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Analysis of Underwater Robot Designs[*]

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This article is devoted to the analysis of existing domestic and foreign designs of underwater robots. First of all, emphasis is placed on the description of structures and the analysis of their influence on the maneuverability of movement in a liquid. Various mechanisms of bringing underwater robots into motion are considered, approaches to modeling are described. A description and comparison of underwater mobile robots driven by screw propellers, depending on their number, location, and shape of the hull, is given, and the designs of robots implementing biosimilar motion in a liquid are considered in more detail. A comparison is made of the methods of movement in a liquid using screw propellers and with biosimilar or screwless methods of movement. An overview of the mechanisms used to form biosimilar movements is given, a description of the materials and properties of the hull characteristic of this type of underwater robots, as well as a description of the mechanism of movement in a liquid, taking into account resistance forces and buoyancy control. Particular attention is paid to the works devoted to the study of the shape of the tail of a fish-like robot, aimed at improving the efficiency of robot movement in liquid. The analysis made it possible to identify the strengths and weaknesses of the mechanisms used to implement biosimilar motion in a liquid. Based on the results of the analytical review, the typical structure of the underwater robot and the requirements to its components are considered. In conclusion, the current technical and scientific challenges facing researchers working on the creation of underwater robots operating both in autonomous and remotely controlled modes are discussed.

Keywords: underwater robots, biomimetics, fish-like robots, hydrodynamics, ROV locomotion, mobile robots.

Underwater robots are classified into two classes, first of them is the ROV (Remotely Operated Vehicles) which is dependent on someone to control them remotely, and the AUV (Autonomous Underwater Vehicles) which can decide their paths and move on their own [1]. There are numerous types of AUVs which contributed a lot to the area of ocean research. Such unmanned vehicles are usually used for military purposes, oil and gas exploration or discovering underwater caves and video recording places that humans can't reach. Therefore, ongoing researches on underwater robots not only benefit the expansion of research fields regarding the ocean sciences, but also plays an important role in securing the borders of our countries.

Alongside the advancement of technology and the advent of tiny electronic parts, there was advancement in the research field of underwater robots, where mini AUVs (less than 20 kilograms) where introduced to the market [2], their small size allows them to be more compact, reliable, silent and with high capability of maneuverability. The miniaturization of the parts makes it easier to involve more equipment and technologies – increasing the efficiency of the underwater robot, while still having the same size [3].

There are two types of underwater robot designs, ones with propellers and bio-inspired ones. This work is devoted more to the study of fish-like bio-inspired underwater robots, while the review of underwater robots with propellers can be found in [4]. The main idea of motion in underwater robots is to convert the electrical signals into mechanical movements, while maintaining a good algorithm to mimic the swimming techniques of the real fish to provide the necessary mechanical motion to accomplish different tasks or missions underwater. Having a powerful control system lets the fish be more autonomous, thus choosing its own paths and form routes around the obstacles [5]. Water is known to be incompressible and has a high density almost 800 times more than the density of air. Due to the physical characteristics of water, all movements required by fish for locomotion will result in motion in the water as a locomotion medium and vice versa. Fish need to overcome the hydrodynamic drag forces by producing thrust. The body shape of the fish and its physical characteristics affects the swimming mechanism of the fish and thus define its abilities in the water.

Where fish that uses BCF (Body and/or Caudal Fin) techniques usually has better agility and maneuverability since their swimming technique involves movement of the body/main axis of the fish, while on the other hand, fish that use the MPF

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(Median and/or Paired Fins) techniques, lack maneuverability but are faster swimmers.

That a fish can be able to swim in the water, it needs to transfer momentum to the surrounding water. Basically, the momentum is transferred from the fish to the water through drag, lift and acceleration force.

The mathematical model and computational software package allow solving problems of optimizing the parameters of the design of the robot and its control system [6]. In the process of intensive and effective development and exploration of the World Ocean, a special role is assigned to uninhabited remote-controlled and autonomous underwater vehicles, that can exclude the direct presence of a person in a dangerous underwater work area. At the same time, in order to perform various technological operations, autonomous underwater vehicles, which are complex multidimensional and multi-connected nonlinear dynamic objects operating under conditions of parametric uncertainty and non-stationarity, must have high-quality control systems and devices [4].

Usually, at the design stage of autonomous uninhabited underwater vehicles, the task is to evaluate the dynamic properties of the device and its control system, taking into account the main factors: structural forms, speed of movement, angular orientation of the device relative to the flow, and the device of the propulsion system. The specific goal is to determine the hydrodynamic drag forces acting on the apparatus and evaluate the basic dynamic and energy properties of the apparatus by modeling [7].

In our work, an analysis is made to identify the strengths and weaknesses of the mechanisms used to implement biosimilar motion in a liquid. Based on the results of the analytical review, the typical structure of the underwater robot and the requirements for its components are considered. Highlighting the current technical and scientific challenges facing researchers working on the creation of underwater robots operating both in autonomous and remotely controlled modes.

Existing underwater robots

There are different types of underwater robots, one of the most used mechanisms, is the one used in submarines. Where propellers are used to achieve locomotion along different 6 degrees of freedom. The shape of the robot decides in which areas it can be used. Where both the shape and the hull type decide the generation of vortexes around the robot. By using the right amount of propellers, optimal hydrodynamic efficiency can be achieved. Some of the traditional propeller-based underwater robots are shown in table 1.The considered robots have designs in which the movement is carried out with the help of thrusters. Usually these are several thrusters in direction of movement (X, Y, Z), and to implement complex three-dimensional movement, it is necessary to combine the rotation of these thrusters. For more information, please refer to the corresponding article to each robot.

Table 1. **Different underwater robots using propellers**

Name	Shape	Hull	Number of Propellers	DoF
Nessie IV[8]	Rectangular	Open	5	6 (pitch, roll, yaw, Y, Z, X)
CISCREA [9]	Cubic	Open	6	5 (roll, yaw, Y, Z, X)
X4-ROV [10]	Cylinder	Closed	4	6 (pitch, roll, yaw, Y, Z, X)
Nessie[11]	Torpedoes	Closed	6	5 (roll, yaw, Y, Z, X)
Blue ROV2[12]	Rectangular	Open	8	6 (pitch, roll, yaw, Y, Z, X)
Daya Bird[13]	Rectangular	Open	6	5 (roll, yaw, Y, Z, X)
Hybrid[14]	Torpedoes	Closed	4	4 (roll, yaw, Y, Z)
Underwater Drone[15]	Torpedoes	Closed	4	6 (pitch, roll, yaw, Y, Z, X)
SAUVIM[16]	Torpedoes	Closed	8	3 (surge, sway, heave)
Super GNOM[17]	Box	Open	6	6 (pitch, roll, yaw, Y, Z, X)

A lot of factors depend on the external shape of the robot, as well as the hull type, as it highly contributes to the hydrodynamics of the robot – hulls can be open, i.e., the body of the robot will have a lot of openings and more exposed, while closed hulls mostly include all of the components inside the robot, providing minimal exposure. Such mechanisms are widely used since they don’t involve any theoretical complications, however they have some disadvantages, the most important of them is the safety issues. When we have a lot of motors used, we need to isolate all of them, so water doesn’t get inside, and by increasing the number of propellers we increase the chance of water leaking into the robot.

Secondly, when the propeller is exposed to the open water without any kind of protection, things like ocean waste can get stuck into the propeller and thus causing the propeller to stop. Thirdly, it can be harmful to the fishes, as small fishes can die if it passes through such propellers. The problem of ingress of algae, underwater nets or living organisms significantly limits the capabilities of widespread modern underwater robots. In addition, underwater robots of such design have low maneuverability [18].

That's why our research is concerned with propeller-less types of underwater robots. Table 2 shows different designs of biomimetic robot, their form, the mechanism used to achieve locomotion, the different techniques used for actuation and controlling the links of the body, as well as the compliance i.e. the ability of the robot to move freely in different directions, perform maneuvers and have a flawless harmonical motion, for more information take a look at the corresponding article to each robot.

*Table 2.***Different biomimetic robotdesigns**

Name	Form	Swimming Mechanism	Actuation	Compliance
Robo Jelly[19]	Jellyfish	Body Propulsion	Shape Memory Alloy	High
Turtle Like[20]	Turtle	Pectoralfins	Electric Actuators (Servomotors)	Medium
Dolphin[21]	Killerwhale	Tailfin	Electric Actuators (Servomotors)	Medium
USM [22]	Eel	Pair of propellers and fin	Tunnel Thrusters	High
Casi Tuna[23]	Tuna	Tailand pectoral fin	DC Motors	Medium
Multi-Join tFish[24]	Carangiform	BCF Undulation	Electric Actuators (Servomotors)	Medium
Stingray Robot[25]	Stingray	MPF Undulation	Electric Actuators (Servomotors)	Medium
Octobot[26]	Octopus	Body Propulsion	Chemical Reaction	High
Robotic Manta Ray[27]	Manta Ray	MPF Undulation	Ionic polymer–metal composites	Medium
Starfish Robot[28]	Starfish	Body Propulsion	Shape Memory AlloyWires	High
Robo Scallop[29]	Scallop	Jet Propulsion	FEA	Medium
PATRICK[30]	BrittleStar	Crawling	Shape Memory AlloyWires	High
Starfish-LikeSoftRobot[31]	Starfish	Crawling	Shape Memory Alloy Wires	High
Morphing Limb Amphibious Turtle Robot[32]	Turtle/Tortoise	Drag-induced Swimming/Walking	Variable Stiffness Material- pneumatic Actuators	Medium
Biomimetic Fish[33]	Fish	BCF/MPF Oscillation	Ionic polymer–metal composites	Medium
Underwater Bionic Robot [34]	Fish	BCF Undulation	Electric Actuators (Servomotors)	High

The most popular swimming mode is the Carangiform, since it offers a fair compliance, taking into consideration that the Carangiform swimming robots doesn't need a lot of complicated ideas and are rather simple than complex compared to other swimming modes like the jellyfish or the octopus, which are difficult to assemble and control, due to their complicated designs and they are still being experimented by researchers.

Fish swimming mechanisms

Hydrodynamics

There are two types of swimming techniques that fish depend on. The first one is the BCF - which is movement using the Body orCaudalFins or using both of them, fish create thrust by bending their main axis into a backward-moving propulsive wave that extends to the caudal fin. The other technique of swimming is the MPF - where the fish uses the Median and a Paired Fin or both of them for propulsion, they their pectoral and pelvic fins alongside with the dorsal and anal fins to transfer momentum to the surrounding water and thus generate thrust [35].

It has proven to be a difficult task to understand how fish really moves in the water [36], or how they generate force to swim in a steady motion and provide agility and maneuverability. So various models including fluid mechanics and newton's mechanics has been under research in the previous decades to try to provide a mathematical modeling and a simulation of how the fish really swims.

To construct a mathematical model, the forces acting on the robot should be taken into consideration. Vertical forces acting on the fish underwater are buoyancy plus the hydrodynamic lift, in addition to weight of the fish, while the horizontal forces are thrust and resistance.

As for the swimming drag, it consists of three components. Firstly, the skin drag or the friction between the surface of the skin and the boundary layer of water. Which means that the material used to create the robot should be chose carefully, as it can cause higher friction and thus affect the overall swimming efficiency of the robot. Secondly, the pressures created by the fish while pushing the water around it to pass in-between, here the fish that have a perfect streamlined shape can achieve higher speeds than other fish. Accordingly, the body shape of the robot decides its locomotion speed. Thirdly, the loss of energy in the vortices during the procedure of creating lift or thrust, where the shape of the fins plays a big role in deciding the induced drag, thus, the tail shape, as well as the pectoral and paired fins, decide the stability of the robot underwater. Both the second and the third component can be combined to act as pressure drag [37, 38]. However, different calculations contribute to calculating and estimating the acceleration reaction, based on whether the robot is stationary and the water is accelerating around it or vice versa [39].

Taking a look into the momentum transfer, there are three factors that determine the contribution of the momentum transfer mechanisms to thrust and resistance, which are the Reynolds number, reduced frequency and the shape of the fish [40].

Reynolds number (RE) is the ratio of inertial forces over viscous forces, where at low Reynolds numbers the flow tends to be laminar, and as the Reynolds number increases, the flow tends to be turbulent. To achieve stability for the robot, low Reynolds numbers are preferred, it would lead to less vortexes and thus less drag. The reduced frequency, indicates the importance of unsteady (time-dependent) effects in the flow, where it compares the time needed by a water particle to transverse the length of an object with the time taken to complete one movement cycle and it is used as a measure of the relative importance of acceleration reaction to pressure drag and lift forces. Taking into the shape of the fish, a lot of studies and research have been made into this issue, however there is a little information about how the shape of the fish affects its swimming efficiency. The streamlined shape of the body of the fish, helps it reduce friction between its skin and the water, thus leading to higher swimming speeds. The streamline shape of the fish reduces the drag by reducing the pressure difference over the body [41], where that reduced pressure lets the boundary layer of the water to flow without separation from the surface of the skin until the trailing edge [42]. Another shape feature that contributes to the efficiency of the fish is the shape and type of the caudal fins. As the surface area of the fins and also the shape contributes to the value of the forces acting on the fish.

Depending on the nature of the environment where the fish lives, they tend to use different mechanisms for swimming. Anguilliform, Carangiform and Thunniform have been a big source of interest for scientists in the last decades. Where it’s obvious that the Anguilliform has the best maneuverability and the most agile, since it uses all its body as a propulsive element to produce undulatory motions which adequately cancels out lateral forces and reduces the chances of the fish body to recoil [43]. Anguilliform are also capable of backward swimming by shifting the propagation direction of the propulsive wave [44]. As for the Carangiform swimming mode, it is always related to higher thrust and thus higher swimming speeds, since in such mode, the caudal fin and the last third of the body is mainly used to generate thrust. However, such swimming mode lack agility and maneuverability since a bigger percentage of their body is rigid. It also has a high chance to recoil since lateral forces are concentrated at the posterior. While as for the Thunniform mode, it is one of the most efficient swimming modes, and can maintain high cruising speeds for a long period of time since nearly 90% of the thrust force is caused by the caudal fins. Also, its streamlined shape helps it to reduce the pressure drag. However, such swimming mechanism is only suitable for calm waters like rivers, and is not suitable for rapidly moving streams. In addition to that, Thunniform swimming modes doesn’t help the fish to make fast turning maneuvers or to swim slowly.

Buoyancy

The organs, muscles and bones of the fish, have higher density than that of the water, so the fish will eventually sink if it doesn’t overcome the force of gravity. However, there are some kinds of fish that have credits of organic compounds that have a low density, enough to make the density of the fish equal to the density of the water. Other fish uses their pectoral fins to dive, accordingly with the dynamic lift theory, fish moves the pectoral fins up or down to help it ascend or descend, where the pectoral fins have a function similar to the wings in the birds. Depending on the angle of attack, an area of lower pressure is formed and thus allowing the fish to elevate using the rules of hydrodynamic lift.

Most fish have a swim bladder, which is a balloon of gas inside the body of the fish, where the fish secretes gas to make the bladder bigger and thus float, or on the other hand fish can release gas to achieve a negative buoyancy and dive [45, 46].Similar biomimetic mechanisms have been developed for robots, where an artificial swimming bladder can control the depth of the robot. Other method include the hydrodynamical lift theory, where the paired fins decide whether the robot will ascend or descend.

Description of underwater robot construction

Latest studies on robotic fish have focused on Thunniform, Anguilliform and Carangiform swimming modes. In the Anguilliform mode, all the body moves in a large sinusoidal undulation as in eels [47]. One big disadvantage in the Anguilliform swimming mode, is that it is very difficult to program and control the robot, since it has a lot of joints, as almost all the body is used to generate thrust. In the Carangiform mode, body undulations are limited to the last third of the body length and propulsion is generated by a rather caudal fin. Where the fastest is the Thunniform which uses only the caudal fin to produce thrust, it is also known to be the most efficient, since it benefits from the turbulence in the wake of the fish to generate inwards turning vortexes on both of its sides, creating a peak thrust behind the fish's tail known as reverse von Karman vortex street [48].Even though this swimming mode is very efficient, a key challenge in the design of robotic fishes is the design of a mechanism that could achieve this swimming mode with accuracy and efficiency, also Thunniform swimming modes lack the maneuverability and agility.

Our main concern in this article will be the middle choice which considered to be theCarangiformswimmers,which are mostly faster than Anguilliform swimmers but have less agility due to the rigidity of their bodies,they have better agility than Thunniform swimmers [49]. Figure 1 shows the physical model of the Carangiform motion based on Lighthill's theory. The governing equation of Carangiform motion can be implemented as equation:

$$y_{body}(x,t)=\left(c_1x+c_2x^2\right)\sin\left(kx+wt\right),$$

where y_{body} is coordinate of the body along a y-axis, t is time, x is the displacement along the main axis, c_1 and c_2 are linear wave and quadratic wave amplitudes respectively, $k = 2\pi/\lambda$ is the body wave number, λ is the body wavelength, $w = 2\pi f$ is the body wave frequency and f is the flapping frequency of the robotic fish.

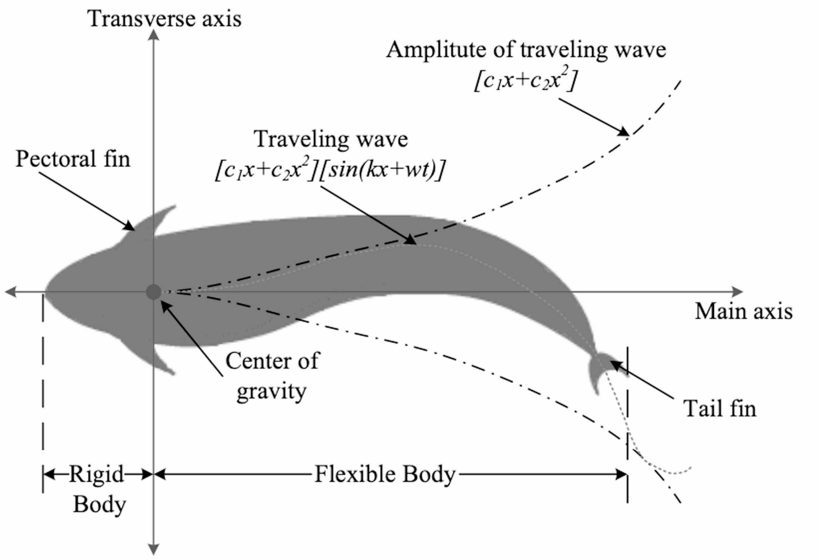

Fig. 1. Physical model of Carangiform motion [50]

After deciding which swimming mode would be the best for the robot, now we have to take into consideration some other variables that affect the swimming efficiency. First of all, we chose the Carangiform swimming mode for the robot, since it is slightly maneuverable than the Thunniform fishes, however its maneuverability is still lower than the Anguilliform. The Carangiform fish uses the last third of its body to produce thrust needed for locomotion, where the other two thirds of the body is rigid. The rigidity of its body leads to increasing the tendency of the body to recoil since the lateral forces are concentrated at the posterior part of the robot. Two main adaptations were taken into consideration to lower the tendency of the anterior part to recoil: i) reducing the depth of the robot body in the part where the caudal fin connects with the trunk, referred to as caudal peduncle. ii) concentrating the depth of the body and the mass towards the anterior. These two adaptations will decrease the sway movements of the head and thus increasing the stability of the robot and minimizing the recoil forces.

Different design types

There are different designs of under biomimetic underwater robots, each of them has its advantages and disadvantages. Let's take a look at some of them. As shown in figure (2) such construction offers great control of the rear part of the robot fish, having three motors to control the body and the tail, however the rigid head contributing to almost 50 % of the body length is considered a minus, high recoil should be expected, as well as lack of accuracy when it changes direction to the left or right. Also using a lot of motors makes it difficult to maintain harmony between them.

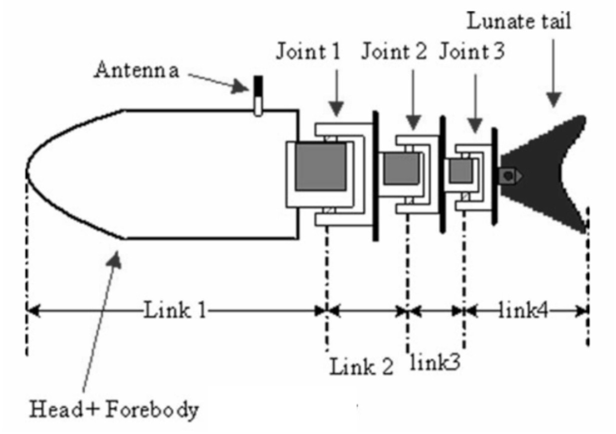

Fig. 2. Mechanical configuration of robotic fish [51]

On the contrast, such design shown in figure (3) has pectoral fins which helps to control the depth level and also allows the robot to perform some combined movements which other robots without pectoral fins can't perform. However, a disadvantage is also the rigid front part which contributes more than 50 % of the total body length. And another noticeable disadvantage here can be the gap between the front body and the caudal fin, which divide the robot into two different parts, leading to unexpected behavior of the robot under higher pressure, as well as unexpected results due to vortices.

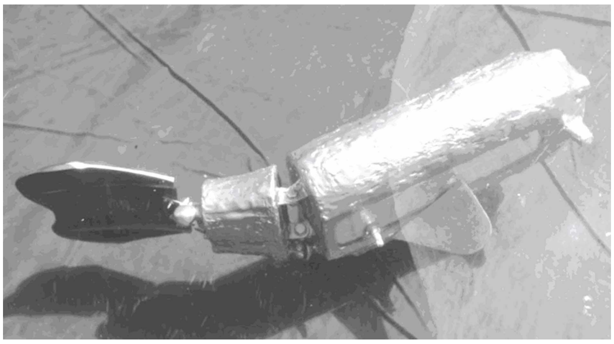

Fig. 3. Fishlike robot [52]

The construction of the robot basically depends on the required tasks and missions, in some cases, a larger battery can be needed, as shown in figure (4) where almost 80% of the robot internal space is filled by batteries, The Beihang University Robotics Institute has developed a robot which has unspecific biometrical features to be used as autonomous underwater vehicle.SPC-III has a two-joint BCF type propulsion module. It has a roughly fishlike appearance designed with a large side profile area for quickspinning abilities, it has a length of 1.2 meters, however can dive only 5 meters but proved to be useful as a visual assistant for underwater archaeology [54].

One of the swimming modes that has a high maneuverability is the Anguilliform, as shown in Figure (5), an eel shaped robot consisting of separate links – each of them powered by a servo motor. By controlling a series of servo motors, any kind of motion can be achieved. Eels are known to be excellent swimmers, also the undulatory BCF movements of the eels reduces the swim drag and takes benefit from the formed vortices to achieve higher efficiency locomotion. Eels are also an ideal variant for exploring narrow underwater caves.

While it might not seem like a disadvantage, but the presence of a lot of servo motors makes it harder to program and control the whole mechanism. And a worth to mention advantage, is that the robot can still function even if it lost one of its servo motors powering one of the links.

Different tactics to control the fishlike robot

Taking into consideration the caudal fin. To control the tail to move left and right. This is usually done with the help of the reverse and forward movement of the servomotor. but some research suggest using a continuously rotating DC motor in combination with a gearbox as shown in Figure (6) to control the tail beat instead of the forward and reverse motion of the servomotor. This method proves its effectiveness and allows us to achieve higher tail pulse frequencies.

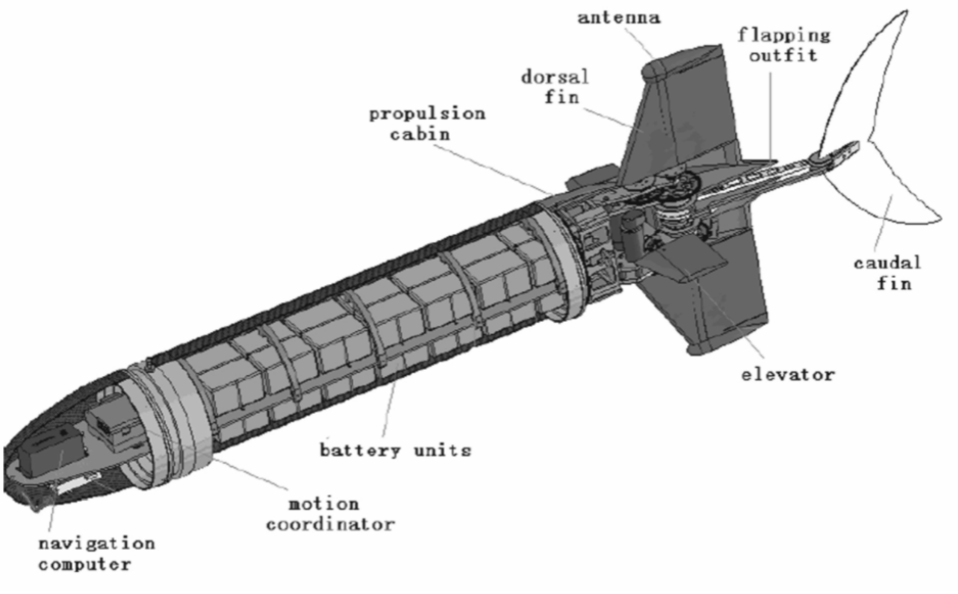

Fig. 4. CPS-3UUV[53]

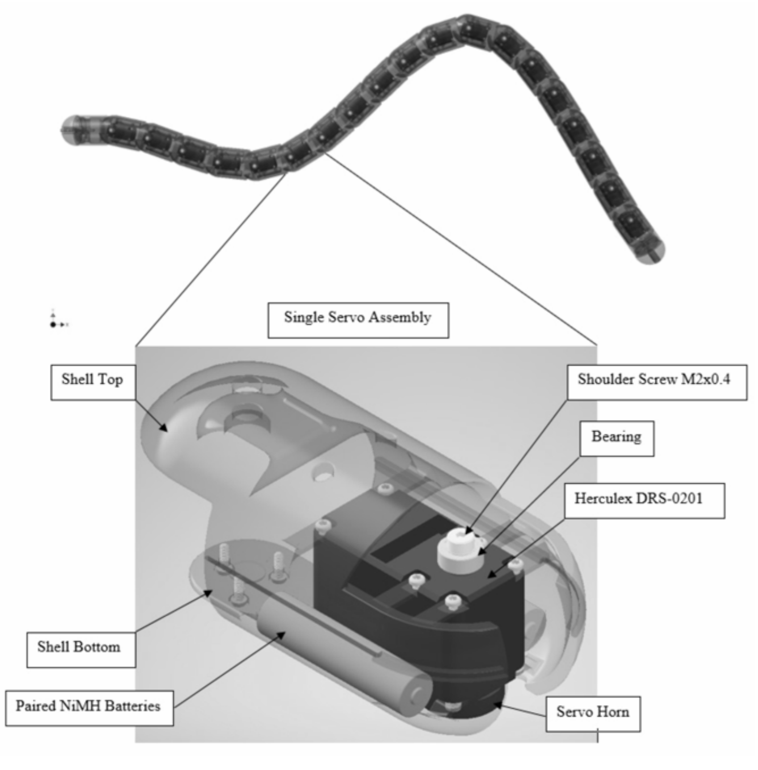

Fig. 5. A detailed view of an Eel-shaped robotlink [15]

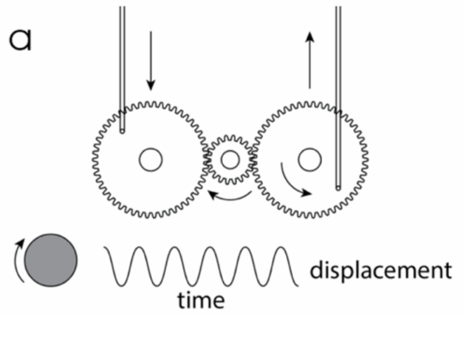

*Fig.6.*Continuously rotating DC motor [55]

Another important thing to take into consideration is the technique used by the robot to ascend and descend in the water. Where three types of techniques are used, first of them involves changing the center of mass and thus achieving positive or negative buoyancy as shown in figure (7). This technique uses a motor to control a weight block, and by changing its place, it can help the fish dive and ascend.

The second method is by using the pectoral fins to achieve hydrodynamic lift as shown in Figure (8). Where the two pectoral fins will be controlled by a servo motor to control the angle of attack and thus descend and ascend inside the water.

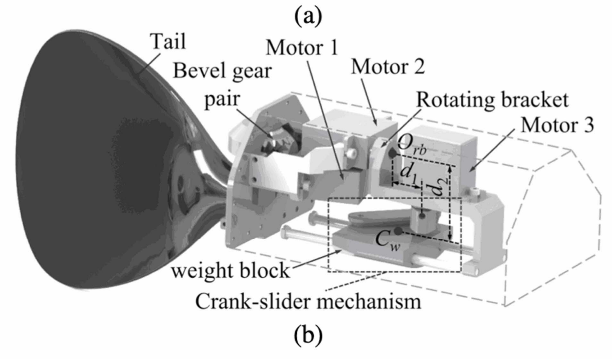

Fig. 7. Weight block and crank-slider mechanism [56]

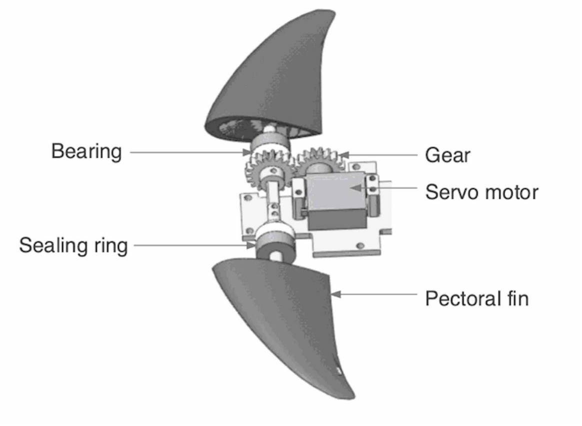

Fig. 8. Mechanical design of pectoral fins [57]

The third technique, is by using an artificial swim bladder, where this method relies on expanding a balloon inside the robot to achieve a positive buoyancy and ascend, or shrinking the balloon to achieve negative buoyancy and thus descend as shown in Figure (9).

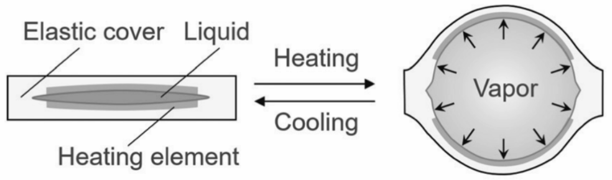

Fig. 9. A swim bladder is filled with a liquid which has a low boiling point, thus when boiled it expands forming vapor [45]

From the author's point of view, the use of artificial swim bladder proves to be more efficient because it doesn't use any mechanical mechanisms, thus increasing the number of motors used inside the robot, also it proves to be more efficient than using the pectoral fins in tight caves where there won't be enough space for the pectoral fins to move freely, and finally because it lessens the joints needed to be waterproofed after the project is done, since no motors will be needed to be used with the pectoral fins, and thus decreasing the chances of water to get inside the body of the robot.

During performing task and different required missions, underwater robot can get stuck, especially in narrow caves. Using propulsive method like the MPF and BCF movements could eventually lead to damage to the inner links or even to the motor itself, thus we could lose the robot. As shown in figures 10, 11 recent research approach suggests self-propulsion method which leads to indirect movement of the external body using internal vibrations or rotor movements.

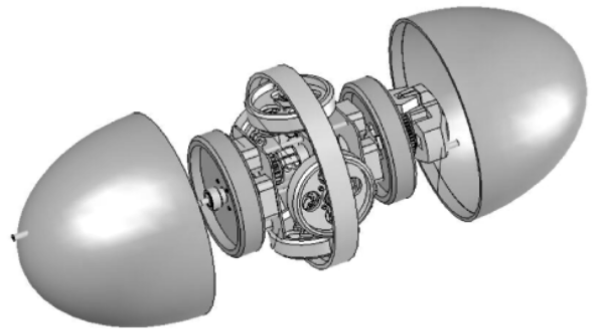

Fig. 10. Ellipsoid design [18]

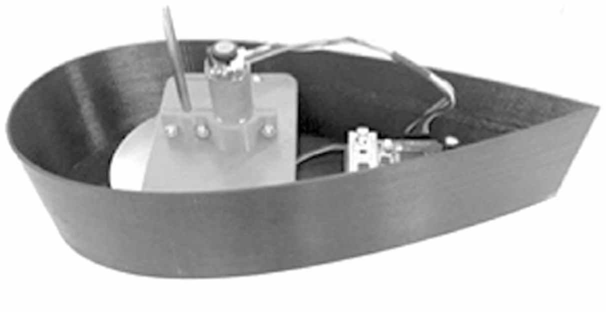

Fig. 11. Sharp-edged foil design [58]

Which seems to be useful as an additional internal part for the fishlike robots, so whenever the robot gets stuck, it could make internal vibrations which indirectly moves the robot gradually away from the place where it got stick at without risking any internal damage to the motor or any of the internal parts. Such part consists of a body in the form of a symmetric sharp-edged foil as in figure (11) or ellipsoid shape as in figure (10), control electronics and rotors, whose torsional oscillations are used to set the robot in motion. The motion of such devices is achieved by periodically changing the position of internal masses and by rotating rotors. It should be pointed out that the motion of such devices is possible only if the medium has resistance. Otherwise, their motion would be prevented by the laws of conservation of linear and angular momenta [58].

Control

To control the robotic fish, several sensors, navigation instruments and thrusters must be combined together to perform the desired mission. On the figure 12 a brief look about the robotic fish design.

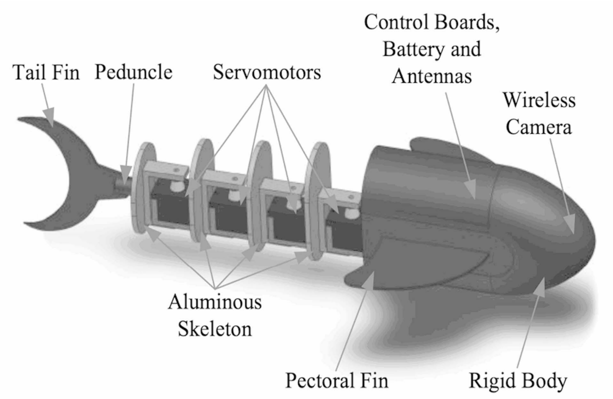

Fig. 12. Robotic fish structure [59]

Different components used include but not limited to:

Pressure sensor which is essential to determine the depth at fish the robot is swimming

Temperature sensor in some certain cases where the fish would be used in cold waters, might be necessary to be coupled with the pressure sensor, since the change of temperature can affect the general swimming efficiency of the robot as well as the functionality of some of its parts and sensors.

IMU sensor which is used to collect various data about the movement of the robot.

GPS can be used for near water surface operations that aren't far from the mainland.

Cameras can be used to record underwater, and can also be used for achieving complex algorithms using digital signal processing.

Inertial system to measure linear acceleration and angular velocity.

Pressure meter to measure vehicle depth.

Frontal sonar to measure distance from obstacles.

Vertical sonar to measure distance to the seafloor.

Ground speed sonar to measure the relative velocity between the vehicle and the seafloor.

Current meter to measure the relative velocity between the vehicle and the current

Compass to determine orientation.

Acoustic baseline to determine absolute position in known area. One of the most reliable methods is based on the use of acoustic systems such as the baseline systems: the long-baseline system (LBL), the short-baseline system (SBL), and the ultrashort-baseline system (USBL). These systems are based on the presence of a transceiver mounted on the vehicle and a variable number of transponders located in known positions. The transceiver's distance from each transponder can be measured via the measurement of an echo delay, from this information the position of the vehicle can be calculated by basic triangulation operations. The USBLcan be used with a single transponder, which is usuallymounted on a surface ship whose position is measuredby GPS [60].

Acoustic Doppler current profiler to determine water current at several positions. By processing the acoustic energy reflected from the seafloor and the water column from three or more beams, we can obtain a fairly accurate estimate of the vehicle velocity relative to the seafloor and relative water motion.

DC motor to control the tailbeat propulsion.

Stepper motor to control the pectoral fins movement.

Luminaries can be used to provide light in dark environments, and can also be coupled with the video cameras to recognize other nearby robots.

Batteries on which the running time of the underwater robot depends.

Microcontroller to connect all the components, electronic units and control them.

Communication unit **-** when it comes to the communication of the robot with other robot of the swarm, a lot of problems and difficulties occur due to the fact that underwater there is a lack of Wi-Fi connection and also the Bluetooth devices behave badly. Optical sensors can be used, however, one of the main difficulties in designing underwater optical wireless systems is the complexity of modeling the physical and chemical characteristics of ocean water [61]. A group of scientists have an interesting project where underwater robots can communicate with each other at a distance not more than 15 meters using radio frequency, then connect to a modem based on a buoy on the water surface via ultrasound, then maintain a Wi-Fi connection with the operation room [62].

Conclusion

Robotic fish are nowadays a point of interest for most researchers, since there are a lot of unsolved questions which remain open. Different types of fish were discussed, there are a lot of swimming forms as for the linear and 3D locomotion, but as for every project the required locomotion technique might be different. In other words, sharks might be good swimmers, but they won't do the job when it comes to exploring small underwater caves.So, depending on the mission the robot has to do, its external shape will be formed to suit the developer's needs. Where small agile robots can be used to cave exploration, and bigger robots with higher thrust but less maneuverability can be used for missions that require covering a longer distance in a short period of time.

Having a lot of actuators, links and control devices inside the robot fish will eventually lead to control complications, since it is not so east What makes the robotic fish a good robot, is the control algorithm used to drive the mechanical and electrical parts of the fish. When it comes to the diving mechanism, fish should always be able to ascend and descend without the need to do any mechanical movements, and as for that case, an artificial swimming bladder is essential.

A lot of attention should be paid to the external design of the robotic fish, since a lot of factors affect its swimming efficiency such as the skin drag, the size and the flexibility of its fins.

References

1. Russell B. Wynn, Veerle A.I. Huvenne, Timothy P. Le Bas, Bramley J. Murton, Douglas P. Connelly, Brian J. Bett, Henry A. Ruhl, Kirsty J. Morris, Jeffrey Peakall, Daniel R. Parsons, Esther J. Sumner, Stephen E. Darby, Robert M. Dorrell & James E. Hunt (2014) Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience, Marine Geology, vol. 352, pp. 451-468. DOI: 10.1016/j.margeo.2014.03.012

2. Gafurov Salimzhan & Klochkov Evgeniy (2015) Autonomous Unmanned Underwater Vehicles Development Tendencies. Proc. Engineering. DOI: 106.10.1016/j.proeng.2015.06.017.

3. Rodriguez Pablo & Piera Jaume. (2005). Mini AUV, a Platform for Future Use on Marine Research for the Spanish Research Council. Instrumentation View Point, 2005, no. 4, p. 6.

4. Filaretov V.F., Lebedev A.V., Yukhimets D.A. (2005) [Devices and control systems of underwater robots]. Moscow Nauka Publ., 272 p. (in Russ.)

5. Ay M., Korkmaz D., OzmenKoca G., Bal C., Akpolat Z.H., Bingol M.C. (2018) Mechatronic Design and Manufacturing of the Intelligent Robotic Fish for Bio-Inspired Swimming Modes. Electronics, 2018, 7(7):118. https://doi.org/10.3390/electronics7070118

6. Lushnikov B.V., Yatsun S.F., Politov E.N., Tarasova E.S. (2010) [Computer simulation of the dynamics of a bionic floating robot]. *Materialy Samarskogo nauchnogo centra Rossijskoj akademii nauk*, 2010, no. 4-3. URL: https://cyberleninka.ru/article/n/kompyuternoe-modelirovanie-dinamiki-bionicheskogo-plavayuschego-robota (accessed: 02/19/2023) (in Russ.).

7. Kiselev L.V., Medvedev A.V. (2012) [Comparative analysis and optimization of dynamic properties of autonomous underwater robots of various projects and configurations]. *Podvodnye issledovanija i robototehnika*, 2012, no. 1 (13), pp. 24-35 (in Russ.)

8. Neira J., Sequeiros C., Huamani R., Machaca E., Fonseca P., Nina W. (2021) Review on Unmanned Underwater Robotics, Structure Designs, Materials, Sensors, Actuators, and Navigation Control. J. of Robotics, vol. 2021, Article ID 5542920, p. 26, https://doi.org/10.1155/2021/5542920

9. Rui Y., Benoit C., Ali M., Ming L. & Nailong W. (2015) Modeling of a Complex-Shaped Underwater Vehicle for Robust Control Scheme. J. of Intelligent & Robotic Systems, 2015, 80, 1-16. DOI: 10.1007/s10846-015-0186-2

10. Zain Z. M., Noh M. M., Ab Rahim K. A. & Harun N. (2016) Design and development of an X4-ROV. IEEE International Conference on Underwater System Technology: Theory and Applications (USYS), 2016, pp. 207-211. DOI: 10.1109/USYS.2016.7893910

11. Radojevic M., M.Nawaf M. & Maurelli F. (2011) Nessie VI AutonomousUnderwaterVehicle. Retrieved from: https://braincadet.com/papers/nessie11.pdf

12. Yang X & Xing Y. (2021) Tuning for robust and optimal dynamic positioning control in Blue ROV2. IOP Conference Series: Materials Science and Engineering, 1201, 012015. DOI: 10.1088/1757-899X/1201/1/012015

13. Hidaka S., Kawashima S. & Nam S. (2015) System design and hardware development of autonomous underwater robot "daryabird". Proc. of the AUVSI&ONR's 18th Annual RoboSub Competition Journal Paper, San Diego, CA, USA. Retrieved from: https://robonation.org/app/uploads/sites/4/2019/10/Kyutech_RS15_Paper.pdf

14. Ai X., Kang S. and Chou W. (September 2018) System design and experiment of the hybrid underwater vehicle. Proc. of the 2018 International Conference on Control and Robots (ICCR), Hong Kong, China. DOI: 10.1109/ICCR.2018.8534493

15. Islam A. & Taravella B. (2021) Design of a Depth Control Mechanism for an Anguilliform Swimming Robot. Biomimetics, 2021, 6, 39. DOI: 10.3390/biomimetics6020039

16. Giacomo M. & Junku Y. (2014) The SAUVIM Underwater Vehicle-Manipulator System. Springer Tracts in Advanced Robotics, Retrieved from: https://link.springer.com/book/10.1007/978-3-642-54613-6

17. Rozman B.Ya. & Rimsky-Korsakov N.A. (2017) EQUIPMENT COMPLEXES FOR REMOTE OBSERVATIONS IN THE HYDROSPHERE. International J. of Applied and Fundamental Research, 2017, No. 11-2, pp. 276-280. Retrieved from: https://applied-research.ru/ru/article/view?id=12013

18. Karavaev Y., Kilin A., Klekovkin A. (2016) Experimental investigations of the controlled motion of a screwless underwater robot. Regular and Chaotic Dynamics, 2016, 21, 918-926. DOI: 10.1134/S1560354716070133

19. Salunkhe S., Patil S. (2021) A Review on Actuator and Manipulator Techniques in Soft Robotics.

Advances in Automation, Signal Processing, Instrumentation, and Control. i-CASIC 2020. Lecture Notes in Electrical Engineering, vol. 700. Springer, Singapore. https://doi.org/10.1007/978-981-15-8221-9_12

20. Guocai Y., Jianhong L., Tianmiao W., Xingbang Y., Qi S., Yucheng Z., Hailiang W. & Weicheng T. (2013) Development of a turtle-like underwater vehicle using central pattern generator. IEEE International Conference on Robotics and Biomimetics, ROBIO 2013, 44-49. DOI: 10.1109/ROBIO.2013.6739433

21. Liu J., Wu Z. and Yu J. (2016) Design and implementation of a robotic dolphin for water quality monitoring. 2016 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 835-840. DOI: 10.1109/ROBIO.2016.7866427

22. Sverdrup-Thygeson J., Kelasidi E., Pettersen K.Y. and Gravdahl J.T. (2016) The underwater swimming manipulator-a bio-inspired AUV: Proc. of the 2016 IEEE/OES Autonomous Underwater Vehicles (AUV), pp. 387-395, IEEE, Tokyo, Japan. DOI: 10.1109/AUV.2016.7778701

23. Du S., Wu Z., Wang J., Qi S. and Yu J. (2021) Design and Control of a Two-Motor-Actuated Tuna-Inspired Robot System: In IEEE Transactions on Systems, Man and Cybernetics: Systems, vol. 51, no. 8, pp. 4670-4680. DOI: 10.1109/TSMC.2019.2944786

24. Jindong L. & Huosheng H. (2010) Biological Inspiration: From Carangiform Fish to Multi-Joint Robotic Fish. J. of Bionic Engineering, 2010, 7, pp. 35-48. DOI: 10.1016/S1672-6529(09)60184-0

25. Cloitre A., Subramaniam V., Patrikalakis N. & Alvarado P. (2012) Design and control of a field deployable batoid robot: 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 707-712. DOI: 10.1109/BioRob.2012.6290739

26. Wehner M., Truby R.L., Fitzgerald D.J., Mosadegh B., Whitesides G.M., Lewis J.A., & Wood R.J. (2016) An integrated design and fabrication strategy for entirely soft, autonomous robots. Nature, 536 (7617):451-5. PMID: 27558065. DOI: 10.1038/nature19100

27. Yang T. & Chen Z. (2015) Development of 2D maneuverable robotic fish propelled by multiple ionic polymer-metal composite artificial fins. 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 255-260. DOI: 10.1109/ROBIO.2015.7418776

28. Jin H., Dong E., Alici G., Mao S., Min X., Liu C., Low K.H. & Yang J. (2016) A starfish robot based on soft and smart modular structure (SMS) actuated by SMA wires. Bioinspir Biomim, 2016, 11 (5):056012. PMID: 27609700. DOI: 10.1088/1748-3190/11/5/056012

29. Robertson M.A., Efremov F. & Paik J. (2019) RoboScallop: A Bivalve Inspired Swimming Robot: IEEE Robotics and Automation Letters, 2019, vol. 4, no. 2, pp. 2078-2085. DOI: 10.1109/LRA.2019.2897144

30. Patterson Z.J., Sabelhaus A.P. Chin, K., Hellebrekers T. & Majidi C. (2020) An Untethered Brittle Star-Inspired Soft Robot for Closed-Loop Underwater Locomotion, 2020, pp. 8758-8764. DOI: 10.1109/IROS45743.2020.9341008

31. Mao S., Dong E., Jin H. (2014) Gait study and pattern generation of a starfish-like soft robot with flexible rays actuated by SMAs. J Bionic Eng, 2014, vol. 11, pp. 400-441. DOI: 10.1016/S1672-6529(14)60053-6

32. Baines R.L., Booth J.W., Fish F.E. & Kramer-Bottiglio R. (2019) Toward a bio-inspired variable-stiffness morphing limb for amphibious robot locomotion: 2nd IEEE International Conference on Soft Robotics (RoboSoft), 2019, pp. 704-710. DOI: 10.1109/ROBOSOFT.2019.8722772

33. Ye Z., Hou P., Chen Z. (2017) 2D maneuverable robotic fish propelled by multiple ionic polymer–metal composite artificial fins. J. Intell Robot Appl 1, 2017, pp. 195-208. DOI: 10.1007/s41315-017-0019-5

34. Lushnikov B.V., Yatsun S.F., Kazaryan K.G., Savin S.I., Boys A.V., Tarasova E.S., Politov E.N., Yatsun A.S. (2009) Useful model 124656 Russian Federation, IPC B62D57/00. Underwater floating robot with bionic principle of motion. Retrieved from: https://poleznayamodel.ru/model/12/124656.html (in Russ.).

35. Sfakiotakis M., Lane D.M. & Davies J.B.C (1999) Review of fish swimming modes for aquatic locomotion, in IEEE Journal of Oceanic Engineering, vol. 24, no. 2, pp. 237-252, DOI: 10.1109/48.757275.

36. Lauder G. & Drucker E. (2003) Forces, Fishes, and Fluids: Hydrodynamic Mechanisms of Aquatic Locomotion. News in physiological sciences: an international journal of physiology produced jointly by the International Union of Physiological Sciences and the American Physiological Society, 2003, 17, pp. 235-40. DOI: 10.1152/nips.01398.2002

37. Lang, Amy & Motta, Philip &Habegger, M. Laura & Hueter, Robert (2012) Shark Skin Boundary Layer Control. DOI: 10.1007/978-1-4614-3997-4_9

38. Hu Q., Yu Y. (2021) Hydrodynamic scaling law in undulatory braking locomotion. Sci. China Phys. Mech. Astron. 64, p. 274711. https://doi.org/10.1007/s11433-021-1701-5

39. Winfried P. (2022) Underwater-sailing locomotion in intertidal gastropods: a comparison of Neotropical species. Archiv für Molluskenkunde International J. of Malacology. DOI: 151. 93-105. 10.1127/arch.moll/151/093-105

40. Nesteruk I. (2022) Shapes of the fastest fish and optimal underwater and floating hulls. Theoretical and Applied Mechanics Letters, 2022, 12 (6), p. 100378. DOI: https://doi.org/10.1016/j.taml.2022.100378

41. Huang S., Qiu H. & Wang Y. (2022) Aerodynamic performance of horizontal axis wind turbine with application of dolphin head-shape and lever movement of skeleton bionic airfoils. Energy Conversion and Management, 2022, 267, p. 115803. DOI: https://doi.org/10.1016/j.enconman.2022.115803

42. Kimoto T., Yamano A., & Chiba M. (2023) Estimation of Fluid Forces on a Snake-like Robot Swimming in Viscous Fluids Considering Boundary Layer Thinning: 2023 IEEE/SICE International Symposium on System Integration (SII), pp. 1-6. DOI: 10.1109/SII55687.2023.10039336

43. Martínez-García E.A., Lavrenov R., & Magid E. (2022) Robot Fish Caudal Propulsive Mechanisms: A Mini-Review. DOI: 10.5772/acrt.09

4. Nguyen D. Q., & Ho V.A. (2022) Anguilliform Swimming Performance of an Eel-Inspired Soft Robot. Soft Robotics, 2022, 9 (3), pp. 425-439. DOI: https://doi.org/10.1089/soro.2020.0093

45. Beomchan K., Yongkyu L., Tailin P., Zhengbing D. & Wei W. (2021) Robotic soft swim bladder using liquid - vapor phase transition: Materials Horizons., 8. DOI: 10.1039/D0MH01788D

46. Wang J., Wu Z., Dong H., Tan M., & Yu J. (2022) Development and Control of Underwater Gliding Robots: A Review. IEEE/CAA J. of AutomaticaSinica, 2022, 9 (9), pp. 1543-1560. DOI: 10.1109/JAS.2022.105671

47. Yu J., Wang L., & Tan M. (2005) A Framework for Biomimetic Robot Fish's Design and its Realization: Proc. of the 2005, American Control Conference, 2005, vol. 3, pp. 1593-1598. DOI: 10.1109/ACC.2005.1470195

48. Guo B., Xu J., Zheng S., Wang K., Chang J. (2022) Flow Characteristics of a Fish-Like Body Based on Taguchi Method under Different Strouhal Numbers. Mathematical Problems in Engineering, 2022, Article ID 1592792, p. 13. https://doi.org/10.1155/2022/1592792

49. Yang X., Zheng L., Lü D., Wang J., Wang S., Su H., Wang Z. and Ren L. (2022) The Snake-Inspired Robots: a Review. Assembly Automation, 2022, vol. 42, no. 4, pp. 567-583. https://doi.org/10.1108/AA-03-2022-0058

50. Korkmaz D., Akpolat Z. H., Soygüder S., & Alli H. (2015) Dynamic Simulation Model of a Biomimetic Robotic Fish with Multi-Joint Propulsion Mechanism. Transactions of the Institute of Measurement and Control, 2015, 37 (5), pp. 684-695. DOI: 10.1177/0142331214565710

51. Chao Z., Zhiqiang C., Zeng-Guang H., Shuo W. & Tan M. (2013) Backward Swimming Gaits for a Carangiform Robotic Fish. Neural Computing and Applications, 2013, p. 23. DOI: 10.1007/s00521-012-1106-z

52. Dorofeev V.Y., Kurnosov A.A., Lopota A.V., & Polovko S.A. (2022) Global Goals, Design Principles, Interaction Mechanisms, Destabilizing Effects and Rational Organization of the Development of RIC Systems. Izvestiya SFedU, Technical Science, 2022, no. 1 (203). URL: https://cyberleninka.ru/article/n/globalnye-tseli-printsipy-proektirovaniya-mehanizmy-vzaimodeystviya-destabiliziruyuschie-effekty-i-ratsionalnaya-organizatsiya (in Russ.).

53. Wang T., Wen L., & Liang J. (2010) Fuzzy Vorticity Control of a Biomimetic Robotic Fish Using a Flapping Lunate Tail: J. Bionic Eng, 7, pp. 56-65. DOI: 10.1016/S1672-6529(09)60183-9

54. Liang J., Wang T., Wang S., Zou D., & Sun J. (2005) Experiment of Robofish Aided Underwater Archaeology, 2005, 27, pp. 499-504. DOI: 10.1109/ROBIO.2005.246318

55. Berg S., Scharff R., Rusák Z. & Wu J. (2020) Biomimetic Design of a Soft Robotic Fish for High Speed Locomotion. DOI: 10.1007/978-3-030-64313-3_35

56. Zheng X., Xiong M., Tian R., Zheng J., Wang M. and Xie G. (2022) Three-Dimensional Dynamic Modeling and Motion Analysis of a Fin-Actuated Robot: IEEE/ASME Transactions on Mechatronics, 2022, vol. 27, no. 4, pp. 1990-1997. DOIi: 10.1109/TMECH.2022.3174173

57. Yu J., Chen S., Wu Z. & Wang W. (2016) On a Miniature Free-Swimming Robotic Fish with Multiple Sensors. International J. of Advanced Robotic Systems. DOI: 10.5772/62887

58. Karavaev Y.L., Klekovkin A.V., Mamaev I.S., Tenenev V.A., Vetchanin E.V. (2021) A Simple Physical Model for Control of a Propellerless Aquatic Robot. ASME. J. Mechanisms Robotics. February 2022, 14 (1), pp. 011007. https://doi.org/10.1115/1.4051240

59. International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion, 2012, pp. 1187-1192. DOI: 10.1109/SPEEDAM.2012.6264510

60. Tomczak A., Stępień G., Abramowski T. & Bejger A. (2022) Subsea wellhead spud-in marking and as-built position estimation method based on ultra-short baseline acoustic positioning. Measurement, 2022, 195, p. 111155. https://doi.org/10.1016/j.measurement.2022.111155

61. Miroshnikova N.E., Petruchin G.S. and Sherbakov A.V. (2019) Problems of Underwater Optical Links Modeling. Systems of Signal Synchronization, Generating and Proc. in Telecommunications (SYNCHROINFO), 2019, pp. 1-9. DOI: 10.1109/SYNCHROINFO.2019.8813996

62. Centelles D., Soriano-Asensi A., Martí J.V., Marín R. & Sanz P. J. (2019) Underwater Wireless Communications for Cooperative Robotics with UWSim-NET Applied Sciences 9, 2019, no. 17, p. 3526. DOI: 10.3390/app9173526

Анализ конструкций подводных роботов

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Данная статья посвящена анализу существующих отечественных и зарубежных конструкций подводных роботов. Прежде всего делается упор на описание конструкций и анализ их влияния на маневренность движения в жидкости. Рассмотрены различные механизмы приведения подводных роботов в движение, описаны подходы к моделированию. Дается описание и сравнение подводных мобильных роботов, приводящихся в движение с помощью винтов, в зависимости от их количества, расположения, а также формы корпуса, и более подробно рассматриваются конструкции роботов, реализующих биоподобное движение в жидкости. Проводится сравнение способов передвижения в жидкости с помощью винтовых движителей и биоподоб-

ными или безвинтовыми способами передвижения. Дается обзор механизмов, используемых для формирования биоподобных движений, описание материалов и свойств корпуса, характерных для данного вида подводных роботов, а также описание механизма движения в жидкости с учетом сил сопротивления и управления плавучестью. Особое внимание уделяется работам, посвященных исследованию формы хвоста рыбоподобного робота, направленных на повышение эффективности движения робота в жидкости. Проведенный анализ позволил выявить наиболее сильные и слабые стороны используемых механизмов реализации биоподобного движения в жидкости. На основании результатов аналитического обзора рассмотрена типовая структура подводного робота и требования к ее компонентам. В заключении обсуждаются актуальные технические и научные задачи, стоящие перед исследователями, работающими над созданием подводных роботов, функционирующих как в автономном, так и дистанционно управляемом режимах.

Ключевые слова: подводные роботы, биомиметика, рыбоподобные роботы, гидродинамика, движение подводных аппаратов, мобильные роботы.

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