Pomiary Automatyka Robotyka, ISSN 1427-9126, R. 26, Nr 3/2022, 17–22, DOI: 10.14313/PAR_245/17

Trajectory Tracking Control of Autonomous Underwater Vehicle Called PAST

Piotr Szymak, Rafał Kot
Polish Naval Academy, Śmidowicza 69, 81-127 Gdynia, Poland

Abstract: The increasing development of Autonomous Underwater Vehicles (AUVs) with varying levels of autonomy can be seen globally. The paper is devoted to the new AUV called PAST being developed and built within the Polish development project entitled „Development of the underwater autonomous transport system" (no. POIR.01.01.01-00-0893/20). Mainly, the paper focuses on high-level control of PAST AUV devoted to controlling along the desired trajectory. It demands a set of tuned controllers of advanced velocity, course, depth, and trim. The trajectory tracking algorithm should be implemented and verified for different trajectories set in practice. At the beginning of the article, an introduction to the research is inserted. Then, the following scientific issues are presented: the mathematical model of AUV motion, high-level control structure, and the trajectory tracking algorithm. Next, the results of numerical research in the Matlab environment are presented. In the end, the conclusions for future research are formulated.

Keywords: trajectory tracking, high-level control, autonomous underwater vehicle

1. Introduction

Autonomous Underwater Vehicles (AUVs) are robots that can perform many different underwater missions, both civilian and military. Civilian usage of AUV is mainly connected with various inspections of the aquatic environment, especially for oceanography and marine biology purposes [2, 3]. Considering military applications of AUV, the following missions should be mentioned: mine countermeasure, anti-submarine warfare, and Intelligence, Surveillance, and Reconnaissance (ISR). The innovative underwater autonomous vehicle PAST will transport different payloads from starting to target waypoints.

According to the desired purposes of project no. POIR.01.01.01-00-0893/20, AUV PAST's essential function will be transporting various types of cargo. The underwater autonomous transport system will be equipped with wireless communication and control systems. It will be capable of independent (autonomous) motion to the user-programmed location on the surface or underwater and detect and avoid obstacles on its route.

The offshore wind energy market and the offshore mining installations market will be the most important target group for the project results. PAST will enable faster, safer, and cheaper execution of works and inspections of underwater offshore facilities: drilling platforms, underwater installations, dams, locks, bridges, docks. The underwater autonomous transport system will be used to construct and inspect offshore wind farms, underwater ICT networks, and pipelines. In addition, it is required to deliver various types of tools, equipment, and a supply of air cylinders for divers during underwater works.

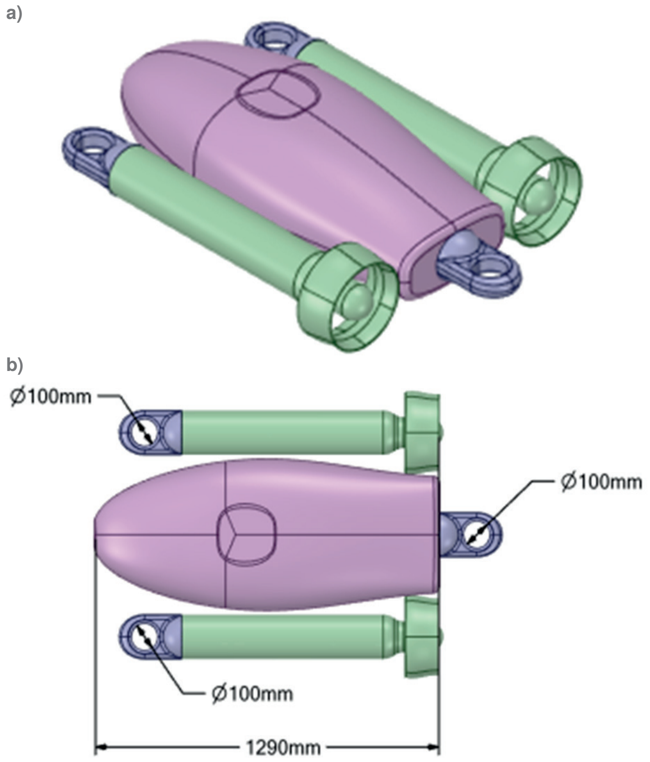
In Figure 1, the initial 3D project of PAST is illustrated. The vehicle consists of a transport compartment in the middle with two cylindrical containers with batteries and power electronics ended with the screw propellers. Such construction can be easily changed with the larger or smaller source of electric energy and/or propeller producing the larger or smaller thrust. Moreover, three manoeuvre thrusters are attached to the transport compartment.

The microprocessor and sensor systems are located in the bow part of the middle compartment, while the stern part of this compartment is destined for holding the transported load. To counteract no neutral buoyancy of the shipments, additional ballast tanks are planned to be used.

The PAST is planned to be an autonomous vehicle capable of moving across the desired trajectory with obstacle detection and avoidance, which demands the implementation of precise underwater navigation and autonomy algorithms [5, 6]. Moreover, the high-level control system requires an earlier set of the AUV motion parameters controllers. Usually, control of the following three main parameters is essential: an advance velocity, a course angle and a trim angle. In work [9], the mentioned controllers for the AUV PAST are described. In that case, the controller's settings were tuned using a Genetic Algorithm (GA). Also, different optimisation methods can be used for this purpose, e.g. a Particle Swarm Optimization (PSO) [7].

Autor korespondujący:
Rafał Kot, r.kot@amw.gdynia.pl

Artykuł recenzowany
nadesłany 24.08.2022 r., przyjęty do druku 15.09.2022 r.



Source: project no. POIR.01.01.01-00-0893/20

Fig. 1. 3D project of the AUV PAST: a) the top view, b) the main dimensions
Rys. 1. Trójwymiarowy projekt AUV PAST: a) widok z góry, b) podstawowe wymiary

In the next section, the mathematical model is described [1]. Then, a high-level control structure with the trajectory tracking algorithm is considered. Next, the plan, assumptions and finally, results of numerical research of the PAST are presented and discussed. In the end, the conclusions and the bibliography are inserted.

2. Mathematical model of AUV

To model the motion of the AUV PAST, the classical model of a rigid body with three planes of symmetry moving in six degrees of freedom at a low speed in the viscous liquid was applied [1]. The details of the model and all results of the identification of the PAST motion model are included in [8].

In the further part of this section, only the model's main features necessary for understanding the presented results of the numerical research are inserted.

The vehicle's motion is described using two reference systems: (1) the movable coordinate system associated with the vehicle xoyozo and (2) the immovable coordinate system associated with the Earth xyz. The origin of the movable coordinate system O responds to the vehicle's centre of gravity. At the same time, its axes are defined as: (1) xo is a longitudinal axis directed from the stern to the bow, (2) yo is a transverse axis directed to the starboard, and (3) zo is a perpendicular axis directed from top to bottom. Changes in the position of the movable coordinate system xoyozo are described for coordinate system xyz associated with the Earth. Because the vehicle moves at a relatively low speed, the acceleration of points on the Earth's surface is ignored, and the coordinate system xyz is considered stationary. Therefore, the centrifugal and centripetal forces and moments of force caused by the Earth's spin may be neglected.

The movement of the AUV is described by six differential equations, represented in the compact matrix form:

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

here:
v – 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 added masses),
$D(v)$ – 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 the vector of forces and moments of force generated by propulsion system τ_p and by environmental disturbances τ_d).

The assumptions presented earlier in this section cause simplification of the matrices shown in equation (1) to the main diagonal. The details are included in [1, 8].

The left side of the equation (1) includes forces and moments of force caused by the following physical phenomena: the vehicle's body's inertia and the added masses of a viscous liquid, hydrodynamic dumping water environment, a balance of gravity and buoyancy. In contrast, the right side of 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 the water's surface, especially a sea current). The vector of forces and moments of force τ_p generated by the propulsion system consists of the following elements:

$$\tau_p = [X,\ Y,\ Z,\ K,\ M,\ N] \qquad (2)$$

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 consider the specific configuration of the propulsion system [4]. In Fig. 1, the 3D design of AUV PAST with the propellers is illustrated. The vehicle is driven by two main thrusters mounted on its stern (acting in the horizontal plane), three manoeuvre thrusters installed on the stern, and two others mounted in the bow part of the vehicle (operating in the vertical plane).

Two main thrusters produce thrust in the longitudinal axis of symmetry which is responsible for the advanced velocity of the vehicle. Moreover, the difference in generated thrusts makes a moment of force relative to the vertical axis of symmetry, changing the PAST course. Because of locating the main thrusters in an extreme position, it is expected to receive good manoeuvrability on the horizontal surface.

Three manoeuvre thrusters acting on the vertical surface enable us to generate thrust in the vertical axis of symmetry, i.e., submerging and emerging vertically. Moreover, the difference in generated thrusts allows inducing moments of force relative to the longitudinal and lateral axes of symmetry, i.e., to change respectively roll and trim of the PAST. The most important seems to be trim change which enables to control depth.

3. High-level control

The high-level control is the subsystem superior to the low-level control system, which consists of the set of controllers of the main motions parameters of the AUV. The high-level control is primarily responsible for:

- Communication with the human operator supervising the mission being carried out;
- Adjusting the configuration of the controllers depending on the task performed underwater;
- Introducing the set values of the motion parameters in the specified time of the task being performed;
- Enabling and disabling controllers at appropriate points of a given trajectory.

In addition, the high-level control system performs the functions of registration and archiving linear and angular physical quantities describing the movement of the underwater vehicle, i.e., the vector state and vector of forces and moments of force.

In the case of a control task along a given trajectory, a superior control system determines the next set of set values of motion parameters for the next waypoint at the moment of reaching the current position at a distance equal to or less than the set one distance r_s from the current waypoint.

When moving along the trajectory sections, the high-level control system checks whether the set motion parameters have changed due to, for example, the "pushing" effect of the sea current. If given parameters have changed by a certain range of values, they are updated. The following rules are satisfied:

$$\text{if } |u_s - u_{sn}| > 0.2 \text{ [m/s], then } u_s = u_{sn} \tag{3}$$

$$\text{if } |\psi_s - \psi_{sn}| > 5 \text{ [deg], then } \psi_s = \psi_{sn} \tag{4}$$

$$\text{if } |\vartheta_s - \vartheta_{sn}| > 5 \text{ [deg], then } \vartheta_s = \vartheta_{sn} \tag{5}$$

here:

u_s, ψ_s, ϑ_s – current set values of respectively the advanced velocity, the course angle, the trim angle,

u_{sn}, ψ_{sn}, ϑ_{sn} – new set values of respectively the advanced velocity, the course angle, the trim angle.

To ensure reaching the waypoint in the expected time, the initial advanced velocity is 10% greater than the value resulting from the distance and time to the next waypoint. Then, after reaching the position at a distance of r_s from the waypoint, the AUV reduces the motion velocity to a minimum value of 0.5 m/s to effectively perform course and/or trim manoeuvres. Depth change on the trajectory is carried out by changing the trim, which is the most effective manoeuvre for the vehicle with the elongated shape of its hull due to a decrease of hydrodynamic dumping.

4. Numerical Research

The AUV motion model and its low- and high-level control systems were implemented in MATLAB. The simulations were conducted with the 1/10 s time step. The description of the low-level control is included in [9], while the description of the high-level control is in the previous section.

The following subsection defines the parameters for evaluating the AUV tracking along the desired trajectory. Then, the desired trajectories used in the numerical tests are presented. In the next subsection, the research results are illustrated. Finally, the discussion on these results is included.

4.1. Evaluation of the AUV tracking along the desired trajectory

Each trajectory is defined as a set of waypoints with coordinates (x_n, y_n, z_n) and a set time t_n of reaching a waypoint, where n is a number of the following waypoints. Therefore, to evaluate the quality of the AUV tracking along the set trajectory, the deflection should be considered and a performed time of reaching a waypoint. After analysis, the following parameters were accepted for further study:

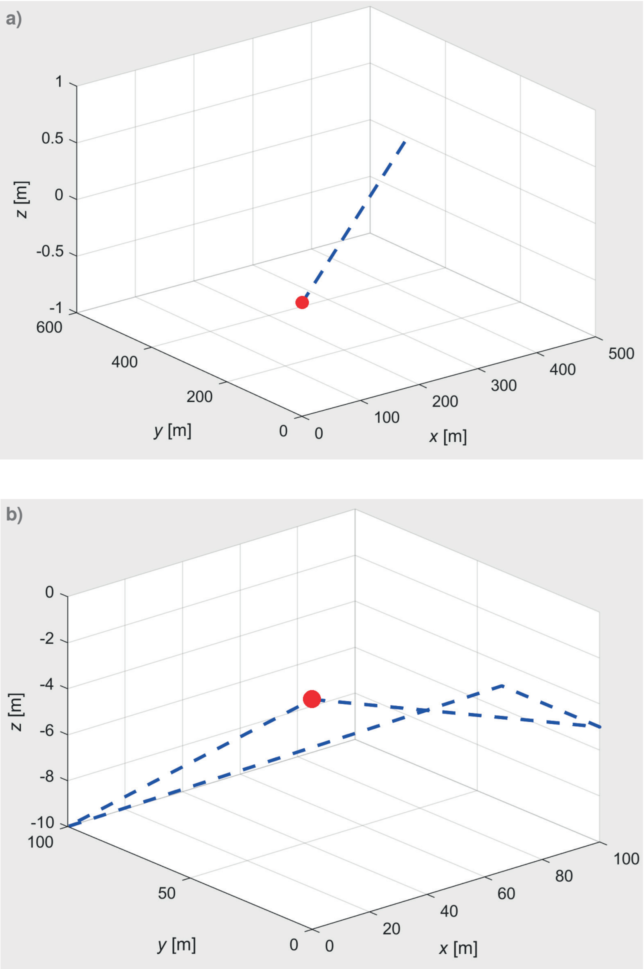
1. The maximum deflection from the trajectory d_{max};
2. The average deflection from the trajectory d_{avg};
3. The maximum time shift between the set t_n and current t_r times of reaching the following waypoint t_{max};
4. The average time shift between the set t_n and current t_r times of reaching the all waypoints t_{avg}.

It is worth mentioning that the deflection is determined as the closest distance from the gravity centre of the AUV to the trajectory in the following simulation steps. Moreover, the time of reaching the waypoint t_r is determined as a time of achieving the distance r_s to the waypoint, i.e., the waypoint is achieved if the AUV goes into a sphere with the radius r_s and origin coordinates equal to the n-th waypoint coordinates (x_n, y_n, z_n). Therefore, for the radius equal to 2 m and the AUV advanced velocity equal to 1 m/s, the 2 s time shift will be received.

4.2. Test trajectories

Different test trajectories can give answers for various aspects. The PAST AUV is primarily designed for an extended mission aiming to reach the destination waypoint with transported shipment and then return to the starting waypoint, possibly with another load. This kind of mission requires a trajectory consisting of two parallel segments.

Another essential issue in the AUV examination is its manoeuvrability. To check how the AUV is manoeuvrable, the trajec-



Source: project no. POIR.01.01.01-00-0893/20

Fig. 2. Test trajectories for the AUV PAST: a) the long-distance trajectory, b) the trajectory demanding high manoeuvrability

Rys. 2. Trajektorie testowe dla AUV PAST: a) trajektoria długodystansowa, b) trajektoria wymagająca dużej manewrowości tory with short segments demanding often and significant course and/or trim changes should be defined.

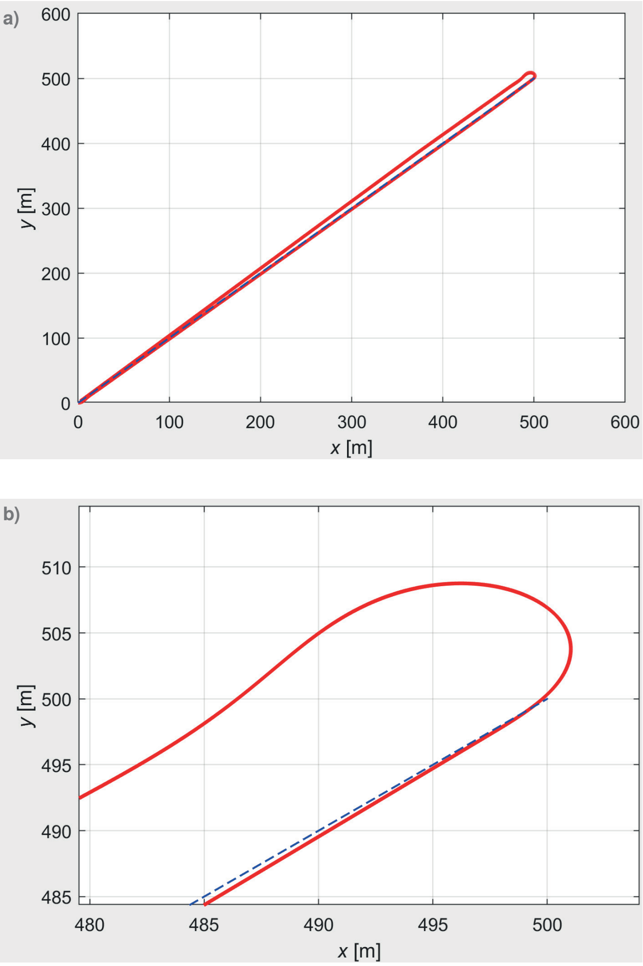
Both trajectories examining different aspects, i.e. the long-distance trajectory (no. 1) and the trajectory demanding high manoeuvrability (no. 2), are illustrated in Figure 2.

As can be seen, trajectory no. 1 consists of two segments 500 m length each with a more extended stop at the destination waypoint needed for vehicle unloading and possibly loading with another shipment. While trajectory no. 2, demanding high manoeuvreability, consists of several shorter segments with the maximal length 100 m and with 90° and more enormous changes of course and 5 m changes of depths. As mentioned earlier, the depth change is achieved using trim changes. In this simulation, the trim changes were limited to the ±10°. In both cases, the trajectories have started and ended in the same waypoint with coordinates (0, 0, 0) [m] marked by the red dot.

4.3. Research results

In Figure 3, the long-distance trajectories are shown. During tracking this trajectory, the AUV had to go to the destination waypoint with coordinates (500, 500, 0) [m] and return to starting waypoint (0, 0, 0) [m], i.e., it had to move on the vertical surface *xy*.

The desired trajectories are marked by a blue line, while a red line marks the real ones. In addition to the whole trajectories (Figure 3a), the selected trajectory segments in the destination waypoint area are visualised in Figure 3b. The latter figure with the date shown in Table 1 enables us to see the most significant deflection from the trajectory equal to 10.68 m. This deflection was registered when the AUV reached the destination waypoint, and the starting waypoint was the goal. This deflection is connected with the AUV manoeuvre of changing course by 180° with a specific value of the advanced velocity larger than 0.5 m/s.



Source: project no. POIR.01.01.01-00-0893/20

Fig. 3. Visualisation of the set (blue line) and actual (red line) trajectory no. 1: a) projection of trajectory on the vertical surface, b) selected segment of the trajectory in the area of the destination waypoint

Rys. 3. Wizualizacja zadanej (linia niebieska) i aktualnej (linia czerwona) trajektorii nr 1: a) rzut trajektorii w płaszczyźnie pionowej, b) wybrany odcinek trajektorii w obszarze punktu docelowego

In Figure 4, trajectories no. 2 are shown. In addition to the projection of trajectories on the vertical surface (Figure 4a) and trajectories in the space xyz (Figure 4b), effects of low-level control are visualised in Figures 4c, d, e, f, respectively the changes of the advanced velocity, the depth and the course and trim angles in time. The additional charts allow making more depth analysis.

Based on Figure 4 a and Table 1, the maximal deflection from the set trajectory equal to 5.8 m can be seen. Similarly to trajectory no. 1, such large deflection is connected with the manoeuvre of significant course change, i.e., by 135° in this case.

Based on Figure 4b, more significant deflections from the trajectory can be seen, especially for the motion in the horizontal plane. These deflections are correlated with the depth changes shown in Figure 4d. As can be seen, the PAST AUV needs almost 40 s for changing depth by 5 m. Such inertia is connected with the limitation of the trim changes to ±10°. Possibly, this limit can be increased two or even four times. Due to the lack of data on the manoeuvrability of the AUV prototype at this stage of the research, the safer limit was accepted. In general, an increase of trim change will result in a faster change of the AUV depth, which gives us less deflection in the horizontal plane.

Table 1. Evaluation of the AUV tracking along test trajectories no. 1 and 2

Tabela 1. Ocena śledzenia przez AUV trajektorii testowych nr 1 i 2

Number of trajectory	d_{max}	d_{avg}	t_{max}	t_{avg}
	[m]	[m]	[s]	[s]
1	10.69	3.55	1.8	1.8
2	5.8	2.03	5.4	3.67

Source: Project no. POIR.01.01.01-00-0893/20

4.4. Discussion

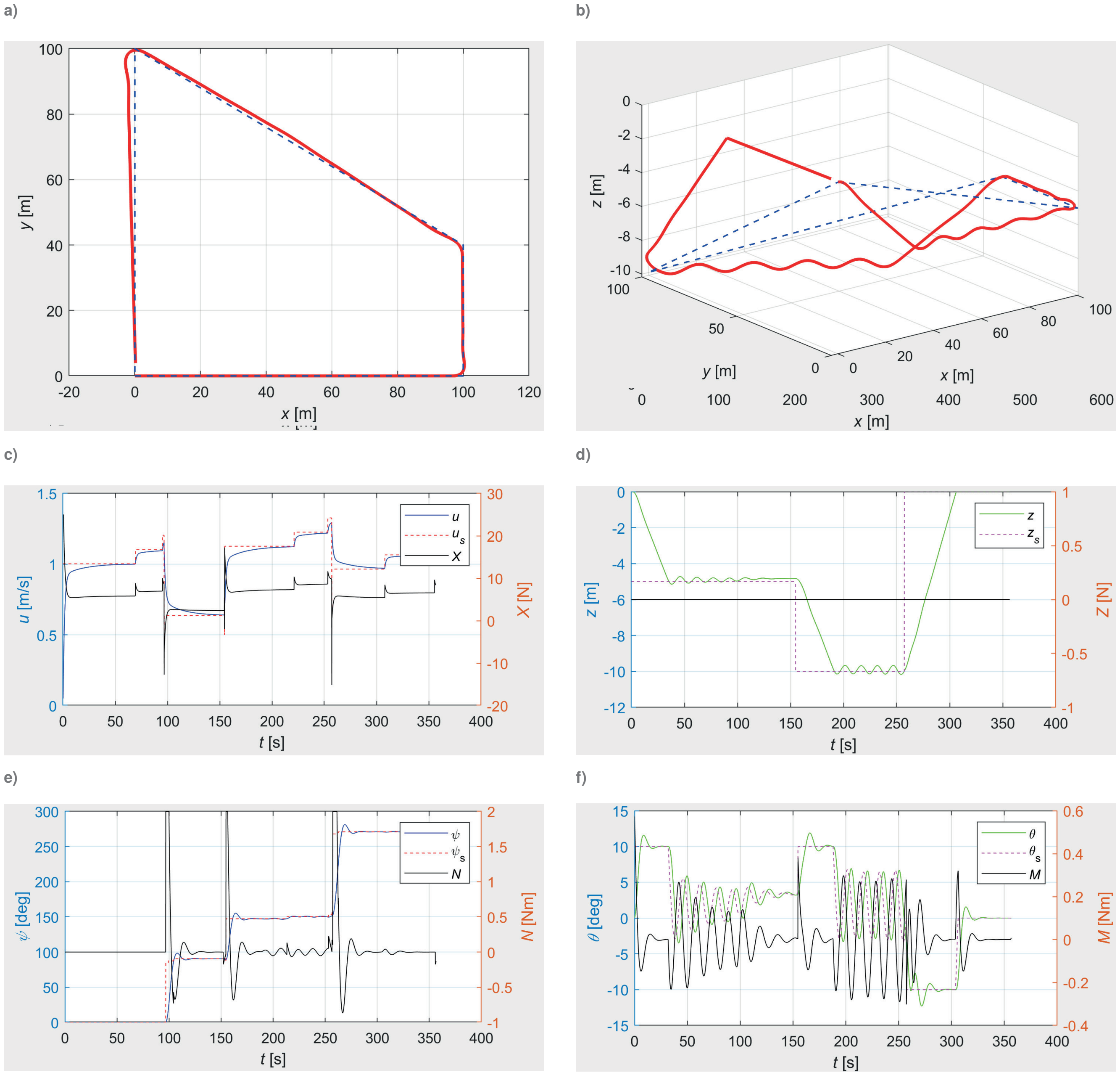
In the project's first stage, the following milestone was formulated: deflection from the set trajectory of the simulated PAST model moving along a straight segment of 500 m, using selected low-level regulators. It was assumed that the deflection from the trajectory would be no more than 20 m in the horizontal plane and 5 m in the vertical plane.

As is shown in the previous subsection, smaller deflections from the trajectory were obtained. Moreover, there are possible improvements to receive a more accurate control system of the PAST AUV. If it is desired to reduce the deflection from the trajectory in the space of the destination waypoint, the AUV advanced velocity should be decreased even to zero. The driving system of the PAST enables to change course almost in the same place. Considering the observed deflections in the vertical surface, the increase of the trim change limit can be introduced.

The additional improvement of the vehicle behaviour along the desired trajectory may be observed using the path following instead of the trajectory tracking.

5. Conclusions

Designed and implemented in MATLAB mathematical model of the motion of underwater vehicle PAST [8], low-level con-



Source: project no. POIR.01.01.01-00-0893/20

Fig. 4. Visualisation of the set (blue line) and real (red line) trajectory no. 2: a) projection of trajectory on the vertical surface, b) trajectory in the space, the changes of c) advanced velocity, d) depth, e) course, f) trim in time

Rys. 4. Wizualizacja zadanej (linia niebieska) i aktualnej (linia czerwona) trajektorii nr 2: a) rzut trajektorii w płaszczyźnie pionowej, b) trajektoria w czasie, zmiany c) prędkości postępowej, d) głębokości, e) kursu, f) trymu w czasie

trol [9] and finally described in this paper, high-level control allow us to make numerical tests of the PAST AUV tracking across test trajectories. The research enables confirming that the partial milestone of the project was achieved and formulating several proposals of the control system improvements. Their implementation and verification can be made after receiving the initial results of the PAST prototype operation in the water environment.

During the following research, the improvements mentioned above in the PAST control system will be verified initially using the verified simulation model and then the prototype of the PAST AUV.

Acknowledgments

The research results presented in the paper were achieved within the project entitled “Development of the underwater autonomous transport system” (no. POIR.01.01.01-00-0893/20), co-financed by the Polish National Centre of Research and Development.

Bibliography

1. Fossen T., Handbook of Marine Craft Hydrodynamics and Motion Control, John Wiley & Sons, 2011.
2. Kondeti L., Review of Autonomous Underwater Vehicles, [In:] Autonomous Vehicles, Intech, 2018.
3. Ozgur Y., Bulent O., Yilmaz A., A review on motion control of the Underwater Vehicles, Proceedings of 6th International Conference on Electrical and Electronics Engineering, ELECO 2009, DOI: 10.1109/ELECO.2009.5355247.
4. Praczyk T., Szymak P., Naus K., Pietrukaniec L., Hożyń S., Report on research with biomimetic autonomous under-

water vehicle – low level control, "Scientific Journal of Polish Naval Academy", Vol. 212, No. 1, 2018, 105–123, DOI: 10.2478/sjpna-2018-0006.

5. Praczyk T., Szymak P., Naus K., Pietrukaniec L., Hożyń S., Report on research with biomimetic autonomous underwater vehicle – navigation and autonomous operation, "Scientific Journal of Polish Naval Academy", Vol. 213, No. 2, 2018, 53–67, DOI: 10.2478/sjpna-2018-0013.
6. Sandeep J., Mahender S., A Review Paper on: Autonomous Underwater Vehicle, "International Journal of Scientific and Engineering Research", Vol. 6, 2015, 38–40.
7. Szymak P., Piskur P., Using Particle Swarm Optimization for Tuning Course Controller of Biomimetic Underwater Vehicle, Proceedings of 8th International Maritime Science Conference / ed. Špiro Ivoševic, Pero Vidan, Kotor: University of Montenegro; University of Split, 2019, 255–262.
8. Szymak P., Piskur P., Piątek P., Muchowski J., Trawiński S., Modeling and simulation of innovative autonomous underwater vehicle PAST, Nase More Conference, 2021, 332–346.
9. Szymak P., Low-Level Control of Unmanned Marine Vehicle PAST, Proceedings of the Polymer Diagnosis Conference, Male, 2022.

Sterowanie autonomicznym pojazdem podwodnym o nazwie PAST z wykorzystaniem śledzenia trajektorii

Streszczenie: Na całym świecie można zaobserwować rosnący rozwój autonomicznych pojazdów podwodnych (AUV) o różnych poziomach autonomii. Artykuł poświęcony jest opracowywaniu i budowie nowego AUV o nazwie PAST w ramach polskiego projektu rozwojowego pt. „Rozwój podwodnego autonomicznego systemu transportowego" (nr POIR.01.01.01-00-0893/20). Artykuł koncentruje się głównie na wysokopoziomowym sterowaniu pojazdem PAST przeznaczonym do podążania wzdłuż pożądanej trajektorii. Wymaga to zaawansowanego zestawu dostrojonych kontrolerów prędkości, kursu, głębokości i trymu. Algorytm śledzenia trajektorii powinien być zaimplementowany i zweryfikowany dla różnych trajektorii wyznaczanych w praktyce. Na początku artykułu zamieszczone zostało wprowadzenie do badań. Następnie przedstawiono następujące zagadnienia naukowe: model matematyczny ruchu AUV, wysokopoziomową strukturę sterowania oraz algorytm śledzenia trajektorii. Następnie przedstawiono wyniki badań numerycznych w środowisku MATLAB. Na koniec formułowane są wnioski dla przyszłych badań.

Słowa kluczowe: śledzenie trajektorii, sterowanie wysokopoziomowe, autonomiczny pojazd podwodny

Piotr Szymak, Cdr., Assoc. Prof. PhD, Eng.
p.szymak@amw.gdynia.pl
ORCID: 0000-0002-4714-6192

Since 2001 he has been serving in Polish Naval Academy (PNA) in the following positions: assistant, lecturer, adjunct, head of department, assistant professor, associate professor. He was a director of Institute of Electrical Engineering and Automatics in PNA in the years 2015–2019. Since 2019 he has been Polish naval Captech National Cooridnator in European Defence Agency. In 2004 he received PhD degree in Polish Naval Academy and in 2016 he obtained the academic degree of habilitated doctor in Cracow University of Technology. His research area is strictly connected with modeling and control of marine objects, especially unmanned surface and underwater vehicles, including recently biomimetic underwater vehicles.

Rafał Kot, Lt. M. Eng.
r.kot@amw.gdynia.pl
ORCID: 0000-0002-9273-353X

Graduated from the Military University of Technology in Warsaw with a degree in Electronics and Telecommunication Studies in 2016. He worked for almost 6 years in the Marine Aviation Base in the Polish Army where he gained experience in servicing and maintenance of aircraft in the avionics area. From the beginning of 2022, he is working at Polish Naval Academy. His main research includes underwater obstacle detection systems, path planning algorithms, and collision avoidance systems for Autonomous Underwater Vehicles.