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RESEARCH ON BIOMIMETIC UNDERWATER VEHICLES UNDERTAKEN AT INSTITUTE OF ELECTRICAL ENGINEERING AND AUTOMATICS

ABSTRACT

In the recent years, a dynamical development of an underwater robotics has been noticed. The robotics is developed in several different directions by many foreign and a few national R&D centers. The development is focused on both an improvement of construction and features of the underwater vehicles (a hardware development) and an increase of underwater vehicle autonomy providing to a swarm control (a software development).

In the paper, new research area focused on biomimetic underwater robots undertaken at the Institute of Electrical Engineering and Automatics in the recent years is presented. The area concern both hardware and software development of the underwater vehicles. In the paper, the research on biomimetic underwater vehicles developed within national and international projects is described. At the end of the paper, a summary containing foreseen research is included.

Key words:
biomimetic underwater vehicle, undulating propulsion, autonomous control.

INTRODUCTION

Increasingly, biomimetic robots are designed that imitate living organisms in the term of their appearance, way of movement and principles of operation [1, 2]. These living organisms, e.g. insects, reptiles, fishes and mammals often arise as a result of a long-term evolution. In the last decade, a number of interesting designs of underwater vehicles was created which mimic the appearance and way of motion of

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underwater creatures, e.g. fishes. One of the most famous constructions that imitate the fishes are Robocarp built by researchers at the University of Essex, Tai robot kun developed by Japanese scientists at the University Kitakyushuu, RoboTuna made by Boston Dynamic.

Nowadays, there is also example of biomimetic underwater vehicle used in US Navy. This vehicle is called Ghost Swimmer. The name is connected with the features crucial from the military point of view: their propulsion is more energy efficient and more silent [3] than classical propulsion based on screw propellers (based on initial research carried out in Polish Naval Academy), they may be very difficult to differentiate from the real inhabitants of underwater environment (larger secrecy and potential range of operation, depended on the degree of similarity to BUV's living counterpart).

In the next section, the selected results of research on biomimetic underwater vehicles BUVs undertaken in the Institute of Electrical Engineering and Automatics are described. The presented results of the research on BUVs were achieved within two projects. The first project (with codename: SLEDZIK) 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. The main objective of the SLEDZIK project is to build heterogeneous torpedo-shaped BUVs with undulating propulsion for selected scenarios of underwater ISR. In this case, the degree of similarity to the living organisms is rather small. The second project (with codename: SABUVIS) was started in connection with Unmanned Maritime Systems Programme in European Defense Agency EDA. The SABUVIS project is carried out by the consortium consisted of the mentioned above Polish partners and additional foreign partner, i.e. Bundeswehr Technical Center for Ships and Naval Weapons WTD 71 in Eckernförde, Germany. The main objective of this international project is to build BUVs characterized by a greater similarity to real inhabitants of underwater environment and also taking into account the capabilities of their operation as a swarm.

BIOMIMETIC UNDERWATER VEHICLES — CYBERFISH

New constructions of the BUVs developed within SLEDZIK and SABUVIS projects are based on experiences from building five versions of Polish BUV called

CyberFish. All the versions of CyberFish were built in Cracow University of Technology. The 3rd and 5th versions, illustrated adequately in the figures 1 and 2, were built in cooperation with Polish Naval Academy.

In general, the CyberFish is composed of four rigid segments connected with rotary kinematic pairs. The first largest segment is an artificial head with lateral fins and the next three segments create a movable artificial tail of a fish. The vehicle was designed to mimic fresh water carp fish as close as possible. More details about construction and principles of operation of CyberFish are included in [4].

In the figure 2, the silicon coating of CyberFish is illustrated. This artificial skin mimics fish scales and allows CyberFish to increase its similarity to the inland water fish called carp. The vehicle 'wearing' such a coating and moving in undulating way is hardly perceptible from the real inhabitants of the underwater environment.

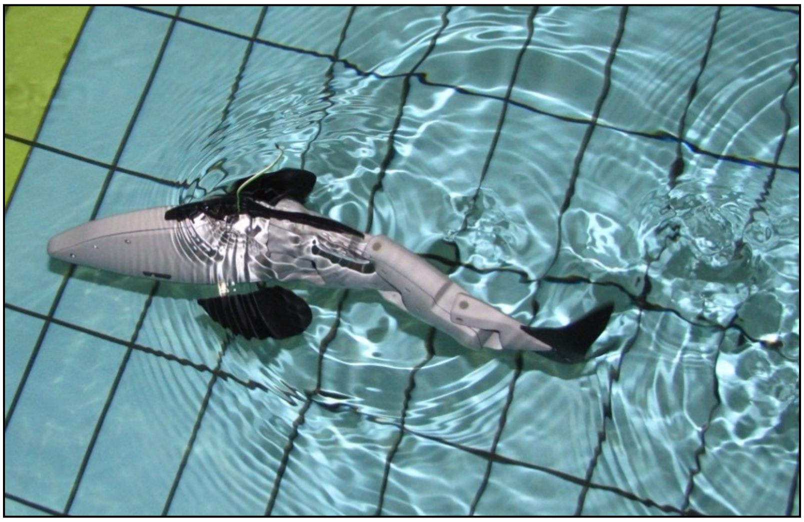

Fig. 1. CyberFish ver. 3 in a swimming pool [phot. M. Malec, M. Morawski]

The CyberFish is a good demonstrator of the biomimetic technology showing possible advantages of the BUV in the field of underwater ISR, especially in the range of operation secrecy. The disadvantage of this technology demonstrator is no posibility of testing and finally demonstrating most of the underwater sensors, e.g. sonar, hydrophone, etc. This drawback is mainly due to the small size of the CyberFish. Also the onboard control system has insufficient computing power for high level control algorithms implementing autonomous behaviors.

Fig. 2. Silicon coating of the CyberFish ver. 5 [7]

The good experience and results achieved during process of designing, building and finally testing CyberFish were one of the main reasons for starting Polish project and then due to international interests also EDA project.

BIOMIMETIC UNDERWATER VEHICLES — SLEDZIK

The Polish project has started at the end of 2013. It should be completed at the end of 2016. The final effect of the project will be two technology demonstrators of the BUVs: the one built in Cracow and the second built in Gdynia. Until now, the following research tasks were conducted: design of operational scenarios resulting in tactical and technical requirements, tests of undulating propulsion with different fins and different parameters of the artificial tail operation, tests of the navigation and communication subsystems, design of 3D model and then implementation of the BUVs (in progress).

Considering operational needs and capabilities, several different scenarios were designed in cooperation with experts from the special forces. Taking into account problems of autonomous control, the general scenario can be defined in the following steps:

- the operator defines desired trajectory consisting of several waypoint with the set behavior in the selected waypoints, e.g. emergence and register video signal on the course … and in the range …;
- the BUV moves in autonomous way along desired trajectory with possible obstacles detection and avoidance and desired signals (e.g. video) registration;

– registered signals are transferred to the control station and depending on the decision taken by the operator the mission is ended or continued for achieving more information.

Taking into account the general scenario presented above, the BUV should be equipped with algorithms for autonomous motion along desired trajectory with the obstacles avoidance. This task requires to design low and high level control subsystems. The low level control subsystem is understood as a set of controllers executing commands received from the high level control subsystem, e.g. move on the course 90°. The high level control is considered as a control system responsible for generating all the autonomous behaviors, e.g. to move forward, to change course on the left, to submerge, etc. The work at the Institute was mainly focused on low level control.

The general scenario with technical specification of the BUVs [7] were used as assumptions for the following research in the SLEDZIK project. At the beginning, the laboratory stand for measurement of thrust generated by the tail fin module was designed and built (fig. 3). The stand consists of the following components:
– the frame for mounting the measurement system;
– 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 vehicle);
– 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 [9];
– the PC with software for control, registration, visualization and archiving of motion parameters of the tail fin module.

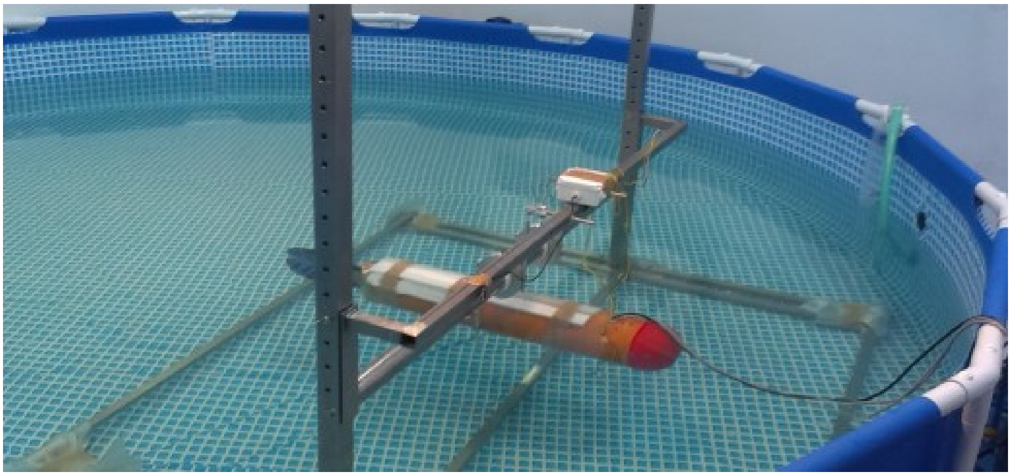

Fig. 3. The laboratory stand for the thrust measurement of the tail fin module at the Institute of Electrical Engineering Automatics (Polish Naval Academy) [7]

The frame has height-adjustable mounting point of the measurement system, which make it possible to measure thrust generated by different vehicle acing on different depths. Each of the strain gauges used in the stand can measure maximal value of force equal to 50N. The microprocessor system allows us to exchange the gauges, in case there is the need to measure force larger than 50N.

The laboratory stand enables to compare thrust generated by different fins (different shape, dimensions and stiffness) and different parameters of oscillation (amplitude, frequency). The artificial tail fin of BUV examined in this tests consists only of one segment controlled by single servomotor with planetary gearbox and crank mechanism.

It was assumed that the real BUV will be equipped with driving system consisting of one tail fin and two side fins. In the figure 4, side view of BUV No. 2 designed within SLEDZIK project (mainly by Polish Naval Academy and Forkos company) is presented [7]. The BUV is based on torpedo shaped hull with the modules containing the following sensors and equipment (beginning from the bow): (1) video and front echosounder module, (2) hydromodem, USBL transponder, sonar and top and down echosounders, (3) side fins, (4) microprocessor system and batteries, (5) tail fin. The diameter of the cylindrical hull is about 0.2 m and the length (without tail fin) about 1.7 m.

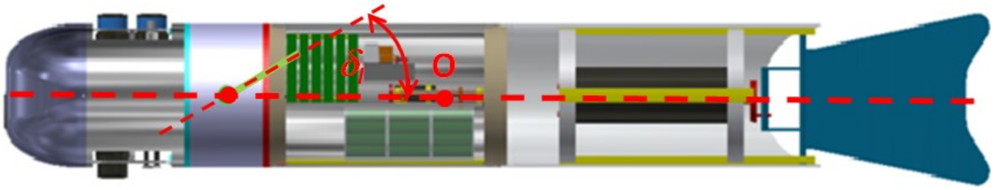

Fig. 4. Side view of BUV No. 2 designed within Polish project (3D model made by B. Szturomski): O — origin of gravity, δ_l — angle of position of left side fin [7]

In the figure 5, the example measurement of thrust generated by tail fin with heart shape is illustrated. The received responses on different frequency of oscillation in the form of generated force *X* and moment of force *N* were used in the next research focused on designing mathematical model of the BUV and then designing and tuning low level control. The details of the designed mathematical model of the BUV are included in [10]. Designed mathematical model of the motion of the BUV allows us to make initial tests on the vehicle maneuverability and possibly low-level control behaviors described in [10].

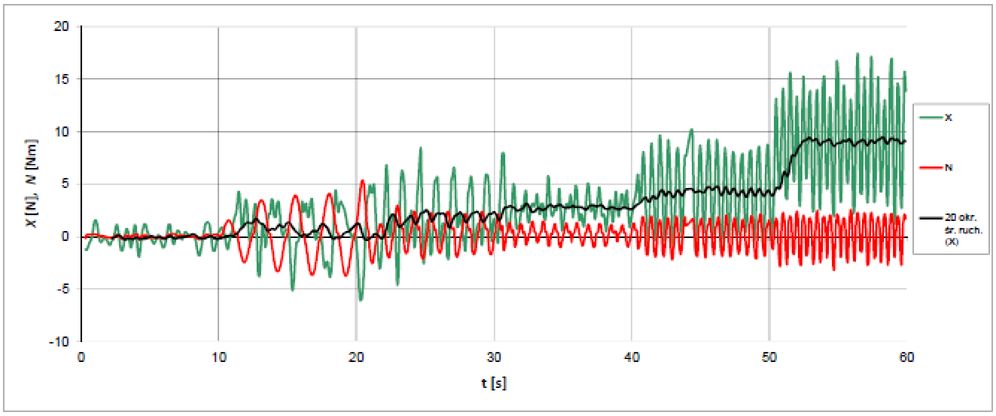

Fig. 5. Force acting in longitudinal axis of symmetry *X* and moment of force relative to vertical axis of symmetry *N* for fins with heart shape, oscillating with increasing frequency every 10 seconds (0; 0,47; 0,85; 1,3; 1,6 and 2 Hz) [own work]

In the figure 6, the results of numerical research on further research on autonomous control along desired trajectory using simple slide controllers of course and trim angles are illustrated. The parameters of the slide controllers were tuned in empirical way based on the observation of direct control quantity indexes. The parameters of the controllers will be precisely tuned in the future research on real BUV.

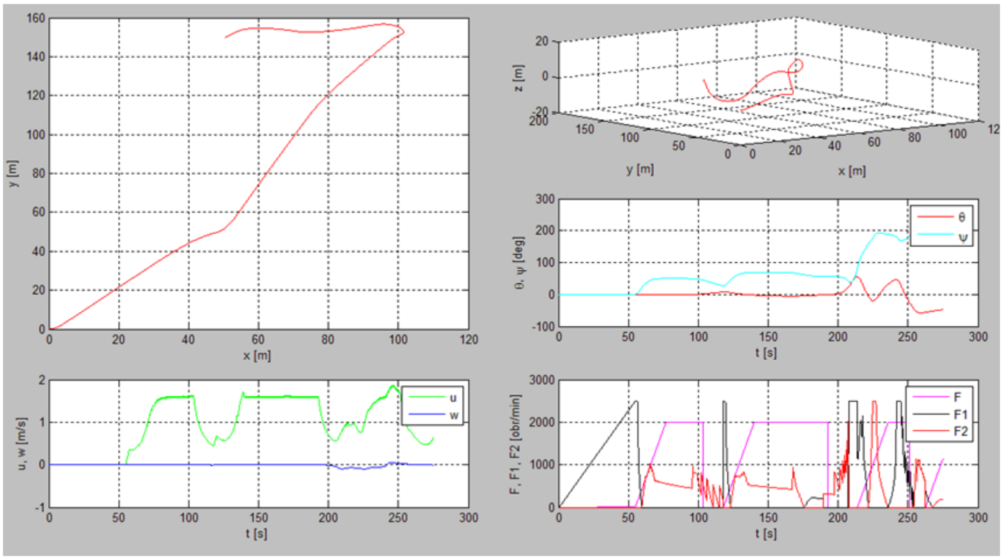

Fig. 6. Control of BUV along desired trajectory: *x*, *y*, *z* are position coordinates, *u*, *w* are linear velocities in longitudinal and transverse axes of symmetry, *ψ*, *θ* are course and trim angles, *F*, *F1* and *F2* are respectively forces generated by tail, side left and side right fins [own work]

One of the most important subsystems of each Autonomous Underwater Vehicle AUV, also biomimetic ones are navigation and communication subsystems. The first subsystem is responsible for safe and accurate navigation under and above the surface of water. One of the key function of the subsystem is an obstacles detection. The second subsystem is responsible for supporting communication channels between control station and BUV for two or more BUVs (a swarm) in underwater and air environment. To test these systems, the physical model of the BUV's navigation and communication subsystems by the Forkos company was built.

The model allows us to record in a synchronous way a set of following data, e.g. the distance to obstacles using looking forward Tritech Micron Echo Sounder (fig. 7), the position and orientation using IMU NAV-200 (fig. 8). Selection of the sensors and equipment mentioned above was performed in the initial phase of the project. The main criteria of the selection were: miniaturization of the sensors, limited budget of the project.

The tests of navigation and communication subsystems were carried out in Gdynia Marina. The physical model of the BUV with senosors was transferred under the hull of the Surface Underwater Vehicle. The underwater communication was provided on the distance of 400 m and the air communication on the distance of 2000 m [9].

During tests on obstacles detection, the USV transferring the physical model was swimming into direction of different obstacles with oscillations characteristic for undulating propulsion (fig. 7). Based on the obtained results, it can be stated that Micron Echo Sounders correctly indicate the distances to obstacles. Almost in all the cases, acoustic beams 'stop' at the obstacles during different motion patterns.

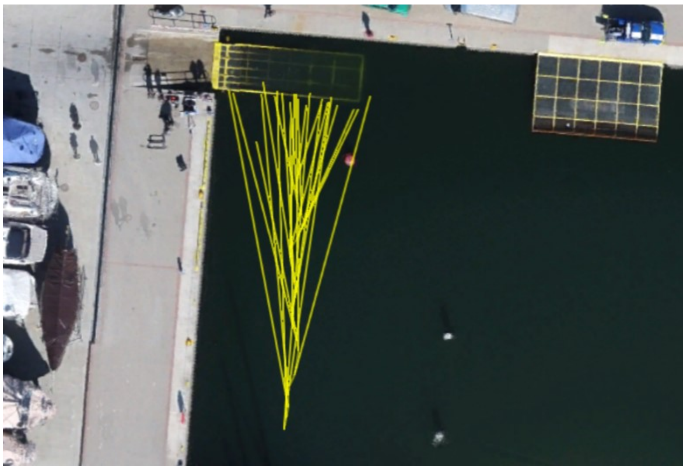

Fig. 7. The acoustics beams during oscillating motion of USV with physical model of the BUV in Gdynia Marina (visualization made by K. Naus) [9]

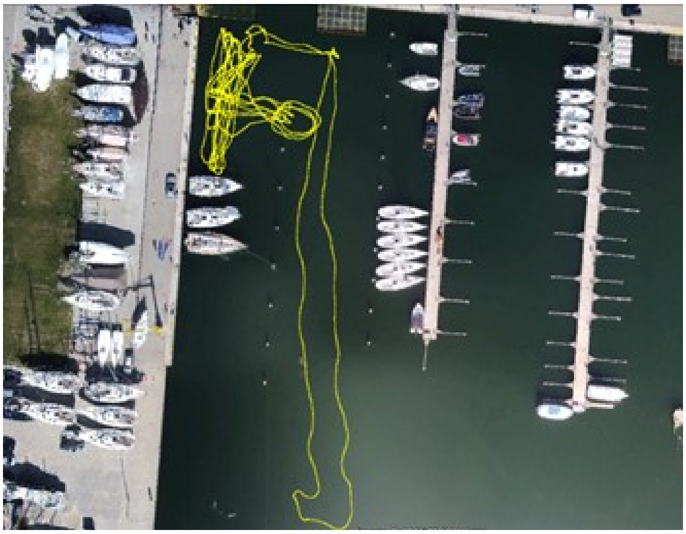

Fig. 8. The whole trajectory of the USV presented on the orthophotomap of Gdynia Marina (visualization made by K. Naus) [9]

During tests of the navigation subsystem, operation of the following devices were verified: electromagnetic log from the Alize company, the INS integrated with the GPS receiver NAV-200, USBL system MicronNav from the Tritech company.

In the figure 8, the whole trajectory of the USV during the measurements is shown in the background of the developed orthophotomap. It consists of several different transitions: the straight sections, the straight sections with a simulated oscillating motion around in circles and at the end of a longer transition to the breakwater and return to starting position.

BIOMIMETIC UNDERWATER VEHICLES — SABUVIS

The objective of the SABUVIS project is to build heterogeneous Biomimetic Underwater Vehicles BUVs with silent undulating propulsion for Intelligence, Surveillance and Reconnaissance ISR operations with larger than in the SLEDZIK project level of similarity to the real marine animals. The assumption is that the BUVs will be able to operate in autonomous (or semi-autonomous) mode and to communicate with each other for future cooperative swarm operation.

To build BUVs effective for underwater ISR, during the first stage of the project extensive analysis of the current and possible future operational needs and technical capabilities of the BUVs was performed. The final result of the analysis was to determine tactical and technical specification of the BUVs and scenarios of final demonstration of the BUVs. The specification and the scenarios take into account both operational needs and technical capabilities. Therefore, the specification and the scenarios are the compromise between that of what is needed and what current technology offers. The specification and the scenarios are included in the Technical Report on WP-100 'Operational scenarios'.

The main objective of this second stage of the project was to develop lists of sensors and equipment which will be mounted on board of the BUV No. 1 and 2 during the next steps. The specification and the scenarios are included in the Technical Report on reporting period M2 in SABUVIS project. Moreover, the second stage of SABUVIS was focused on three additional topics:

- initial design of 3D models of BUV No. 1 and BUV No. 2, including mechanical structures of heterogeneous BUVs with propulsion system, sensors and equipment;
- designs of test stands for investigating BUV prototypes;
- analysis of signals received from underwater sensors and pattern recognition in camera captured images.

More information about the first and third topics are included in [7]. The main efforts of the Institute of Electrical Engineering and Automatics was focused on second topic mentioned above. In the figure 9, conception of the test stand of mini CyberSeal is presented.

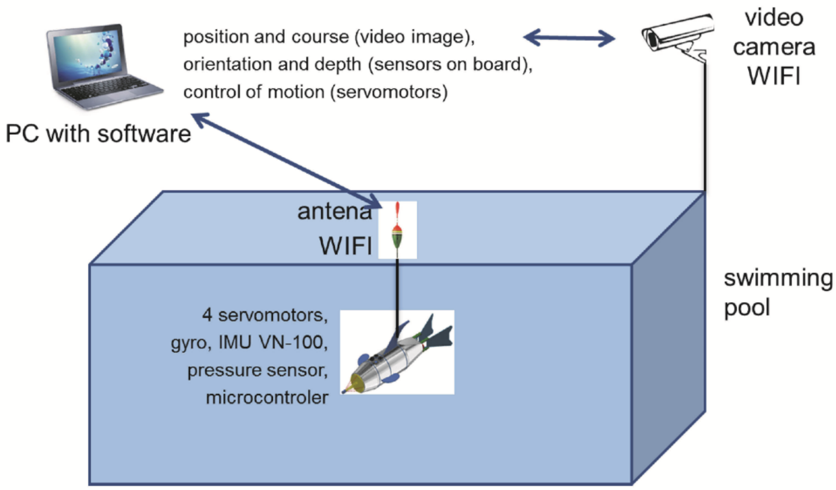

Fig. 9. Conception of the test stand of mini CyberSeal [own work]

The objective of this test stand is to examine construction, especially propulsion of the BUV no. 2 and algorithms for controlling its motion. To this end, the following components of the stand will be applied:

- mini CyberSeal, equipped with 4 servomotors for driving each fin separately, gyro compass, IMU and pressure sensor for navigation, WIFI antenna mounted on a float for communication and microcontroller for low-level control;
- video camera for capturing images needed for determination of a position and a course of the mini CyberSeal;
- PC with software for determination of a position and an orientation of the mini CyberSeal and its control, e.g. testing different control algorithms.

Construction of the mini CyberSeal is planned to be based on POM-C tube housing all electronic components, sensors, accumulator and servomotors.

Mini CyberSeal will be equipped with the following sensors:

- IMU VectorNav VN-100;
- digital compass Ocean Server OS-5000;
- depth sensor Wika A-10 with 0-1 bar range.

The implementation of the mini CyberSeal test stand is in progress.

SUMMARY

Nowadays, both SLEDZIK and SABUVIS projects are in progress. As it was mentioned in the introduction, the research are carried out by consortiums consisting of several R&D centers. Thanks to their efforts, it is expected to achieve two technology demonstrators of the BUVs at the end of 2016 as a main results of the SLEDZIK project. The final demonstration of the BUVs built within SABUVIS project should take place at the end of 2018. Finally, the BUVs should be able to move autonomously along desired trajectory with obstacles avoidance. Before the final demonstration comparison tests of the BUVs and classical Unmanned Underwater Vehicles UUVs are planned to be performed. These tests will be made in terms of maneuverability, energy efficiency and generated physical fields.

The research on the BUVs in Polish Naval Academy, the Institute of Electrical Engineering and Automatics cooperate with 3 different Institutes of: Structure and Exploitation of the Ships, Computer Science and Naval Weapon, Navigation and Marine Hydrography and Department of Technology of Underwater Works.

There is also international interests in the Polish proposal on SABUVIS II project which will be strictly devoted control of swarm of BUVs. The swarm control is also new research area which was undertaken at the Institute of Electrical Engineering and Automatics in the recent years. The research on swarm control are mainly included in [5, 6].

Acknoledgements

Presented in the paper results of research focused on BUVs were achieved within the following projects: development project No. DOBR-BIO4/033/13015/2013 financed by Polish National Centre of Research and Development in the years 2013–2016 and international project no. B-1452-ESM1-GP carried out close to the EDA Unmanned Maritime Programme in the years 2015–2018.

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BADANIA NAD BIOMIMETYCZNYMI POJAZDAMI PODWODNYMI REALIZOWANE W INSTYTUCIE ELEKTROTECHNIKI I AUTOMATYKI OKRĘTOWEJ

STRESZCZENIE

W ostatnich latach obserwuje się dynamiczny rozwój robotyki podwodnej. Rozwija się ona w kilku kierunkach w ramach badań prowadzonych przez wiele zagranicznych i krajowych ośrodków naukowo-badawczych. Rozwój robotyki podwodnej skupia się zarówno na udoskonalaniu konstrukcji i właściwości pojazdów podwodnych (rozwój sprzętowy), jak się na zwiększaniu autonomii pojazdów podwodnych w kierunku sterowania ławicą (rozwój programowy).

W artykule zaprezentowano nowe badania nad biomimetycznymi pojazdami podwodnymi realizowane w Instytucie Elektrotechniki i Automatyki Okrętowej w ciągu ostatnich kilku lat. Badania te skupiają się zarówno na sprzętowym, jak i programowym rozwoju robotyki podwodnej. Opisano badania prowadzone w zakresie biomimetycznych pojazdów podwodnych zrealizowane w ramach projektów krajowego i międzynarodowego. W zakończeniu artykułu zawarto podsumowanie zawierające prognozowane badania.

Słowa kluczowe:

biomimetyczny pojazd podwodny, napęd falowy, sterowanie autonomiczne.