Infrastructure Development for Designing a Bio-Inspired Underwater Robot

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Abstract

The paper describes an infrastructure kit for creating a bio-inspired AUV, which must solve the problem of covert observation of the water area. The kit includes autonomous and remote-controlled robots, for testing and working out various software, hardware, technical and technological solutions, etc. in their natural habitat. Also a method for synchronizing the effectors of a bio-inspired AUV, which was tested on this kit, is presented.

Keywords

Underwater robot, synchronization of effectors, bio-inspired robot.

1. Introduction

One of the most actively developing areas in robotics is the research and development of bio-inspired robotic systems. Adaptation of various biological movement mechanisms, learning, animal behavior patterns, etc. allows robots to solve intangible new tasks [1], [2], for example, movement [3], pattern formation [4], [5], etc.

On the other hand, bio-inspired approach is not only about usage of different animal behavior and models in the robot control system. There’s also a morphological adaptation: usually technical device is similar in some way to a biological original. In this case, we are not talking about similarity in the narrow mean of the word, but in a wide one: it is a necessary condition of solution.

It is essentially important for underwater robotics, for example, for monitoring the target water area in order to detect unwanted activity or reconnaissance of the enemy's water area. Anyway, the reconnaissance underwater device should be concealed for enemy detection equipment. That is why disguising the reconnaissance/patrol robot as typical fauna species of the specific water area, for example, fish, is one of the ways to reduce its visibility. At the same time, focusing only on the robot external resemblance to a fish is not always enough, because echolocation devices can easily distinguish robot from real fish with produced noises of effectors, movement hydrodynamics , etc.

In the wide mean, the similarity of the robot with an original biological object (for example, fish), concretely with original “fish behavior”, reduces the overall visibility of the apparatus for observation equipment. Moreover, in some cases [6] even fish themselves don’t distinguish robot from congeners.

Since it is especially easy to distinguish robot artificial movements from an animal one, it is necessary to make one similar to another. Among fish species, there’re two movement types are defined: eely-like and boxfish-like. They are differentiated with length of body parts, used to make locomotion wave. The most interesting type is scad-like as it is the most widespread among fish species.

It is necessary to bend parts of the body and tail stem to create a locomotion wave. The easiest way with structural perspective is to fix main part, where electronics is located, and use loose tail part, consisting of a propulsion device and a caudal fin. MSU scientists developed robot [7], which uses such motion method(see Figure 1). It is used to monitor ecosystems. Though it’s tail has only one degree of freedom, developers achieved high maneuverability of device with relative simple design. It is also possible to use a flexible tight-fitting shell to create a locomotion wave [8], [9].

Although it is enough just one degree of freedom to create a locomotion wave, it is also insufficient for achieving the required degree of wave-like motion biosimilarity. The BAUV tail [10] is driven by two Maxon EC-i servo motors, which create the oscillatory movements, properly synchronized to create undulating motion. This underwater apparatus is not equipped with sensors and controlled by operator.

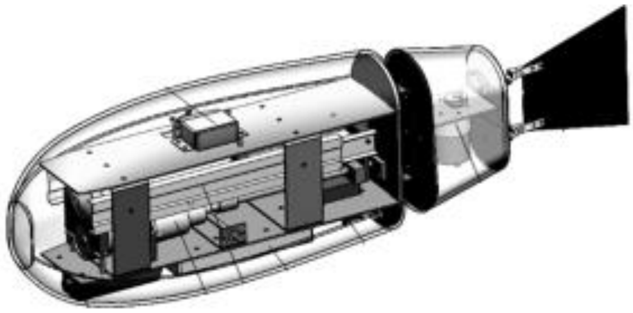


Figure 1: BAUV Robot

There's another method of smooth movement proposed [11]. The developed cam gear mechanism is capable of converting continuous rotation into purely harmonic movement. The driving force is lower than tuna-like movement, but the design is cheaper and easier to produce and operate. This manned underwater vehicle (MUV, Figure 2) wasn't autonomous, it was designed to work out the principle of a cam drive usage.

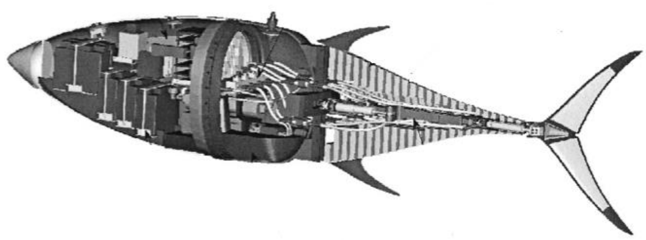


Figure 2: MUV with cam drive with two degrees of freedom

The interesting feature of the devices [12], [13] is the caudal fin design. In both devices it consists of parts, which are form spine equivalent, and a set of plates fixed on it (see Figure 3), which are able to rotate on at a small angles about the axis perpendicular to the vertebrae. When cords of spine are strained, the tail moves. This MUV was also used to prove the usage of cable traction.

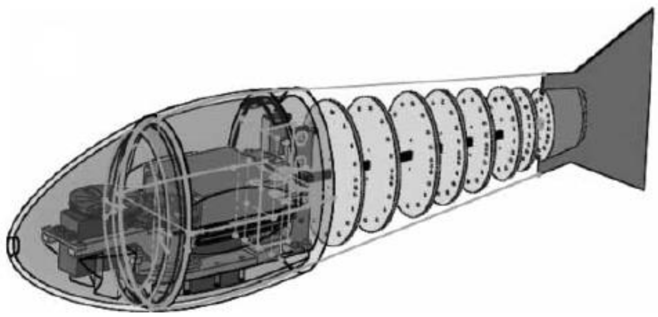


Figure 3: Multi-link MUV on rope systems

The number of freedom degrees in the caudal fin is important, however, when the whole body is housed in a flexible shell, it becomes less significant, meanwhile such characteristics as shell-environment interaction type and principle of spine bending become vital. For example, though the tuna robot [14] (see Fig. 4) has only one tail servo motor, still, because of an advanced mechanics, the robot motions are closer to its research object. The purpose of making this robot was just to work out mechanics of motion, it doesn't localize itself, has no control system.

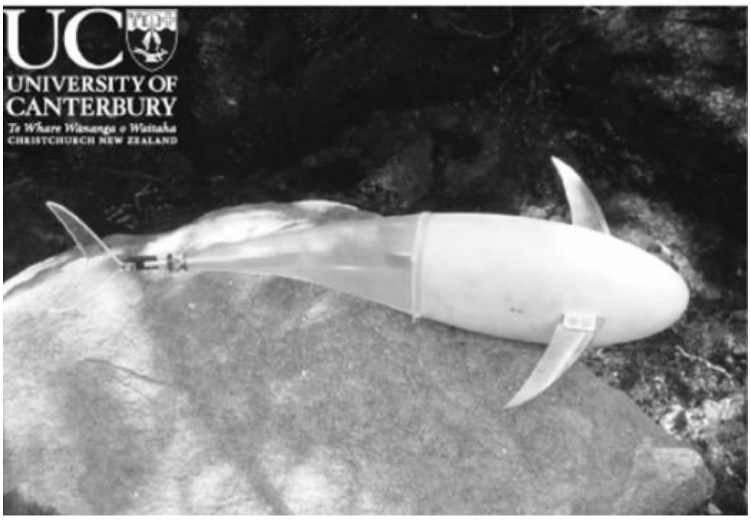


Figure 4: Single link MUV with flexible tail sheath

One of the most famous prototypes of the robot fish is the American SoFi project [15] (see Figure 5). Though it is quite compact, it is fully functional robot, that is able to work in open water controlled remotely. The positive placement pump provides tail motions, expulsive force is created with water volume pumped into each side of tail. Vertical movements are provided with varying angles of lateral fins. Robot is controlled remotely with acoustic waves produced with special control panel. Video camera is set on robot to let divers get video information. An installed pressure sensor allows SoFi to stay on specific depth specified by operator.

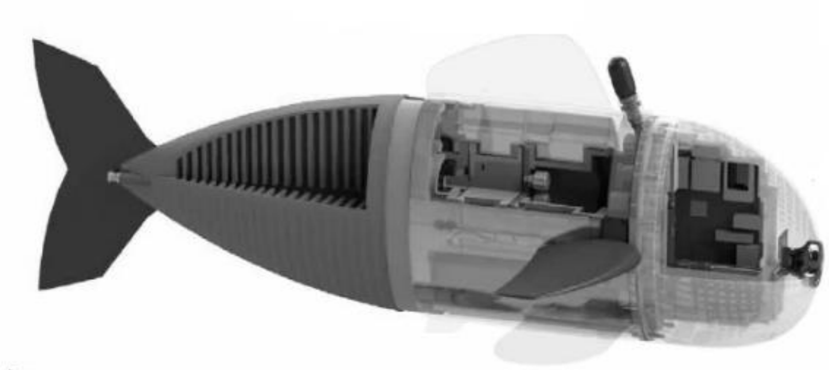


Figure 5: SoFi robot

There are many paper works of technical solutions ([16], [17]), researches of fish movement hydrodynamics ([18]). Generally, bio-inspired robots are developed since 1990s [19], still there's no such mass-produced robots, probably it is due to complexity of design devices. Also, proper proficient sensors are required, that won't expose underwater apparatus, quiet motors to move in water. All subsystems must be energy efficient to stay in water as long as possible and compact for overall size of robot would not exceed the size of fish it imitates.

2. Problem statement

The project goal is to develop autonomous underwater apparatus for covert surveillance in specific water area. Necessity of covertness defines bio-inspired approach: to stay hide, the robot imitates fishes. It is intended, that it lowers chances vehicle being discovered with enemy detection equipment. Successful development of such system requires many tasks to be solved, such as: external resemblance, movements as they are and their flow patterns similarity to fish, usage of advanced sensory system, interactions between native inhabitants of area and artificial object. Solution of the goal requires interdisciplinary work. Additionally, a special infrastructure to test in essential fishes' environment software, hardware, technical and technological solutions.

3. Description of the infrastructure complex

The developed system consists of three underwater robots (two small bio-inspired underwater robot BUR-S-21 and one mid-size bio-inspired underwater robot BUR-M-21) and a small underwater laboratory platform ULP-S-21.

3.1. Small underwater laboratory platform ULP-S-21

ULP-S-21 moves around in exploring water area controlled remotely and registers motions of other objects (targets) with on-board equipment. Among on-board equipment also there's bioenergy equipment.

On-board equipment is set in three modules, they are power, motor-driver and computing modules. Modules are connected with sealed connector wires. All equipment is installed on a bearing frame (Figure 6). The laboratory moves up and down with four brushless motors, to move horizontally only two motors are used. Robot buoyancy is positive.

On-board computation is made on Raspberry Pi 4 controller with ROS deployed on it. Also in computing module there're I2C interface to connect peripheral devices, Wi-Fi and Ethernet interfaces to connect remotely with on-board computer. Wi-Fi works with external antenna.

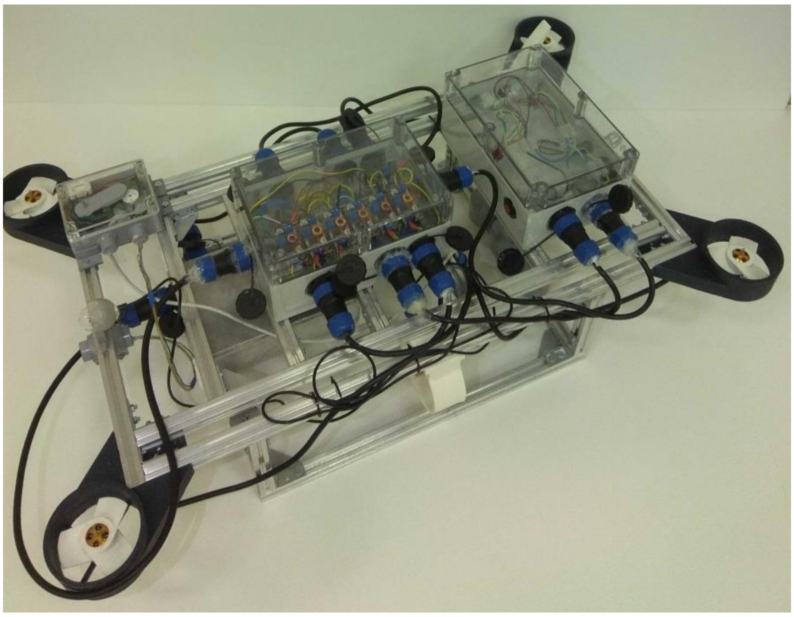
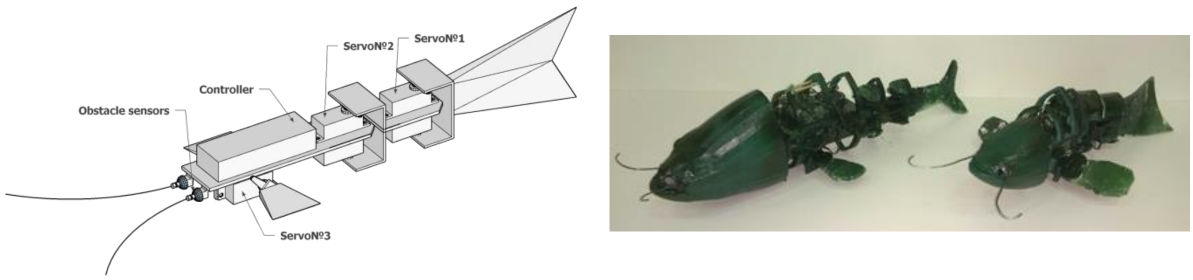


Figure 6: Small underwater laboratory platform ULP-S-21

3.2. Small bio-inspired underwater robot BUR-S-21

BUR-S-21 moves autonomously in exploring with ULP-S-21 water area, submerging, keeping the depth for some time and emerging randomly. It is used as target being observed by operator with equipment of ULP-S-21 during first test procedures of different subsystems, such as, effectors, computer vision system.

The unmanned underwater vehicle (UUV) is made according to the principle of a two-stage fish tail, controlled by two sealed servos. The movement of the robot in a straight line is carried out by servo drive # 1. The turn is carried out using servo # 2. Ascent / dive is controlled by two pectoral fins, which are powered by servo # 3. The schematic structure of the target fish is shown in Figure 7a.



a) b)

Figure 7: a – Scheme of small bio-inspired underwater robot BUR-S-21, b – two BUR-S-21 foto

Robot is controlled with AT-Mega328 microcontroller. Pololu Maestro controller is used to control the servos. There're two crash sensors in front and one humidity sensor to define weather robot is on the surface of the water or under one.

The control program for each servo is set in the form of six numbers: T = <A1, A2, V12, V21, T1, T2>, where A1, A2 are the minimum and maximum angles of rotation; V12, V21 – forward and reverse movement speeds; T1, T2 – delays in the initial and middle phases of movement, i.e. the pause time in state machine.

Main program is implemented by Mealy's finite state machine (Figure 8).

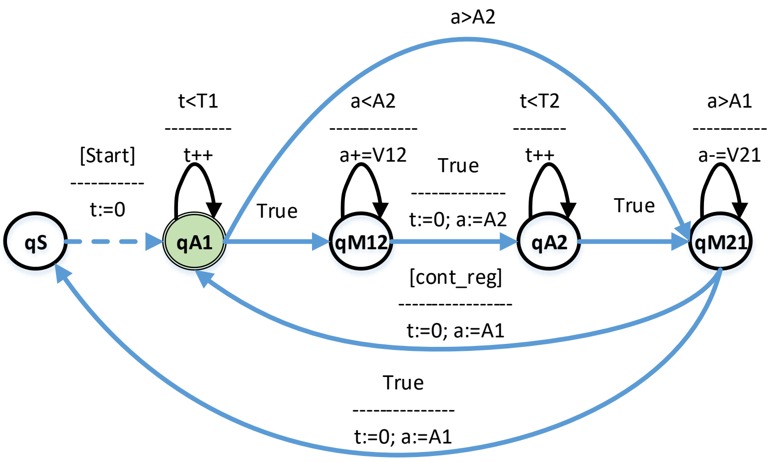


Figure 8: Mealy's state machine for controlling one servo

The effector movement programs are synchronized with each other. Each effector, except for first one, is activated by the previous one at the moments of transitions time when the state machine performs procedures at the qA1→qM12, qA2→qM21, qM12→A2 or qM21→A1, due to procedures on transitions are performed simultaneously, each one per in 1 clock cycle (Figure 9). The work of effectors without synchronization is on Figure 10.

3.3. Medium bio-inspired underwater robot BUR-M-21

BUR-M-21 is a prototype to test in essential fishes' environment new types of effectors, sensory system, i.e., synthetic scale with pressure sensors, algorithms.

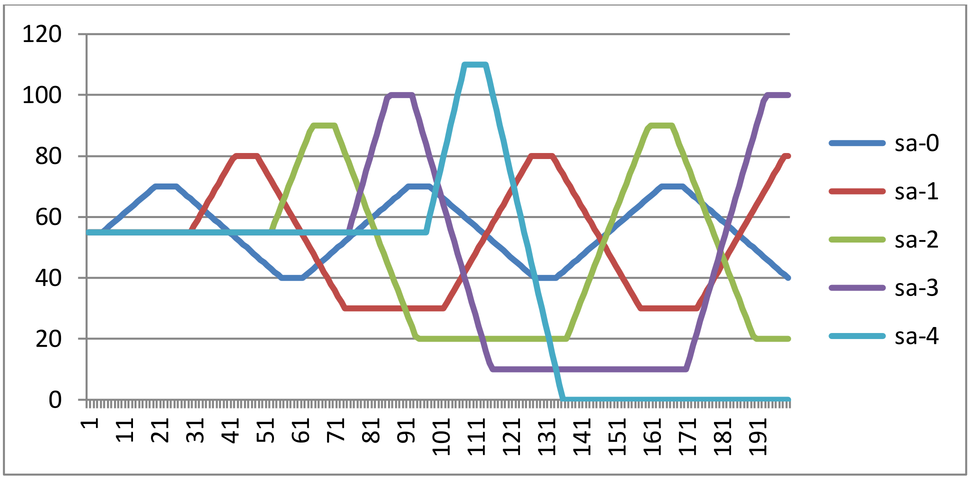


Figure 9: Synchronized work of servos. Each servo starts the next servo. Leader (main initiating) servo – “sa-0”. The x-axis is the time, the y-axis is the angle of rotation of the servo

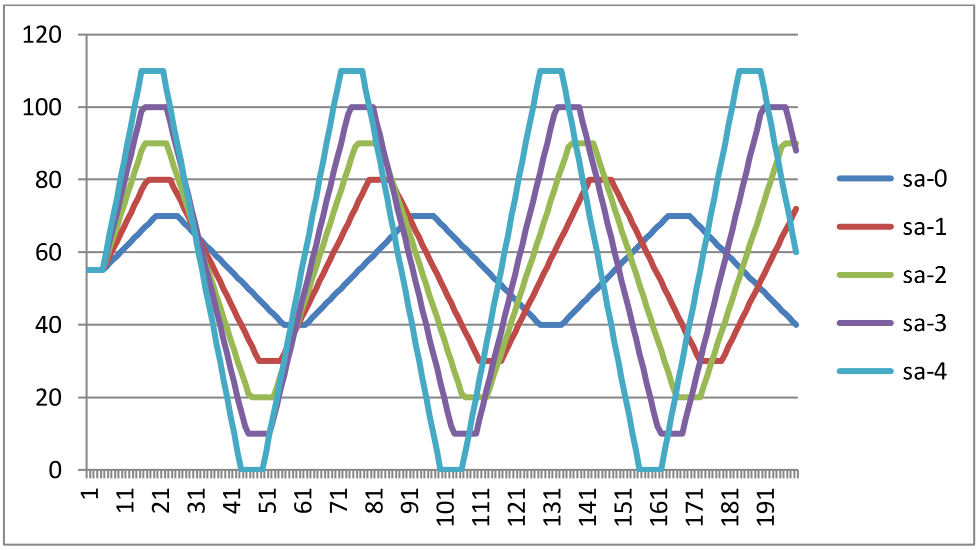


Figure 10: Independent operation of servos. The “sa-0” drive is a head drive with minimal mobility. Next come the drives “sa-1” – “sa-4” with a gradually increasing amplitude and frequency of movement. “Sa-4” drive – tail, most mobile

The design of robot was inspired by perch, which is the most prevailing in Central Russia freshwater predator. Skeleton for both perch and robot is basic structural element, that consists of spine, vertebrae and ribs. Because of such body structure perches are agile and their internals are well protected. There’s model of perch skeleton on Figure 11a.

a) b)

Figure 11: a) - Scheme of the skeleton of the BUR-M-21, b - the robot BUR-M-21

In robot spine, there’re two degrees of freedom made with two bends in specific places. Both bends rigged with belt drive of 1:2 ratio. It allows to reduce payload on motors. Vertical movements are provided with varying angles of lateral fins.

Robot is controlled with AT-Mega2560 microcontroller, connected with Pololu Maestro controller, that is used to control servos. There are four servos: one drives the tail fin, one provides a bend of the spine, the left servos turn lateral fins.

There're also a set of sensors (leakage sensor to detect the leaks and IMU sensor of 10 DOF), RS-485 interface to provide communication with operator and Bluetooth for peripherals.

The main control algorithm is identical to the one for BUR-S-21.

Tests of all objects were carried out in the pool of the robotics laboratory, National Research Center Kurchatov Institute, Moscow, as well as in the pools of the military innovative technopolis Era, Anapa, at the exhibition "Innovation Day of the Ministry of Defense of the Russian Federation".

4. Conclusion

To succeed in designing bio-inspired underwater robots, it is required to use interdisciplinary approach. In the work discussed the necessity of special infrastructure system to test, work out new materials, control methods, new types of locomotors. Such system of four apparatus was proposed and showed its practical importance in the development of technologies for the creation of a bio-inspired underwater robot.

5. Acknowledgements

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