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REPORT ON RESEARCH WITH BIOMIMETIC AUTONOMOUS UNDERWATER VEHICLE — LOW LEVEL CONTROL

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ABSTRACT

The paper presents the first part of the final report on all the experiments with biomimetic autonomous underwater vehicle (BAUV) performed within the confines of the project entitled 'Autonomous underwater vehicles with silent undulating propulsion for underwater ISR', financed by Polish National Center of Research and Development. The report includes experiments in the swimming pool as well as in real conditions, that is, both in a lake and in the sea. The tests presented in this part of the final report were focused on low-level control.

Key words:

autonomous underwater vehicle (AUV), biomimetic autonomous underwater vehicle (BAUV), course and depth control, autonomous control.

Research article

INTRODUCTION

Autonomous underwater vehicles (AUVs), as the name implies, are vehicles which need the ability to operate autonomously, or in other words, independently of a human being. This ability can be used on different levels and in different situations, e.g. during the entire operation of the vehicle — a vehicle completely independent of an operator, or only when a communication system with the operator is broken — a remotely operated vehicle with a function to safely come back to the operator. To act autonomously, not only in emergency situations, each AUV has to be able to perform many different tasks, among other things: to estimate its position, to follow a predefined path, to detect obstacles, to build a map of the environment, to avoid collisions, to record data from the sensors, to receive commands and send data from/to the operator.

The AUV with the abilities outlined above was constructed within the framework of the project No. DOBR-BIO4/033/13015/2013, entitled 'Autonomous underwater vehicles with silent undulating propulsion for underwater reconnaissance' financed by National Center of Research and Development. All the effort necessary to build the AUV, which due to a modern undulating propulsion was called biomimetic AUV, or in short BAUV [1, 7, 8], was divided into many stages. First, conceptual works were done focused on both the hardware and the software. Simultaneously, all external devices and sensors of the future BAUV were tested in separation in order to acquire practical knowledge concerning their application and their actual parameters and properties. The selection of the devices and sensors to include into the BAUV was dictated by vehicle tasks defined in assumptions to the project. In effect of the conceptual works initial designs of hardware and software were proposed. They enabled implementation of some software components and simulation tests whose goal was to lead the software to the state permitting its safe application on ready hardware. Simultaneously with simulation tests, hardware part of the BAUV was gradually constructed. Once both components were ready to combine, the experiments with complete vehicle were conducted.

The 3D model of the BAUV is presented in the figure 1. Beginning from the bow, the following modules are depicted:

- module with camera and 'looking' forward echosounder ('wet' compartment);
- module of the sensors (in the upper part: USBL, hydromodem and 'looking' up echosounder, in the bottom part: sonar and 'looking' down echosounder, pressure sensor — 'wet' compartment);
- module of the lateral fins ('dry' compartment);

- module of electronics and batteries (the batteries located in the bottom part can move along the longitudinal axis of the vehicle — the possibility of trimming, two computers PC-104 and power management system mounted in the upper part — the whole compartment is 'dry');
- module of the caudal fin consisting from two segments (the tail fin driven by an electric motor with nominal power 250W, rotary motion converted into an oscillating motion).

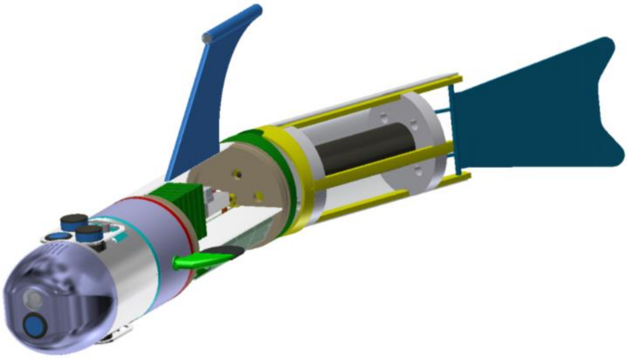


Fig. 1. 3D model of the BAUV [own study]

The present paper describes the first stage of the experiments, which were conducted in order to elaborate software functionalities as well as low-level control and vision data recording. The remaining part of the paper is organized as follows: section 2 gives objectives of all the experiments, section 3 details individual parts of the experiments, and the final section summarizes the article.

OBJECTIVES AND LOCALIZATION OF EXPERIMENTS

The experiments with the real BAUV had the following objectives:

1. Comprehensive testing of all software functionalities (BAUV and Command and Control Console — CCC) and correcting possible errors in implementation. Due to the fact that the software on the console as well as the BAUV side is characterized by a serious complexity, the likelihood of error occurrence was very high. The consequence was the need of testing all individual functions implemented both in the BAUV and console. Moreover, communication between both mentioned components needed a separate tests.

2. Configuration of Low-Level Control System (LLCS). The elementary ability of BAUV as an autonomous vehicle is to maintain a desired course and depth. In order to achieve the above-mentioned ability, Supervision Course and Depth Controller (SCDC) including a PID controller was applied. Correct work of the SCDC together with its PID component required series of tests in which different parameters of the controllers were tuned.
3. Verification of the BAUV ability to record vision data from cameras and sonar. The BAUV is equipped with two cameras (surface and underwater camera) and one sonar. In order to test vehicle ability to use them in the way ordered by the operator, series of tests were necessary.

All the above mentioned tests took place in five various water areas. The first tests of the vehicle that was ready in terms of hardware were held on the lake in the town Iława (fig. 2).

Fig. 2. Tests on lake in town Iława [own study]

Their main objective was to determine the way of turning maneuver. Unfortunately, as it appeared, adjustment of fin operation to a specific turning maneuver is a harder problem than originally seemed. Upon completion of the tests, the turning maneuver was not determined. Another important conclusion from the tests was the necessity to change the design of upper fin (or mast — fig. 1) which appeared to be too heavy and in consequence it significantly disturbed stable behavior of the vehicle.

Next tests were performed in the outdoor swimming pool in Gdynia (fig. 3). Their objective was to continue efforts in searching an effective turning maneuver. Moreover, changing depth maneuver was also designed. The tests revealed that most of initially developed maneuvers requires a total change or a serious improvement. In majority of cases, instability of sensors appeared to be the main cause.

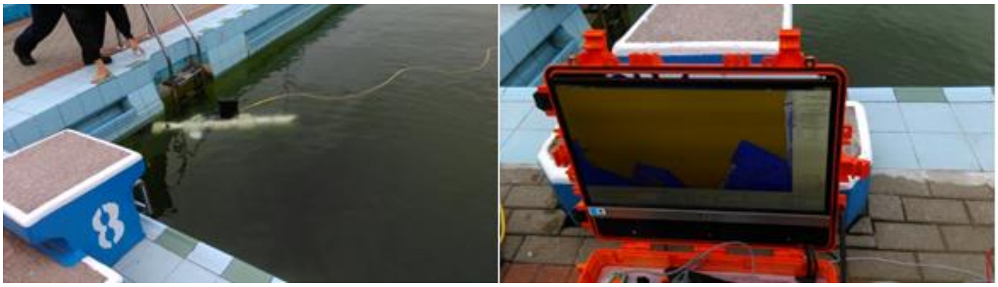


Fig. 3. Tests in outdoor swimming pool [own study]

Due to weather conditions (the tests began in November) and little transparency of water in the outdoor pool, the tests had to be transferred to the indoor swimming pool in the Mercury Hotel in Gdynia (fig. 4).

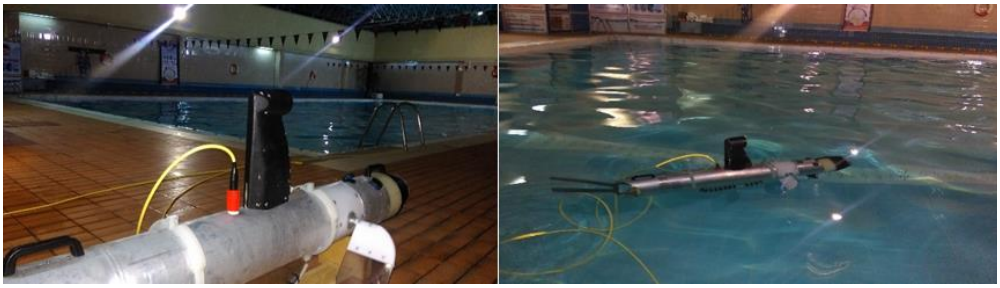


Fig. 4. Tests on indoor pool [own study]

Generally, the tests turned out to be very useful, they made it possible to determine almost the final form of many BAUV components, i.e.: SCDC, NS, collision avoidance, path following behavior, handling emergency situations. The consequence was readiness of the BAUV for the tests in open areas. Moreover, satisfying results of dead reckoning and path following contributed to a decision to start tests without a cable connecting the vehicle with the CCC.

The lake Osowskie nearby Gdynia was a next testing area (fig. 5). During the tests, the vehicle operated fully autonomously without connection to the CCC. The main purpose of the tests was to tune the NS in conditions without the sea current. The vehicle moved along a predefined path, whereas position errors determined by means of GPS (the vehicle moved underwater and once it surfaced the position error was measured) were the source of the information used to tune different parameters of the NS (Navigational System).

Fig. 5. Tests on lake Osowskie [own study]

Unfortunately, the tests in Osowskie lake revealed that water in the lake is not stagnant, unexpected motion of water was noticed which was due to wind and the fact that Osowskie lake is a flowing lake in which we deal with a slight motion of water. This ultimately resulted in changing the testing area and designing a procedure for estimation forces having influence on vehicle behavior, that is, environmental forces and errors resulting from inaccuracies of the vehicle itself (for example, errors being the consequence of systematic compass error, asymmetry in vehicle construction). In detail, the procedure mentioned above is defined in [3].

During the tests on the lake, the vehicle, for security purposes, was assisted by a men in kayak. Generally, the tests showed readiness of the BAUV to trials at sea. The only unknown after the tests was vehicle behavior in sea conditions, that is, in presence of forces disturbing its motion like the sea current.

The last testing area was the Gdańsk Bay near the village Mechelinki (fig. 6). The choice of that area was dictated by its shallowness. Small depth guaranteed safety of the vehicle. As before, during the tests, the vehicle was supported by a men in kayak. Moreover, to increase safety, a small bottle-buoy was assembled to the vehicle (fig. 7). This way, the vehicle behavior could be also observed while underwater.

Fig. 6. Tests in Mechelinki [own study]

The purpose of the tests in Mechelinki was comprehensive survey of all vehicle components and its ability to perform missions assumed in the project. As a result of the tests, the errors in the software that were not detected up to that point were corrected, the parameters of NS were tuned, estimation procedure of environmental forces and vehicle errors was tested and tuned, operation of cameras and sonar was verified, and ultimately, the vehicle was also tested during performing example missions in which it had to move along a predefined trajectory with recording vision data.

Fig. 7. Vehicle with bottle-buoy [own study]

EXPERIMENTS

Test with software

This task was performed during all works with the vehicle [4]. Generally, it appeared that the concept with simultaneous work on the hardware and the software, on the software in simulation [2, 5, 6], contributed significantly to accelerate the works. During the trials with the real vehicle it turned out that majority of the software implemented for simulated vehicle works correctly, the errors which appeared related to a minor part of all the software and they were corrected without necessity of drastic modifications in the entire software architecture.

Tests with LLCS

As already mentioned, the objective of the tests was:

- to develop turning and changing depth maneuvers used in remotely operated mode;

- to develop algorithm of SCDC which was responsible for maintaining the course and depth;
- to determine parameters of PID controllers to be a part of the SCDC.

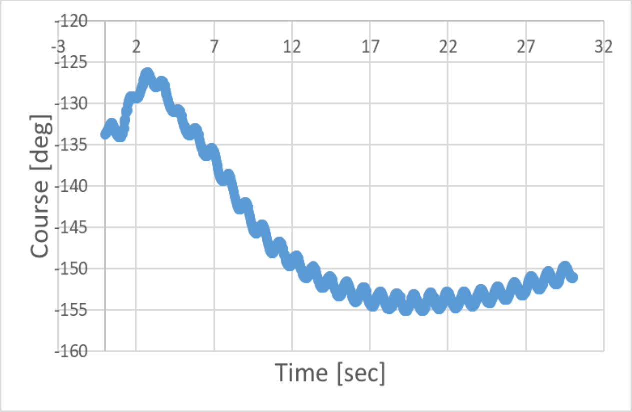
Leaving aside the tests on the lake in Iława town whose result reduced, in principle, to make the project team aware of the problem it faced (lack of the float, difficulty in effective separation of depth and course control by means of two propellers, i.e. one rear fin and two lateral fins), the first tests on LLCS and SCDC were performed on the outdoor swimming pool. During the tests, three methods of turning maneuver were examined. In each method, the rear fin worked as a rudder, i.e. it was maximally tilted to the direction of the turn, whereas individual turning methods differed in operation of lateral fins.

The turning maneuver No. 1 arranged one fin to work forward, whereas the other one was stuck vertically down and it was motionless. Due to the fact that the turning maneuver No. 1 significantly slowed down the vehicle, and in effect, deteriorated its ability to turn, in the maneuver No. 2, the decision was made to change vertical arrangement of the motionless fin to the horizontal arrangement. The fin was still motionless. The turning maneuver No. 3, activated motionless fin, in this turning method, the fin worked in the reverse mode. All the turning maneuvers were examined for different parameters defining motion of the fins. Figures 8 (a–c) and 9 (a, b) displays example results.

Generally, the tests in the outdoor pool showed that the most effective turning method is maneuver No. 3 with the fins operating in the opposite direction. Unfortunately, the following tests on the indoor pool revealed that this maneuver is only possible on the surface. In underwater position, the maneuver causes the vehicle to stop and to immediately surface. Due to lack of the float the vehicle has to use the lateral fins to maintain the depth, using them simultaneously to turn the vehicle appeared to be simply impossible.

Next tests with LLCS took place on the above-mentioned indoor pool in Mercury Hotel in Gdynia. The tests determined the final form of the SCDC and its PID component (originally, two PID controllers were assumed, however, eventually, the decision was made to use the solution with only one PID controller). Generally, the operation of the SCDC can be defined as follows. The depth and course control were almost completely separated, earlier concepts of the SCDC assumed combined application of both type of fins to control the depth as well the course which ultimately appeared to be impossible due to lack of the float. When on the surface, the vehicle turns by means of lateral fins operating oppositely, the rear fin works as a rudder and it is motionless. The flaw of that solution is, as already mentioned, stopping the vehicle, whereas its benefit is a high angular velocity. When underwater, the turning maneuver is performed in a different manner, namely, with application of only the rear fin. When course error is high, that is, it is above a threshold, the rear fin is motionless and it works as a rudder, whereas when the error is below the threshold, the fin moves from zero position (along vehicle hull) to maximum position in the direction of the turn. To control the course, PID controllers as well as any other controllers with a similar modus operandi are not used.

a)



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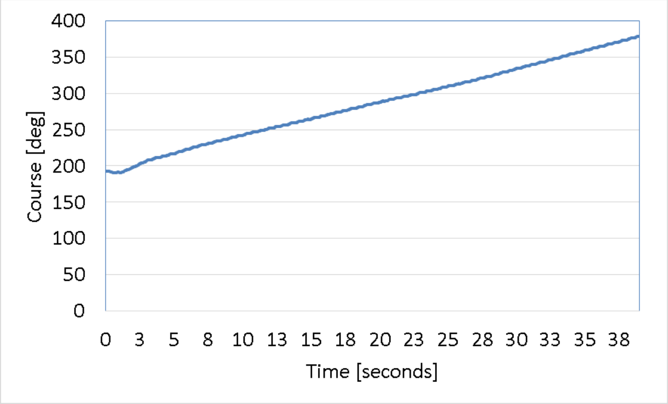


Fig. 8. Example results of experiments for turning maneuver No. 1 for different values of parameters: (a) $F = 1$ Hz, $A = 50$ deg; (b) $F = 2$ Hz, $A = 40$ deg (F — frequency, A — amplitude) [own study]

c)

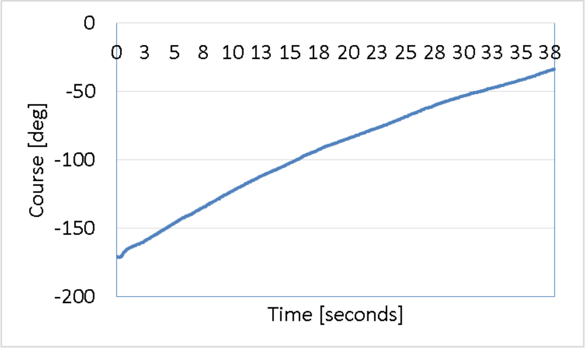
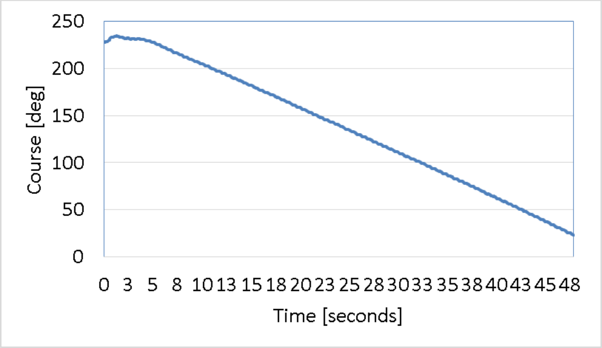


Fig. 8 cont. Example results of experiments for turning maneuver No. 1 for different values of parameters: (c) *F* = 4 Hz, *A* = 40 deg (*F* — frequency, *A* — amplitude) [own study]

a)



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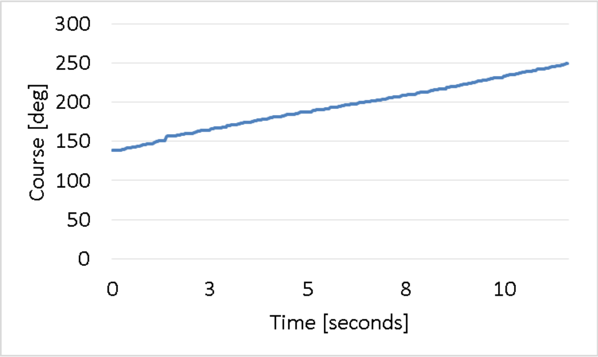

Fig. 9. Example results for turning maneuvers No. 2 (a) and 3 (b) for the fallowing parameter setting: *F* = 2Hz, *A* = 40 deg [own study]

As mentioned above, course control takes place with application of simple controller with three modes of control depending on the course error. The pseudo-code of the course controller may look as follows:

```
If course error < threshold_min then
Rear tail moves according to velocity setting
Else
If course error > threshold_max then
Rear tail is maximally bend to the left/right
Else
Rear tail moves on the left/right side
End If
End If
```

The depth of the BAUV is changed exclusively by means of lateral fins and a single PID controller is used for that purpose whose task is to control working frequency and neutral position of the fins. The neutral position has a limited set of possible settings, the solution in which it is a continuous value with an upper and lower limit turned out to be unsatisfactory due to harmful vibrations of fins.

As mentioned above, the same PID controller decided also about fin working frequency. It was assumed that when the depth error is very small the fins move with the frequency corresponding to a desired vehicle speed, otherwise, the frequency is increased by value provided by PID controller. Detailed specification of the BAUV depth controller may be presented in the form of the following pseudo-code:

```
Input:
P,I,D – parameters of PID controller
DE – depth error
IDE – sum of depth errors
DDE – derivate of DE
V – vehicle velocity
B – parameter
Output:
NP – neutrum of pectoral fins
FP – frequency of pectoral fins

Begin
If DE > 2
       NP = 90; // vertically up
End If
If DE > -2
       NP = -90; // vertically down
End If

If velocity > 0 and Abs(DE) <= 2 then
       pid = P*DE+I*IDE+D*DDE;
       If DE > 0 // vehicle has to go down
              pid = B*pid;
```

```
      End If
      pid = thresholdPID(pid); // thresholding pid
      NP = round(pid/3)*3;
      FP = getFrequency(V);
      pid = Abs(pid/60); //scaling pid
      FP = FP + pid;
End If
End
```

The above concept of SCDC was thoroughly examined for different thresholds used to control the course as well as for various parameters of PID controller. Ultimately, after the tests on the pool, the decision was made to use the following values:

- the range of course error which does not need regulation — the rear fin operates according to a desired vehicle speed, it does not cause the turn of the vehicle: <–5, 5> degrees;
- the range of course error for which the rear fin moves in a 'half' mode — the fin moves from the position along the vehicle hull to the maximum position in the direction of the turn: (5, 30) degrees and (–30, –5) degrees;
- parameters of PID controller: P = 20, I = 0.5, D = 0.

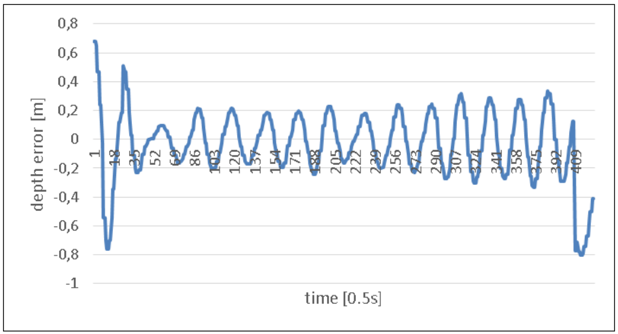

Fig. 10. Example diagram of depth error during tests on Osowskie lake (at the end of diagram change of desired depth occurred) [own study]

A next stage of the research relating to LLCS and SCDC was tests on the Osowskie lake. Example results achieved during those tests are presented in figures 9 and 10. As shown in figure 10, the depth error has oscillation characteristics, and what is more, it grows at the end of the recording almost to the value 1 meter. The oscillations ranging 0.3–0.4 m could be caused by errors of a pressure sensor, or, they could also result from oscillations of the vehicle in horizontal motion. In turn, the growth of the error at the very end of the recording was the effect of changing a desired depth by the autonomy system.

Generally, the results achieved on the lake, at least in relation to the depth control, differed from those accomplished on the pool. The oscillations mentioned above turned out to be exceptionally surprising. However, since the depth error did not exceed an assumed threshold, the project team found the results achieved on the Osowskie lake as satisfactory.

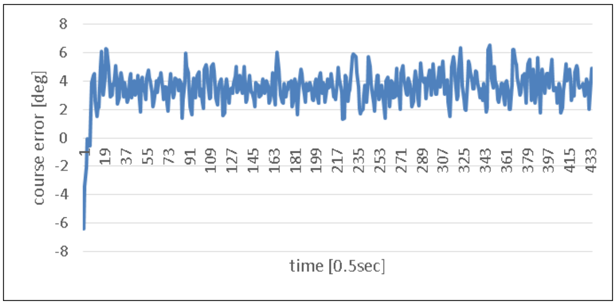

Fig. 11. Example diagram of course error (absolute value) during tests on Osowskie lake (numbers of successive measurements are on X axis, interval between measurements was 0.5 sec.) [own study]

The course control, in spite of simplicity of the applied solution resulting from construction limitations of the BAUV, appeared to be very effective. As depicted in figure 11, the course error only slightly exceeds the threshold 5 degrees for which regulation of the course is activated. What is more, it seems that course control was unnecessary for more than half of the distance presented in the figure.

The last stage of the research on LLCS and SCDC took place at sea. They were carried out in two places. The first one is the Gdańsk Bay in the village Mechelinki, and the second one is also the Gdańsk Bay, however, nearby the War Harbor in Gdynia. In the case of tests in Mechelinki the whose example result are shown in figures 12 and 13, the achieved performances where accepted by the project team. Both the error of course and depth were within acceptable limits.

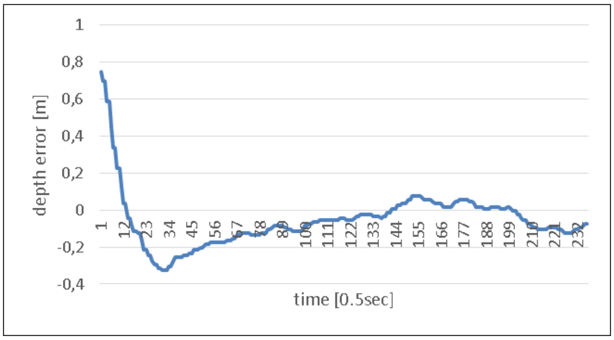

Fig. 12. Example diagram of depth error during tests at sea (numbers of successive measurements are on X axis, interval between measurements was 0.5 sec.) [own study]

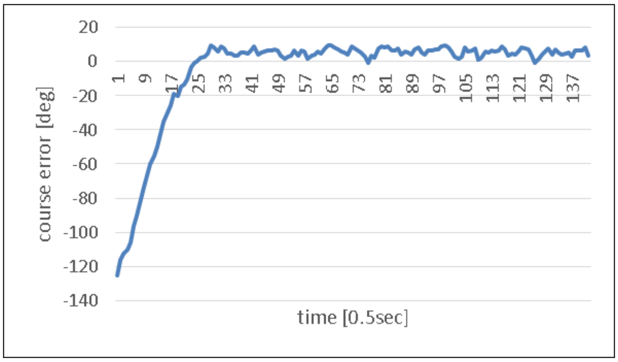

Fig. 13. Example diagram of course error (absolute value) during tests at sea (numbers of successive measurements are on X axis, interval between measurements was 0.5 sec.) [own study]

The tests nearby the War Harbor which according to the assumptions took place in a difficult weather conditions were supposed to show how the solutions designed in the BAUV work in conditions of greater influence of the environment. Unfortunately, it turned out that the solution applied in the BAUV to control the course is insufficient in the case of a stronger sea current. During the tests, the vehicle was unable to maintain the course perpendicular to the current course. The error of vehicle course exceeded even 20 degrees in this case. Unfortunately, the construction solutions used in the vehicle which are result of wrong initial assumptions as well as the need for changes in mechanical construction after a serious breakdown of originally designed rear fin of the vehicle, are definitely insufficient for vehicles that are supposed to operate in the sea.

In order to provide the vehicle ability to work in the sea conditions it is necessary to apply different solutions, for example, the one applied in the CyberFish [9] which is based on the two-segment rear fin. The solution used in the BAUV practically reduces the role of the rear fin to the role of the rudder. Application of the fin as a drive takes place only when the course error is below 5 degrees threshold which for a strong sea current may result in continuous course regulation and practical uselessness of the rear fin as a drive. The approach applied in the CyberFish may solve the above problem. Flexibility of its rear fin makes it possible to use it simultaneously as a rudder and drive which makes the CyberFish able to more effectively counteract the sea current than the BAUV.

Tests on cameras and sonar

Tests with cameras started on the indoor pool and they relied on examination of all vehicle operations working on cameras. The following operations were tested: turning on/off cameras in definite point in time, turning on cameras for a time with simultaneous vehicle rotation around its axis — when performing the operation the vehicle is on the surface, turning on cameras and maintaining a specified course and depth. For each operation above, an extra option is also to turn on/off the lights situated in front of the BAUV. Example video shots recoded during tests on the pool are presented in figure14.

Fig. 14. Example video shots from surface and underwater cameras during tests on the pool [own study]

The tests on the pool showed that the software responsible for controlling cameras works flawlessly. The only noticed problem was impossibility to control vehicle course when it is motionless and underwater. The reason is vehicle construction which for zero velocity (we deal with such velocity while recording video) makes it impossible to change course exclusively by means of the rear fin which works as a rudder but only when the vehicle is in motion. Such property of the vehicle means that video recording for a desired course and depth is performed in two separate phases: first, the vehicle alters the course and depth, once desired parameters are reached it turns on cameras, while recording it continuously maintains the depth, the course is not controlled. In practice, it means that under the water and in conditions of the sea current pushing the vehicle out of the course, it will not be able to observe a specified object.

A next stage of tests on cameras and sonar took place at sea. This stage, as well as the previous one, showed total efficiency of the vehicle in this regard. All recordings were done correctly. The only phenomenon observed during the research was vehicle instability while recording on the surface. Unfortunately, sea waves affect motion of the vehicle which in order to maintain the course had to periodically activate course controller which on the surface runs lateral fins in opposite direction. The effect of so was just instability of the vehicle.

The other noticed thing was also a short range of underwater camera and in consequence its practical uselessness. For good transparency of water, detectability of objects by means of camera remained a lot to be desired. Example video shots as well as sonar photo taken during tests at sea are presented in the following figures.

Fig. 15. Example video shot made with surface camera aiming at promenade in Mechelinki [own study]

Fig. 16. Example video shot made with surface camera aiming at the so-called 'Torpedownia' in Gdynia [own study]

Fig. 17. Another example video shot made with surface camera aiming at promenade in Mechelinki [own study]

Fig. 18. Example video shot made with underwater camera, the photo shows sand on the seabed [own study]

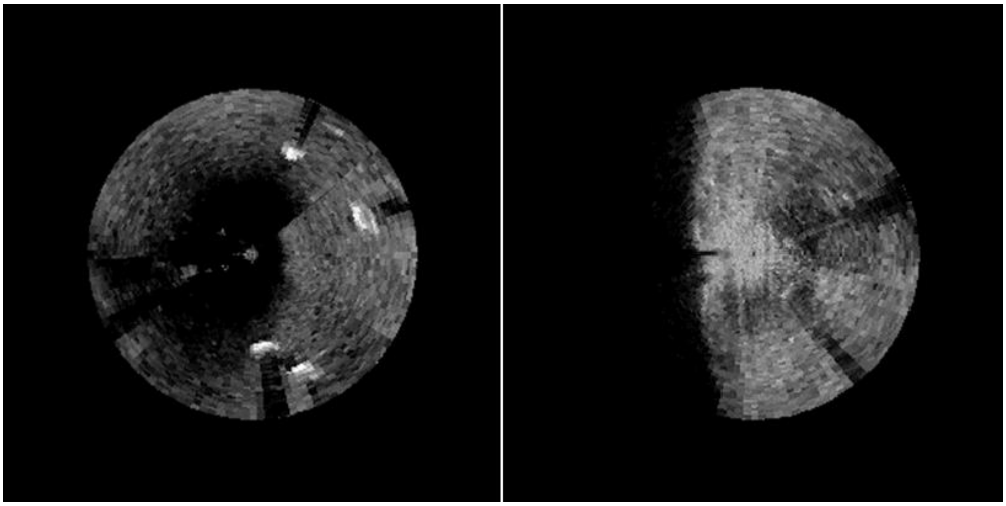

Fig. 19. Example sonar images [own study]

CONCLUSIONS

The paper constitutes the first part of the final report from the experiments carried out with the real biomimetic autonomous underwater vehicle designed within the project entitled 'Autonomous underwater vehicles with silent undulating propulsion for underwater reconnaissance' financed by National Center of Research and Development. The research described in this paper was focused on software functionalities as well as low-level control and vision data recording. All the experiments presented in the final report took place in a different locations and lasted about six months with short breaks. As a result of them, the vehicle is capable of performing almost all predefined tasks and meets massive majority of the assumptions made at the initial phase of the project. In short, the vehicle is able to perform simple commands in remotely operated mode, to autonomously follow a preprogrammed path with simultaneous operation on its sensors, to pass all recorded data by means of three communication channels, including underwater acoustic channel, and to handle different emergency situations.

In spite of the fact that the research described in the report is undeniable success because they produced first in Poland fully equipped (not a toy) autonomous biomimetic underwater vehicle, further experiments are necessary in two areas. The first one is obstacle detection in shallow waters and the second one is accurate underwater navigation based on the odometry and low-cost navigational sensors. Both areas were 'touched' during the project, however, the results which were achieved do not satisfy the project team and generally they require improvement within further works.

Acknowledgements

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RAPORT Z BADAŃ NAD BIOMIMETYCZNYM AUTONOMICZNYM POJAZDEM PODWODNYM — STEROWANIE NISKOPOZIOMOWE

STRESZCZENIE

W artykule przedstawiono część pierwszą końcowego raportu z prac zrealizowanych w ramach projektu „Autonomiczne pojazdy podwodne z cichym napędem falowym” współfinansowanego przez Narodowe Centrum Badań rozwoju w latach 2013–2017.

Słowa kluczowe:
autonomiczny pojazd podwodny, biomimetyczny autonomiczny pojazd podwodny, regulacja kursu i głębokości, sterowanie autonomiczne.

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