amplitude 20° of the deflection of the tail fin with trapezoidal shape [10]

Based on the achieved results of thrust measurement depending on the changes of frequency of fin deflection in time, it was assumed that the thrust generated by fin should be simulated as a sum of two signals: constant average value of thrust (Fig. 7 – Tav) and sine wave with amplitude (Fig. 7 – Tosc). Both signals increase with growth of rotational speed of motor of tail fin (frequency of fin deflection).

The results for thrust measurement (Fig. 6 and 7) were achieved for zero velocity of the vehicle. After modernization of the laboratory stand for thrust measurement (tunnel with flowing water), the characteristics illustrated in the Fig. 7 will be supplemented with new characteristics for non-zero advance velocities.

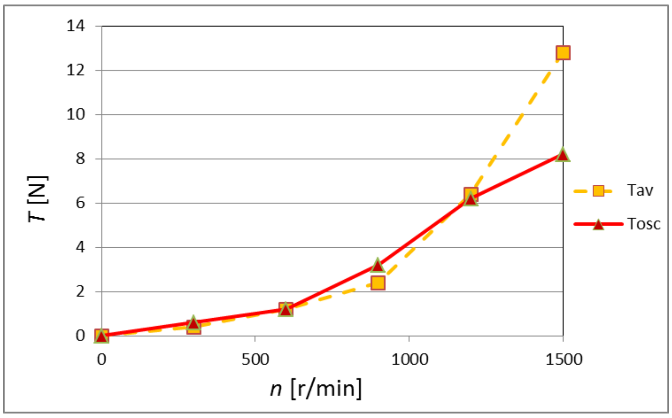

Fig. 7 Change of average thrust Tav and amplitude of thrust oscillation Tosc for different rotation speed of motor of tail fin [10]

4 BUV's Controllers

To control the motion of torpedo-shaped underwater vehicles, usually two main controllers are used. The first is a course controller and the second is a trim controller. The course controller is mainly used for steering motion in horizontal plane, while the trim controller is usually used for steering motion in vertical plane (to submerge or to emerge vehicle).

In the case of underwater vehicle with undulating propulsion, the change of course can be achieved in different way by using tail and/or side fins. Based on the research included in [10], in this paper following behavior was selected for the course change: one of the side fin is oscillating with variable frequency and the other side fin is set perpendicular to the longitudinal axis of symmetry without motion. In this case, the first side fin generates thrust, while the second generates hydrodynamic drag. Finally, the moment of force relative to vertical axis of symmetry is generated with the value depending on the frequency of oscillating fin, assuming that an amplitude of the oscillation is constant. Considering the vehicle shown in the fig. 2-4, the change of trim is achieved by changing neutral points of side fins, i.e. angle δl. For the δl not equal to 0° and 180°, thrusts coming from side fins generate moment of force relative to the transverse axis of symmetry.

Based on the mentioned above assumptions, two proportional-derivative action controllers PD of course and trim were designed and tuned. The course controller produces value of frequency of oscillating fin and the trim controller produces value of neutral points of side fins.

In general, the PD controllers are used to control objects, which are affected by big and rapid disturbances. They are described by the following formula in the discrete form:

$$u(k) = K_P \cdot \left(e(k) + \frac{T_d}{T_p} \cdot \Delta e(k) \right). \tag{17}$$

Where u(k) is a control signal in k step of simulation. Variable e(k) is an error signal in k step of simulation, while Δe(k) is a change of error signals in k step of simulation (e(k)–e(k-1)). Constant quantities are: Kp, Td and Tp, where Kp is a gain factor, Td is a constant of derivative action time and Tp is a sampling time.

For determination of constant quantity values it is necessary to correct action of controller. For this aim different methods could be used. In the paper, the constant quantity values were selected in an empirical way, based on observation of direct control quality indexes: a rise time, a setting time and a first overshoot value. For the course controller following values of constant quantities were received: Kp = 12, Td = 1100 ms and Tp = 55 ms. For the trim controller following values of constant quantities were received: Kp = 36, Td = 825 ms and Tp = 55 ms.

Stability of tuned controllers was tested by simulation for several values of desired angles of course and trim: 10°, 20°, 45°, 60° in the presence of affecting sea current with maximal velocity 0.5 m/s.

5 Control of BUV along desired trajectory

In the simulation, the following values of distances shown in Fig. 3 were accepted:

- r_1 = 0.1 m – the distance between the gravity origin and the center of rotation of the tail module,
- r_2 = 0.4 m – the distance between the center of rotation of the tail module and the center of rotation of the tail fin,
- r_3 = 0.3 m – the distance between the gravity origin and the center of rotation of the side fins,
- r_4 = 0.1 m – the distance between the center of rotation of the side fins and center of rotation of the left or right fin.

Moreover , it was assumed that the biomimetic underwater vehicle has cylindrical hull with following dimensions: length equal to 1.2 m and diameter equal to 0.2 m.

In the first stage of the research, mainly the action of course controller was tested. The BUV had to move only on horizontal plane along the trajectory consisting of the following waypoints:

W0 = (0, 0, 0), *W1* = (50, 50, 0), *W3* = (100, 150, 0),
W4 = (50, 150, 0), *W5* = (0, 100, 0), *W6* = (0, 0, 0)

The coordinates of all the waypoints were given in meters. In the Fig. 8, the trajectory of BUV on horizontal plane xy was illustrated. BUV moved through all the waypoints. Course controller allowed to achieve small deflection from desired trajectory not exceeding in almost all cases 2 m. Only during large change of course (waypoint *W*3) the deflection from trajectory was equal to 5.5 m.

In the Fig. 9, changes of course and trim and rotational speeds of the motors driving tail and side fins during BUV motion along trajectory on horizontal plane was inserted. It can be observed how the course changed in following points of trajectory to minimize deflection from desired trajectory.

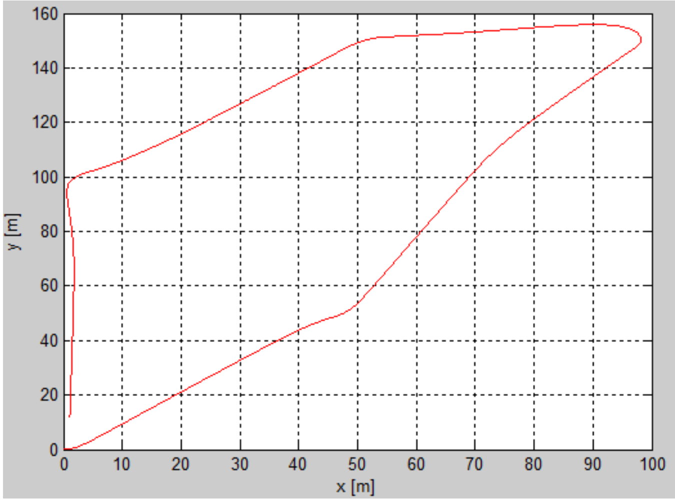

Fig.8. Trajectory of BUV on horizontal plane xy

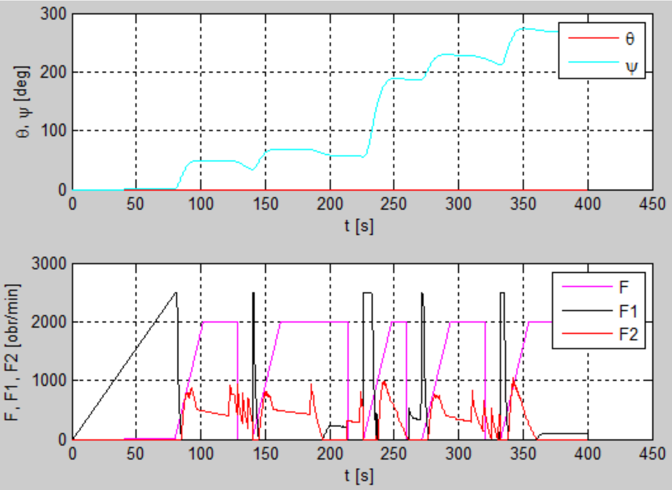

Fig.9. Changes of course ψ, trim θ and rotational speeds of the motors driving tail fin F, left side F1 and right side F2 fin during BUV motion along trajectory on horizontal plane

In the second stage of the research, the more complicated desired trajectory was used. During motion along this trajectory, the BUV had to also submerge and emerge using trim controller. The second trajectory was built from the following waypoints:

W0 = (0, 0, 0), *W1* = (50, 50, 0), *W3* = (100, 150, 0),
W4 = (50, 150, -5), *W5* = (0, 100, -5), *W6* = (0, 0, 0)

In the Fig. 9 and 10, the trajectory and parameters of BUV motion along desired trajectory in 3D space xyz was illustrated. In this case, BUV also moved through all the waypoints. Course and trim controllers working together allowed to achieve small deflection from desired trajectory not exceeding in almost all cases 2 m.

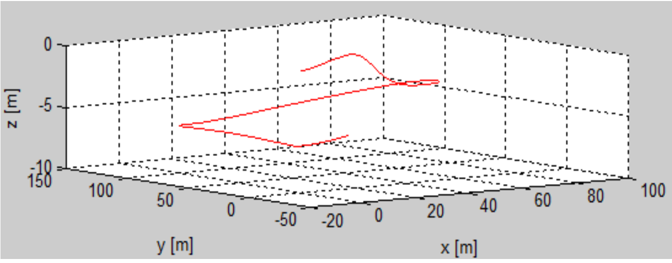

Fig.10.Trajectory of BUV in 3D space xyz

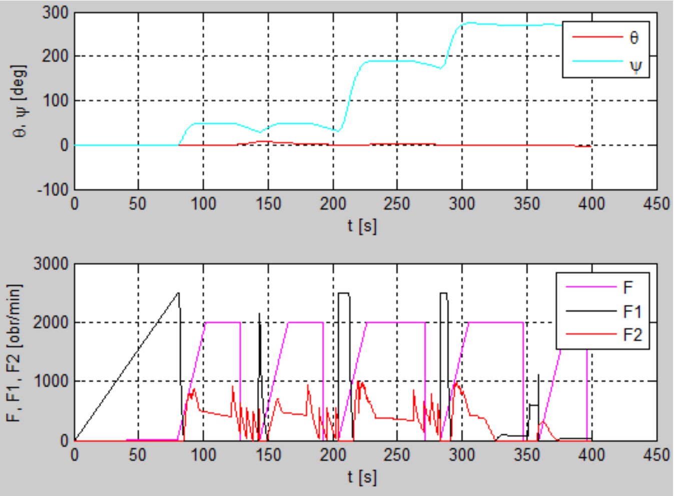

Fig 11.Changes of course ψ, trim θ and rotational speeds of the motors driving tail fin F, left side F1 and right side F2 fin during BUV motion along trajectory in 3D space xyz

5 Conclusions

Designed mathematical model of the motion of biomimetic underwater vehicle allows us to design and tune course and trim controllers of the BUV. Classical PD controllers were used in initial research. The action of controllers were tested during BUV motion along desired trajectories. The achieved deflection from trajectory in almost all cased not exceeded 2 m. During the next research different other controllers of the main parameters of BUV motion will be designed and tuned, e.g slide or fuzzy controllers. In this way they should improve studies planned to carry out on a real BUV.

Acknowledgment

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