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MINI-REVIEW

Robot Fish Caudal Propulsive Mechanisms: A Mini-Review

Edgar A. Martínez-García[1,*], Roman Lavrenov[2] and Evgeni Magid[2,3]

1 Institute of Engineering and Technology, Universidad Autónoma de Ciudad Juárez, Mexico
2 Institute of Information Technology and Intelligent Systems, Kazan Federal University, Russian Federation
3 HSE Tikhonov Moscow Institute of Electronics and Mathematics, HSE University, Russian Federation
*Corresponding author. E-mail: edmartin@uacj.mx

Abstract

Researchers have developed numerous artificial fish to mimic the swimming abilities of biological species and understand their biomechanical subaquatic skills. The motivation arises from the interest to gain deeper comprehension of the efficient nature of biological locomotion, which is the result of millions of years of evolution and adaptation. Fin-based biological species developed exceptional swimming abilities and notable performance in highly dynamic and complex subaquatic environments. Therefore, based on research by the scientific community, this mini-review concentrates on discussing the mechanical devices developed to implement the caudal propulsive segments of robotic fish. Caudal mechanisms are of considerable interest because they may be designed to control inertial and gravitational forces, as well as exerting great dynamic range in robotic fish. This manuscript provides a concise review focused on the engineering implementations of caudal mechanisms of anguilliform, subcarangiform, subcarangiform, thunniform and ostraciiform swimming modes.

Keywords: robot fish, biomechanisms, swimming modes, tail-fin propulsion, compliant robotics, rigid robotics

Citation
Edgar A. Martínez-García, Roman Lavrenov and Evgeni Magid (2022), Robot Fish Caudal Propulsive Mechanisms: A Mini-Review. *AI, Computer Science and Robotics Technology* 2022(0), 1–17.

DOI
https://doi.org/10.5772/acrt.09

Published
21 June 2022

1. *Introduction*

For decades, remotely operated and autonomous underwater robots have been a choice for a large kind of underwater missions. Modern industry faces important changes that demand an increase of locomotive-efficient vehicles than the use of conventional propelled ones. Not to mention a costly demand of numerous missions and operations deploying conventional underwater vehicles. A number of electric rotary actuators are widely deployed for self-propelled marine vehicles using actuating rotors. Rotary electric actuators can afford precision and keep torque magnitudes overtime. Nevertheless, propelling actuators are rigid devices representing considerable energy consumption, adding mass, inertia and friction to a mechanical system. Rotary-based propelling actuation systems are inherently noisy and are prone to harm subaquatic fauna and flora. This mini review presents relevant published implementations of bioinspired robotic fish. Rather than comparing different mechanical developments, it is purposed to illustrate fundamental ideas of mechanical configurations used to implement undulatory caudal systems.

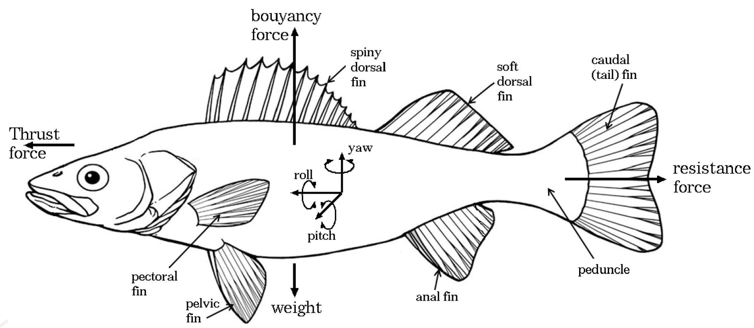
A number of review papers on a robot fishes have reported a diversity of common theories on biological fish-inspired robots and bionics, a considerable number of which are summarized in work [1]. The present manuscript specifically focuses on caudal motion mechanisms deployed in different technological implementations that fall into five general swimming modes: anguilliform, subcarangiform, carangiform, thunniform and ostraciiform. Therefore, fin-based biological species are worth noting models, which inspire to build a variety of artificial biomechanical prototypes capable to mimic biological efficient musculoskeletal structures to improve engineering designs.

The physiology and properties of muscle fiber types of fish, their principles of actuation and control has already been described in [2]. Similarly, the inner muscular and tendon geometrical structure for swimming of cetaceans were reported in [3]. Additionally, multiple comparative studies on fish-inspired robots have been reported. For instance, control of specific locomotion patterns [4], development of robot fish platforms [5], control and modeling [6], analysis on robotic swimming locomotion such as multi-mode swimming, trajectory tracking, maneuverability, perturbations and power-efficiency [7]. Moreover, important studies of biological anatomy, swimming modes and locomotion, which disclose actuation features were reported in [8–11].

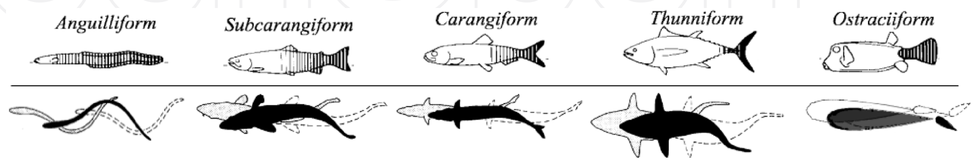
This manuscript is organized in the following sections. Section 2 provides a brief description on the fundamentals of fish swimming and its locomotion physics. Section 3 describes main anguilliform robotic fish. Section 4 discusses some caudal mechanisms on subcarangiform robots. Section 5 presents the carangiform types of artificial fish. Section 6 describes current developments on thunniform-like robotic fish. Section 7 describes relevant caudal mechanisms implemented in ostraciiform robots. Finally, Section 8 provides some conclusive comments.

2. *Fish swimming biomechanics*

This section presents some generalities on undulatory swimmer fishes and their propulsive biomechanical structures. Fishes' biomechanical efficiency to swim exhibits differences in accordance with their body shape, skeletal structures for mobility and hydrodynamic motion waves performed for propulsion and maneuverability. Fish-inspired robots may be improved in their design by



(a) Fish's fins and swimming angles/forces.



(b) Fish swimming locomotion modes (modified from [12]).

Figure 1. Depiction of fish dynamical parameters and undulatory locomotion modes.

considering inner and external forces involved in the hydrodynamic locomotion process. Accomplishing a major suitability may depend on locomotion modalities and hydrodynamic scenarios. Figure 1(a) shows the body of fish's swimming hydrodynamic interaction forces: drag and thrust apply horizontally, while lift, buoyancy and weight apply vertically. The hydrodynamic steady angular orientation motions are analyzed in terms of the roll-pitch-yaw Euler angles. Thus, the body of the fish is compounded by propulsive elements (e.g., fins and musculoskeletal parts), which are segments capable to exert hydrodynamic forces. The fish's body propulsive elements advantageously produce linear and angular momentum during a locomotive interaction with the water surrounding it.

Biomechanical and morphological differences of fishes exhibit natural propulsive undulatory motions based on swimming waves, essentially involving wave-like along caudal body segments. Figure 1(b) shows five fundamental caudal-based locomotion types of fish's undulatory propelling modes [12], which will be discussed in the following sections. Undulatory swimming transfers the linear momentum to the boundary's adjacent fluid via the drag forces and consequently yields changes of velocity. Hence, when acting forces and moments are nearly balanced with respect to a reactive hydrodynamic environment, fishes basically reach a constant speed, otherwise a lift and an acceleration are produced (i.e., effects of elevation and/or braking). Swimming acceleration reaction is a result of inertial forces generated by water resistance around the fish's boundary occurring during speeding up with respect to hydrodynamic changes. For instance, the fish's lift force is experienced when it is perpendicular to the hydrodynamic caudal/flow direction. Likewise, the fish's body shape causes specific flow patterns as a result of the hydrodynamic flow drag pressure. Thus, the swimming drag is a friction between fish's skin and a boundary layer of water. Summing up all these fish's biomechanical hydrodynamic locomotive properties, numerous families of fish can naturally maneuver, accelerate and cruise. Moreover, fish are featured by exhibiting particular swimming capabilities such as gliding, jet propulsion, burrowing, jumping and even flying.

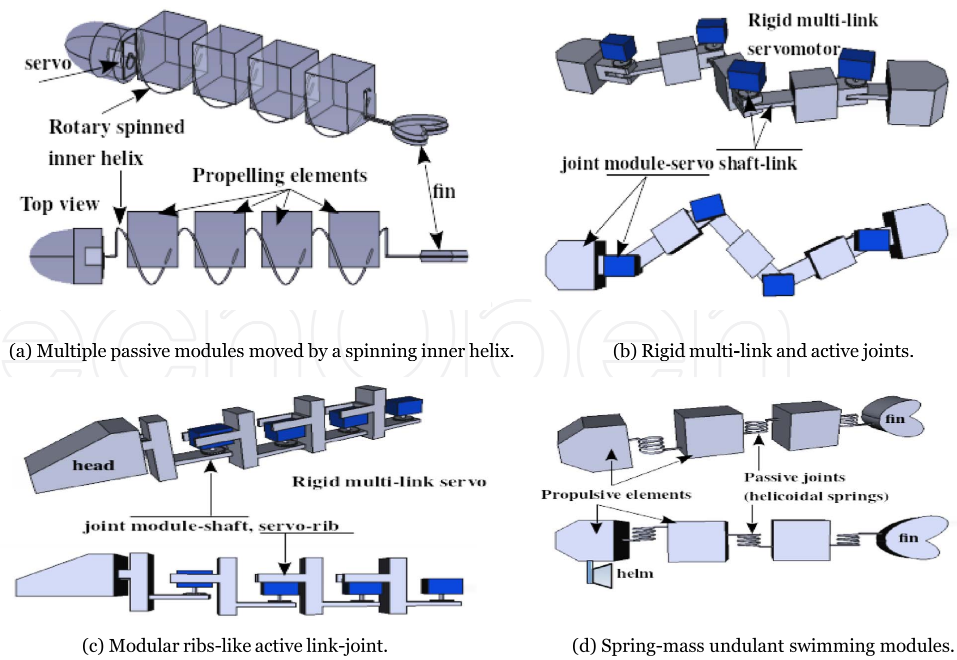
3. Anguilliform swimmer robots

Anguilliform swimmers (i.e., muraenidae, snakes, eels, etc.) are constituted by propulsive body's elements that allow the whole fish's spine performing wide amplitude undulation as a means for an underwater locomotion. Biological anguilliform hydrodynamic propulsive efficiency has been studied previously in [13]. In this type of locomotion, at least one complete wavelength must be performed by a body to carry out either longitudinal displacements or lateral maneuvers. Common anguilliform-type robot fish are built with sets of modular links that are serially connected, dubbed propelling elements (figure 2), which work in a way that allows either wide or narrow undulatory waves.

The authors in [14] developed an autonomous efficient marine anguilliform robot with fifteen propulsive slim modules resembling the structure depicted in figure 2(a). The caudal elements are cleverly undulated by a semi-rigid twisted inner helix (a rod element being rotated by an electric motor) passing throughout the middle of all caudal elements, ending with a plain flexible tail.

In a more traditional manner, work [15] presented a modular 5-link eel-like robot and its kinematic model is illustrated in figure 2(b), which is compounded from serial active joints (servomotors). Similarly, the type of the structure depicted in figure 2(c) approaches the 4-link biomimetic robot of [16] compounded of serially connected rigid modules, interconnected by a servo in each undulating element. Here, driving forces and joint torques have been modeled and controlled using underactuated reference angles for a trajectory tracking. Figures 2(b) and 2(c) are of a similar type having mechanical differences in implementation, degrees of modularity, variations of kinematic models, hydrodynamic parameters [17], and exist by engineering underwater snakes with propulsive modules of orthogonal joint axes [18].

The work reported in [19] was on development of an anguilliform modular structure with two actuators in its head-joint for active undulation and active steering (a helm), as shown in figure 2(d). As for the rest of the serpentine modules, they are connected by springs as passive joints. The spring-based joints are elastic devices to store rotatory mechanical energy during swimming undulation. Hence, this swimming motion approach is efficiently performed by its compliant bending with spring-based joints.



(a) Multiple passive modules moved by a spinning inner helix. (b) Rigid multi-link and active joints. (c) Modular ribs-like active link-joint. (d) Spring-mass undulant swimming modules.

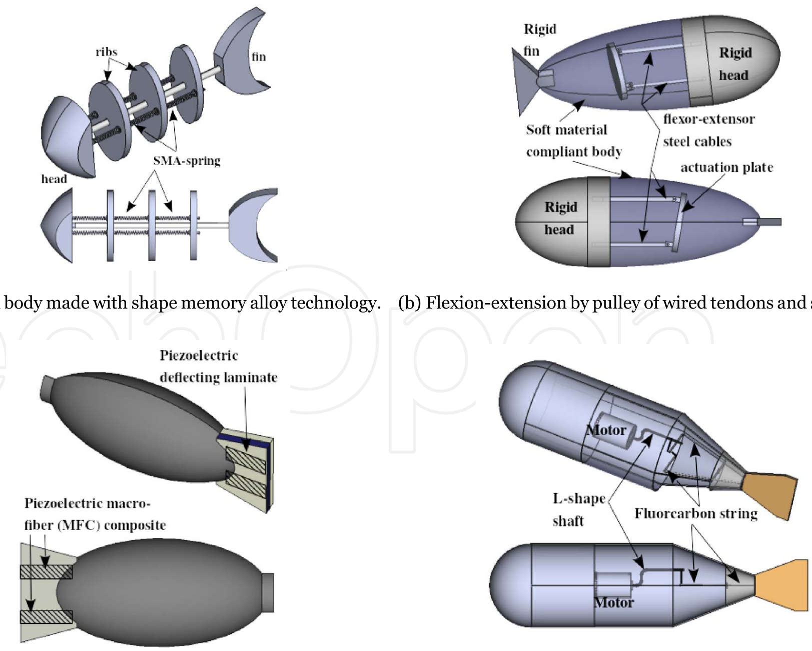
Figure 2. Types of anguilliform caudal mechanisms.

Kinematic swimming patterns, thrust-performance capability, forces and power propulsion, and wake flow patterns were studied from different technological approaches. For instance, polyurethane rods representing swimming bodies were used to generate propulsive waves in [20]. Likewise, anguilliform swimmers using soft pneumatic actuators with 4-link propulsion to imitate eel's muscles were reported in [21]. Finally, studies regarding terrestrial snake robots' mechanisms [22] are worth mentioning as they are relevant to anguilliform robot fish because of their inherent resemblance of their mechanisms [23].

4. Subcarangiform swimmer robots

Subcarangiform swimmers (e.g., salmon, sturgeon, etc.) perform considerable longer undulation waves to empower a thrust motion, which is localized only in its body's posterior portion, starting from very near to its head. Therefore, the caudal fin locomotive process depends on an actuation of a number of muscles along a musculoskeletal system. As for the subcarangiform type robots, they are designed to similarly maintain an extensive part of its anterior portion rigid during swimming. Unlike artificial anguilliform structures, bioinspired subcarangiform robots exhibit higher linear velocities.

Figure 3(a) shows the approach presented in [24], which is an artificial musculoskeletal fish compounded by three ribs. The ribs are mechanically joined by lateral spring-based muscles built of shape memory alloy (SMA). SMAs are



(a) Caudal body made with shape memory alloy technology. (b) Flexion-extension by pulley of wired tendons and soft body.

(c) Piezoelectric-based bending caudal fin. (d) Caudal body oscillation by antagonistic strings pulling.

Figure 3. Different approaches of subcarangiform artificial fish mechanisms.

particular types of advanced materials, which are deformed by external forces at a specific temperature, however being heated or cooled, they restore their original shape. Therefore, the alloy apparently possess a thermomechanical memory. Thus, such type of a robot fish is implemented with lateral muscles working antagonistically, pulling and releasing. SMA-based muscles are controlled by changing their temperature by commuting electrical input currents. A similar caudal mechanism but with different technology was presented in [25], where instead of using SMA-based springs, the fish swimming motion was performed by deploying five ribs pulled by wires inside a compliant body structure.

Furthermore, another similar motion mechanism is shown in figure 3(b), reported by [26]. A robot fish is propelled by pulling and releasing laterally wires representing caudal tendons. A compliant material of a swimming body is a flexible soft material, which is arranged as a non-uniform cantilever beam. The compliant body oscillates by a plate being pulled by wires.

Figure 2(c) shows a subcarangiform swimming robot fish as the one reported in [27]. This work presented studies on a trout-inspired multi-functional soft-robotic fish. This mechanism is an energy harvester that uses flexible macro-fiber composite structures of piezoelectric composites. The piezoelectric laminate yields acting forces bending the caudal body. It generates hydrodynamic propulsion by laminates' bending that are synchronized for expanding one side, and the other one works contractile to create mechanical oscillations.

Figure 3(d) illustrates the work reported in [28], where a smart arrangement of wriggling laces work as antagonistic "tendons". The oscillatory body motion is produced by an L-shape motor shaft rotating continuously.

Work on subcarangiform robot fishes are also built with the traditional approach of interconnected serial links and servo-based joints, such as in [29] with body's tail peduncle and pectoral propulsive fin.

5. *Carangiform swimmer robots*

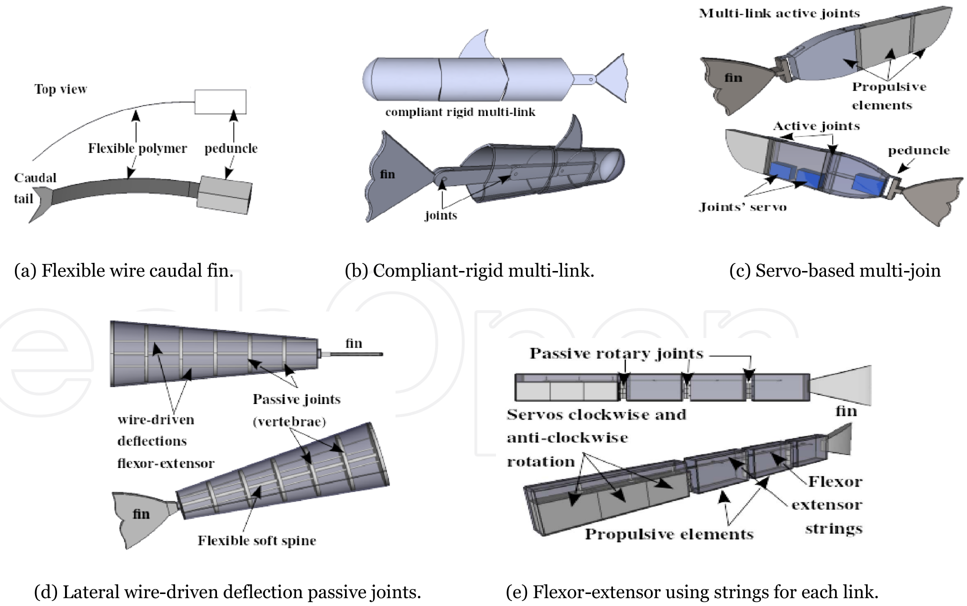
The carangiform swimmers deploy an anterior half of their body, and their biomechanical nature is the fastest swimming of all modes. This mode is exhibited by a diversity of vertebrates such as swordfish, bonefish, giant trevally, etc. Numerous lateral movements basically occur at a caudal fin exerting over 90% of the thrust and at an area near a narrow peduncle. Nevertheless, carangiform musculoskeletal presents a relative rigidity, compromising its swift capability and turning maneuvers. Figure 4 shows some different engineering approaches to biomechanical carangiform swimmers construction. Numerous developments of carangiform robotic fish use soft materials configured with different stiffness for its caudal fin.

Figure 4(a) depicts a peduncle and a polymer-based caudal tail, which was made flexible for a particular use in a carangiform swimmer robot to maximize its thrust propulsion, reported in [30]. The caudal tail was built with different shapes such as rectangular, delta and triangular. Besides, it was developed with different stiffness properties and compositions using polyvinyl chloride/polypropylene/acrylic plates.

Figure 4(b) shows a multi-link dolphin-like robot fish reported in [31]. The design is a redundantly kinematic body compounded by multiple rigid links and actuators, as well as a compliant caudal tail made of silicone. Another similar structure model was reported in [32], it presented a dolphin prototype with three active caudal joints, using rigid rotary actuators and a yaw-turning joint with a servo in-between the lumbar and the caudal body sections.

Likewise, figure 4(c) presents a three active joints of a carangiform type robot resembling a Pearl Arowana fish, reported in [33] and similar in [34], and two active joints carangiform in [35].

Figure 4(c) shows a shark-type robot deploying a wire-driven controlled by a servomotor, an elastic center beam and passive control discs (ribs), which was reported in [36]. In addition, a similar approach was also reported in [37]. Figure 4(d) depicts an interesting approach reported in [38]. A flexor-extensor mechanism pulls and releases a 3-link caudal body by different strings, a single string per link and controlled by a servo.



(a) Flexible wire caudal fin. (b) Compliant-rigid multi-link. (c) Servo-based multi-join

(d) Lateral wire-driven deflection passive joints. (e) Flexor-extensor using strings for each link.

Figure 4. Common carangiform-like locomotion caudal mechanisms.

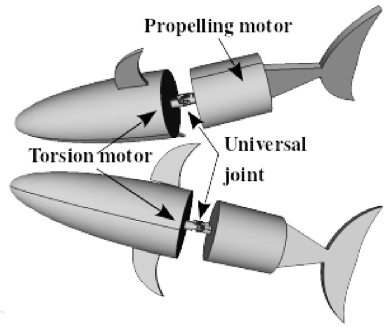
Authors in [39] implemented a multi-link fish and a bionic tail driving system through a planetary gearing mechanism to provide power during a traveling wave generation. Moreover, similar to works depicted in figures 3(c), 6(a) and 6(c), work [40] presented a two active joints (servo and ionic polymer-metal composite) carangiform-type robot fish, a servo for element propelling and a polymer-metal composite for tail steering moment.

Some works on control modeling and traveling wave tracking for carangiform robots were proposed [41, 42].

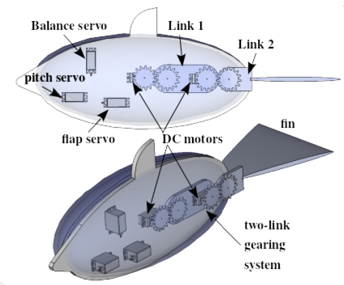
6. *Thunniform swimmer robots*

The family of thunniform swimmers, depending on their species, may deploy between 15% to 30% of their posterior caudal body including a tail fin. This type of swimming anatomy produces fast traveling undulations. Perhaps, it is the most efficient locomotion modality in terms of energy spending, and it allows a long-term thrusting force performance with considerable high cruising speeds.

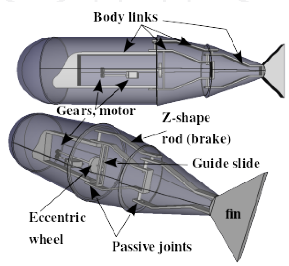
Figure 5 shows six different styles of mechanisms implemented in order to resemble the thunniform swimming performances. The work reported in [43] developed a design of a single link caudal-fin propulsion that mainly takes advantage of the passive bending capability that a universal joint allows. This coupling interconnects two rigid links (a front-side body with a caudal body) allowing their axes being inclined, one with respect to another. A pair of hinges connected and oriented at 90° to each other, form a cross shaft connection to transmit undulatory



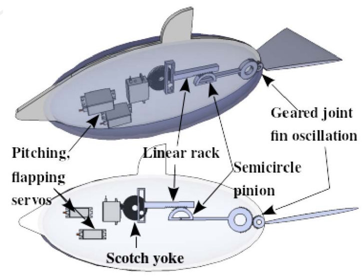
(a) Universal joint for roll and pitch caudal motion.



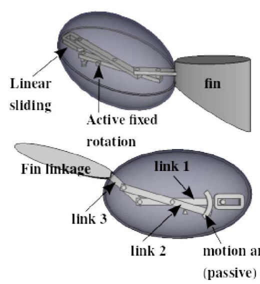
(b) 2-link active joints and active roll, pitch and yaw model.



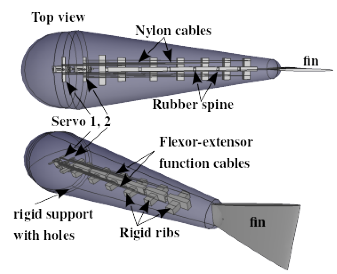
(c) Eccentric wheel and slider underactuated 2-link robot fish.



(d) Scotch-Yoke, linear rack and semi-circle rotary pinion for andactuated 2-link dolphin robot.



(e) Three-bar planar linkage, 1 active/3 passive joints tuna robot.



(f) Multiple wire-driven caudal body soft-spine and rigid-ribs

Figure 5. Thunniform locomotive mechanisms.

motion. The mechanism deploys two rotary motors, as depicted by figure 5(a) and resembles a Tuna-like robot fish where the caudal wave of swimming develops motion in two degrees of freedom, pitch and roll simultaneously.

In [44] authors presented a leaping dolphin-like multi-actuator robot exhibiting a caudal mechanism based on two high torque active joints. This thunniform structure is shown in figure 5(b), which illustrates caudal links for pitching, as well as other additional servos installed in the rigid front side of the body for balancing and maneuvering. The system efficiently emulates a biological dolphin swimming.

The work [45] presented a clever mechanism for a thunniform robot fish resembled by figure 5(c). Here, a single-motor with a gear train transmits rotary motion to an eccentric wheel. The wheel's eccentric axis slides through a vertical linear guide trail to directly produce a yaw motion to joint 1 of the first body link segment. The second consecutive body link that is assembled through joint 2, moves passively in angular motion pushed/pulled as a result of an angular moment transmitted by link 1. The Z-shape rod connecting both body links works as a brake to limiting serpentine motion of link 2.

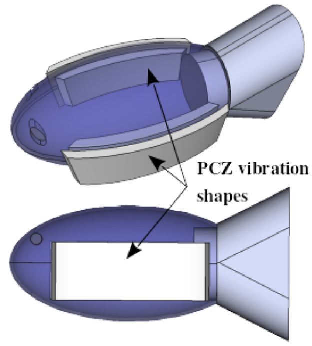
In [46] authors reported an ingenious mechanism based on an oscillatory Scotch Yoke device (figure 5(d)) for a robot resembling a dolphin-like robot. This type of joint is a slotted link mechanism that reciprocates motion by converting a rotary motion into a linear motion sliding along a trail slider engaged by an eccentric pin. The piston is a linear reciprocating rack directly coupled to the sliding yoke with a slot. The rack's linear displacement versus time produces a harmonic motion with constant amplitude and frequency, at a constant rotary speed. Moreover, the rack transmits swinging tangential motion to a rotary semi-circle pinion, where the latter reciprocates rotation. Essentially, the tail undulates, and the fin's servo adds an extra maneuvering tail's oscillation.

Figure 5(e) mainly resembles the passive linkage mechanism developed in [47] for automating a swimming pattern of a tuna-mimetic robot. A high torque motor transmits rotary motion to the link bar 1 through active joint 1. One of the link 1's extreme side slides rotating engaged in a curved trail slider. The link-1 opposite side pulls/pushes link 3, which in order to maintain its suitable reciprocating oscillatory motion, one side of link 3 is mechanically constrained by the linear motion of link 2. Basically, link 3 reciprocates rotations and transmits serpentine motion to the caudal fin.

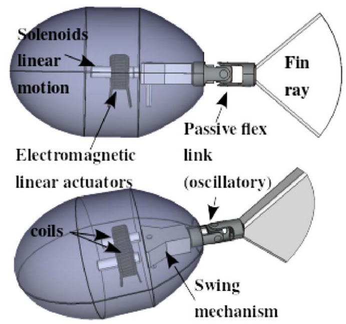
Another work [48], presented an underactuated type of a flexor-extensor mechanism based on pulling/releasing nylon cables at lateral sides, as shown in figure 5(f). Two servos are lined up longitudinally at the rigid head body and are synchronized for a yaw rotation. The servos' double horn pulls/releases six cables per side passing throughout a rigid support with holes between a head and a caudal body. The cables are strapped (three strings for each servo) to six ribs per side. The ribs are rigid material firmly fastened to a flexible rubber spine. When the compliant caudal spine is subjected to servos force, which contracts and extends the cables, the caudal body bends laterally producing a serpentine locomotion.

7. Ostraciiform swimmer robots

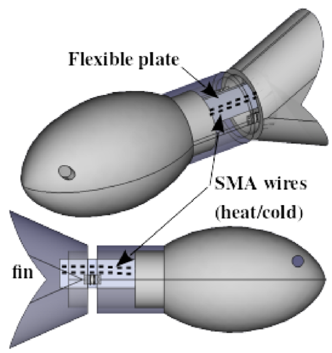
Ostraciiform swimmers oscillate dorsal, pectoral and anal fins to balance, maneuver and control hydrodynamic movements while a fish's body basically prevails rigid and inflexible. This section focuses on the ostraciiform caudal fin mechanism, which completely develops a propulsion oscillatory motion that augments its thrusting force, although lacks of considerable hydrodynamic efficiency.



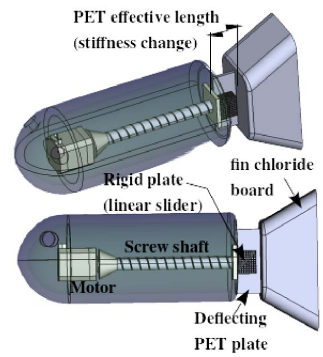
(a) Flexible piezoelectric fiber fin undulation.



(b) Electromagnetic solenoid-like locomotion mechanism.



(c) Shape memory alloy lateral wires, heat_bending fin.



(d)Mechanically bending flexible plastic plate.

Figure 6. Ostraciiform artificial caudal mechanisms.

The work [49] developed a flexible underwater robot based on a thin structure of macro fiber composite (MFC), shown in figure 6(a). It is essentially a set of piled up film layers of polyimide electrodes, epoxy and piezoceramic fibers. This structure is a piezoelectric composite (PZC) fiber that bends when input is supplied with electric energy. The robot fish body is a flexible carbon plate, which undulates by commuting electric pulses to the PZC fixed laterally. The PZC vibrates by expanding and contracting continuously, resulting in caudal fin oscillatory motion.

A similar approach [50], instead of piezoelectric film, used double face magnetostrictive films to deflect a thin micro-robot when subjected to controlled magnetic fields.

Figure 6(b) illustrates the approach presented in [51], which is an ingenious mechanism based on dual mini solenoids. These are electromagnetic coils with ferromagnetic shafts/pistons, magnetically commuted for attraction and repulsion. The coils are arranged in parallel functioning synchronized transmitting linear motion to a swing device. The swing mechanism oscillates the fin tail, which yields ostraciiform mode swimming propulsion. Similar ostraciiform electromagnetic approaches were reported in [52] and [53].

Figure 6(c) illustrates a mechanism proposed by [54] and [55] deploying SMA wires. This morphological implementation might look similar to mechanisms of figures 6(a) (piezoelectric fiber), 4(a) (flexible polymer) and 3(c) (piezoelectric laminate), however it differs in their technological approach. Although, Z. Wang *et al.* developed a Carangiform robot fish, its locomotion model fits suitable for some class of the ostraciiform family, such as Spotted boxfish (*Ostracion meleagris*) and Buffalo trunk fish (*Lactophrys trigonus*). The mechanism shown in figure 6(c) presents a caudal fin with SMA-based lateral wires resembling longitudinal tendons functioning as flexor-extensor. Unlike figure 3(a), it approaches SMA-based multiple serially connected springs to emulate damping muscles. In the ostraciiform version of figure 6(c), such alloy, when mechanically deformed, returns to its original shape once heated at a certain temperature. The lateral SMA wires overlaid an elastic substrate (in the middle) that provides mechanical resistance and stores elastic energy. Therefore, the caudal fin is a noiseless actuation compliant device yaw bending.

A work that used polyethylene terephthalate (PET) as a soft material peduncle, and a flexible caudal tail was reported by [56], which resembles figure 6(d). A basic propulsion mechanism consists of a rotary motor directly rotating a screw shaft to reciprocate a linear motion to a rigid plate. The rigid plate moves linearly overlapping the PET area, as the effective deflection length varies, the PET's undulation apparent stiffness changes its bending capability. Therefore, this effective length is modeled as a spring device with apparent changing stiffness.

In addition, there are works reported on ostraciiform swimming mode, implemented by using gearing trains as active fin-tail servo-based propellers [57, 58], or direct connection servo-tail [59]. Finally, [60] reported a dual-caudal fin robot that yields synchronized double wave propulsion that improved a velocity.

8. Conclusion

This mini review assimilated few of the main ideas on ingenious caudal propulsive mechanisms of different artificial fish types. The caudal mechanisms were classified by the commonly known five undulation modes: anguilliform, subcarangiform, carangiform, thunniform and ostraciiform.

The anguilliform type of robotic fish is one of the most complex mechanisms to model and implement, physically and functionally as it requires sets of serially connected modules (links and joints) to work synchronized and exert vigorous propulsive locomotion. The anguilliform is the most undulatory biomechanical system as it implicates majority of its body (from a head to a tail) to yield locomotive waves. Numerous reported works built up mechanically redundant systems (multiple active joints), requiring considerable amounts of electrical energy.

Nevertheless, anguilliform and subcarangiform exhibit high maneuverability and considerable locomotive dexterity degrees, as compared with the rest of the swimming modes. Anguilliform biomechanics exhibits the greatest maneuverability, although does not perform as the fastest one.

Carangiform and thunniform modes allow a wide range of diverse mechanism approaches. They perform with the highest efficiency in terms of swimming speeds. The types of mechanisms for carangiform and thunniform allow a wide diversity of caudal mechanisms. Thus, still numerous approaches may be explored as an implementation of these swimming structures.

Contrary to anguilliform, the ostraciiform mechanisms merely require a tail bending, being the least energy spending systems. They require at least one active joint, which particularly reduces amount of energy requirements. According to the large list of reported works, the carangiform is likely one of the most artificially implemented robots for the purpose of academic research. Robotic ostraciiform fish exhibit the highest feasibility, the simplest mechanical complexity, the smoothest locomotion mode and reduced in terms of physical space requirements.

Numerous reported mechanical systems in caudal segments (e.g., dorsal spines, ribs, vertebrae) are mostly compounded by servomotors, cables or flexion-extension strings, springs devices, compliant linear artificial muscles, electromagnetic devices, piezoelectric plates and shape memory alloy components.

Linear-based artificial muscles were developed by using different technological approaches. Among electrical properties polymers, pneumatic and hydraulic control devices, the electrical ones are the most interesting due to their small size and energy costs. In addition, underactuated mechanisms are compounded by a reduced number of active joints and exhibit one of the best efficient devices capable to resemble realistic biological swimming behaviors.

It is certain that in the near future, gradually emerging novel artificial muscles technologies will provide increased desired properties. Future robotic fish will be integrated with novel artificial tendons and muscles closely behaving as biological muscles with augmented mechanical power, reduced weight and volume, efficient linear extension/contractile motions electrically commuted.

Nowadays compliant robot fishes are constituted by soft material technology providing suitability to perform efficient swimming maneuverability and are comprised of complex dynamic control models.

At first glance, the most descriptive implementations of fish mechanisms in discussed works, provided us a perspective on a still long way to explore a diversity of novel ingenious mechanical marvels, particularly, for future underactuated robotic platforms. While a broad variety of underactuated subaquatic soft robots had been developed (octopus, bell-shaped medusa, etc.), these types are out of this manuscript's scope.

The present work's authors, suggest the use of mechanisms mostly developed with a reduced number of electric rotary actuators and involving a major number of underactuated components. Likewise, a particular exploitation and improved applications of electrical linear electromagnetic devices (e.g., solenoids) are suggested. A countless number of additional mechanism components with considerable mechanical advantage rates can be explored as robot fish's biomechanical structures, such as combining gyroscopic linkages, mechanical oscillators based on electrostatic and/or helicoid springs, systems of pulleys, hydraulic pistons, bar linkages, etc. In addition, the application of mechanical synthesis techniques may provide addition degrees of sophistication such as locomotive reconfiguration and adaptive maneuverability.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

The first author acknowledges the support of Laboratorio de Robótica and thanks the reviewers for their valuable comments and suggestions. The second and the third authors acknowledge the support of the Kazan Federal University Strategic Academic Leadership Program ("PRIORITY-2030").

References

1 Salazar R, Fuentes V, Abdelkefi A. Classification of biological and bioinspired aquatic systems: A review. *Ocean Eng*. 2018;**148**: 75–144. doi: 10.1016/j.oceaneng.2017.11.012.

2 Rome LC. Principles of actuation in the muscular system of fish. *IEEE J Ocean Eng*. 2005;**30**(3):630–646. doi: 10.1109/JOE.2005.852346.

3 Pabst DA. Intramuscular morphology and tendon geometry of the epaxial swimming muscles of dolphins. *J Zoology*. 1993;**230**(1):159–176. doi: 10.1111/j.1469-7998.1993.tb02679.x.

4 Raj A, Thakur A. Fish-inspired robots: design, sensing, actuation, and autonomy—a review of research. *Bioinspir Biomim*. 2016;**11**: 031001. doi: 10.1088/1748-3190/11/3/031001.

5 Faudzi AAM, Razif MRM, Nordin NAM, Natarajan E, Yaakob O. A review on development of robotic fish. *J Transport Syst Eng*. 2014;**1**(1):12–22.

6 Duraisamy P, Sidharthan RK, Santhanakrishnan MN. Design, modeling, and control of biomimetic fish robot: A review. *J Bionic Eng*. 2019;**16**(2019):967–993. doi: 10.1007/s42235-019-0111-7.

7 Colgate JE, Lynch KM. Mechanics and control of swimming: A review. *IEEE J Ocean Eng*. 2004;**29**(3):660–663. doi: 10.1109/JOE.2004.833208.

8 Nesteruk I, Passoni G, Redaelli A. Shape of aquatic animals and their swimming efficiency. *J Marine Biol*. 2014;**2014**(9):1–9. doi: 10.1155/2014/470715.

9 Fish FE. Advantages of natural propulsive systems. *Marine Technol Soc J*. 2013;**47**(5):37–44. doi: 10.4031/MTSJ.47.5.2.

10 Lauder GV. Fish locomotion: Recent advances and new directions. *Annu Rev Marine Sci*. 2014;**7**: 521–545. 2015, doi: 10.1146/annurev-marine-010814-015614.

11 Breder CM. The locomotion of fishes. *Zoologica*. 1926;**4**: 159–297. doi: 10.5962/p.203769.

12 Sfakiotakis M, Lane DM, Davies JBC. Review of fish swimming modes for aquatic locomotion. *IEEE J Ocean Eng*. 1999;**24**(2):237–252. doi: 10.1109/48.757275.

13 Vorus WS, Taravella BM. Anguilliform fish propulsion of highest hydrodynamic efficiency. *J Marine Sci Appl*. 2011;**10**: 163–174. doi: 10.1007/s11804-011-1056-3.

14 Struebig K, Bayat B, Eckert P, Looijestijn A, Lueth T, Ijspeert A. Design and development of the efficient anguilliform swimming robot – MAR. *Bioinspir Biomim*. 2004;**15**(3):035001. doi: 10.1088/1748-3190/ab6be0.

15 McIsaac KA, Ostrowski JP. A framework for steering dynamic robotic locomotion systems. *Int J Rob Res*. 2003;**22**(2):83–97. doi: 10.1177/0278364903022002001.

16 Xu J-H, Niu X-L. Modeling, control and locomotion planning of an anguilliform robotic fish. *Unmanned Syst*. 2014;**2**(4):295–321. doi: 10.1142/S230138501440007X.

17 Raj A, Thakur A. Hydrodynamic parameter estimation for an anguilliform-inspired robot. *J Intell Rob Syst*. 2020;**99**: 837–857. doi: 10.1007/s10846-020-01154-8.

18 Kelasidi E, Liljebäck P, Pettersen KY, Gravdahl JT. Innovation in underwater robots: Biologically inspired swimming snake robots. *IEEE Robot Automat Magazine*. 2016;**23**(1):44–62. doi: 10.1109/MRA.2015.2506121.

19 Fremerey M, Fischheiter L, Mämpel J, Witte H. Reducing complexeness of control by intellignet mechanics in undulant swimming robots. *Int J Des Nat Ecodyn*. 2012;**7**(1):1–13. doi: 10.2495/DNE-V7-N1-1-13.

20 Lim JL, Lauder GV. Mechanisms of anguilliform locomotion in fishes studied using simple three-dimensional physical models. *Bioinspir Biomim*. 2016;**11**(4):046006. doi: 10.1088/1748-3190/11/4/046006.

21 Nguyen DQ, Ho VA. Anguilliform swimming performance of an eel-inspired soft robot. *Soft Rob*. 2021;**9**: 425–439. doi: 10.1089/soro.2020.0093.

22 Liljebäck P, Pettersen KY, Stavdahl O, Gravdahl JT. A review on modelling, implementation, and control of snake robots. *Robot Auton Syst*. 2012;**60**: 29–40. doi: 10.1016/j.robot.2011.08.010.

23 Liu J, Tong Y, Liu J. Review of snake robots in constrained environments. *Robot Auton Syst*. 2021;**141**: 103785. doi: 10.1016/j.robot.2021.103785.

24 Muralidharan M, Palani IA. Development of subcarangiform bionic robotic fish propelled by shape memory alloy actuators. *Defence Sci J*. 2021;**71**(1):94–101. doi: 10.14429/dsj.71.15777.

25 Zhong Y, Li Z, Du R. A novel robot fish with wire-driven active body and compliant tail. *IEEE/ASME Trans Mechatron*. 2017;**22**(4):1633–1643. doi: 10.1109/TMECH.2017.2712820.

26 El Daou H, Salumae T, Toming G, Kruusmaa M. A bio-inspired compliant robotic fish: Design and experiments. In: *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2012), Saint Paul, MN*. IEEE; 2012. p. 5340–5345.

27 Tan D, Wang Y, Kohtanen E, Erturk A. Trout-like multifunctional piezoelectric robotic fish and energy harvester. *Bioinspir Biomim*. 2021;**16**(4):6024, doi: 10.1088/1748-3190/ac011e.

28 Fujiwara S, Yamaguchi S. Development of fishlike robot that imitates carangiform and subcarangiform swimming motions. *J Aero Aqua Bio-Mech*. 2017;**6**(1):1–8. doi: 10.5226/jabmech.6.1.

29 Nilas P. A prototypical multi-locomotive robotic fish parametric research and design. In: *Proceedings of the World Congress on Engineering and Computer Science (WCECS 2011), San Francisco, CA*. vol. 1, 2011.

30 Park Y, Jeong U, Lee J, Kwon S, Kim H, Cho K. Kinematic condition for maximizing the thrust of a robotic fish using a compliant caudal fin. *IEEE Trans Robot*. 2012;**28**(6):1216–1227. doi: 10.1109/TRO.2012.2205490.

31 Park Y, Cho K. Stabilizing the head motion of a robotic dolphin with varying the stiffness of a caudal fin. In: *Proceedings of the 13th International Conference on Control, Automation and Systems (ICCAS 2013), Gwangju, Korea*. IEEE; 2013. p. 901–904.

32 Cao Z, Shen F, Zhou C, Gu N, Nahavandi S, Xu D. Heading control for a robotic dolphin based on a self-tuning fuzzy strategy. *Int J Adv Robot Syst*. 2016;**13**(28): doi: 10.5772/62289.

33 Nguyen T-T, Nguyen N-P, Dang M-N. Swimming of robotic fish based biologically-inspired approach. In: *Proceedings of the 11th International Conference on Control, Automation and Systems (ICCAS 2011), Gyeonggi-do, Korea*. IEEE; 2011. p. 625–630.

34 Low KH, Chong CW, Zhou C. Performance study of a fish robot propelled by a flexible caudal fin. In: *Proceedings of the International Conference Conf. on Robotics and Automation (ICRA 2010), Anchorage, Alaska*. IEEE; 2010. p. 90–95.

35 Low KH. Parametric study of modular and reconfigurable robotic fish with oscillating caudal fin mechanisms. In: *Proceedings of the International Conference on Mechatronics and Automation (ICMA 2007), Harbin, Heilongjiang*. IEEE; 2007. p. 123–128.

36 Lau WP, Zhong Y, Du R, Li Z. Bladderless swaying wire-driven robot shark. In: *Proceedings of the 7th International Conference Cybernetics and Intelligent Systems (CIS), Angkor Wat, Cambodia*. IEEE; 2015. p. 155–160.

37 Zhong Y, Song J, Yu H, Du R. A study on kinematic pattern of fish undulatory locomotion using a robot fish. *J Mech Robot*. 2018;**10**(4):041013. doi: 10.1115/1.4040434.

38 Shriyam S, Agrawal A, Behera L, Saxena A. Robotic fish design and control based on biomechanics. *IFAC Proc Volumes*. 2014;**47**(1):662–669. doi: 10.3182/20140313-3-IN-3024.00235.

39 Wang S-Y, Zhu J, Wang X-G, Li Q-F, Zhu H-Y. Kinematics modeling and simulation of a bionic fish tail system based on linear hypocycloid. *Appl Bionics Biomech*. 2015;**2015**: 1–8. doi: 10.1155/2015/697140.

40 Chen Z, Hou P, Ye Z. Robotic fish propelled by a servo motor and ionic polymer-metal composite hybrid tail. *J Dyn Syst Meas Control*. 2019;**141**(7):071001. doi: 10.1115/1.4043101.

41 Guang R, Chao W, Fei W. A traveling wave fitting method for robotic fish with a multi-joint caudal fin. In: *Proceedings of the 26th Chinese Control and Decision Conference (CCDC 2014), Changsha, China*. IEEE; 2014. p. 3311–3315.

42 Sikandar UB, Muhammad A. Modeling and simulation of surface-and-dive behavior of a bottlenose dolphin. In: *Proceedings of the International Conference on Robotics and Biomimetics (ROBIO 2013), Shenzhen, China*. IEEE; 2013. p. 1784–1789.

43 Zhou L, Dong E, Huang H, Kong X, Yang J. Design and research of a novel caudal – fin propulsion mechanism with two degrees of freedom. In: *Proceedings of the International Conference on Real-time Computing and Robotics (RCAR 2017), Okinawa, Japan*. IEEE; 2017. p. 454–458.

44 Yu J, Su Z, Wu Z, Tan M. Development of a fast-swimming dolphin robot capable of leaping. *IEEE/ASME Trans Mechatron*. 2016;**21**(5):2307–2316. doi: 10.1109/TMECH.2016.2572720.

45 Yu J, Zhang C, Liu L. Design and control of a single-motor-actuated robotic fish capable of fast swimming and maneuverability. *IEEE/ASME Trans Mechatron*. 2016;**21**(3):1711–1719. doi: 10.1109/TMECH.2016.2517931.

46 Junzhi Y, Yonghui H, Jiyan H, Long W. Dolphin-like propulsive mechanism based on an adjustable Scotch yoke. *Mech Mach Theory*. 2009;**44**(3):603–614. doi: 10.1016/j.mechmachtheory.2008.08.011.

47 Masoomi SF, Haunholter A, Merz D, Gutschmidt S, Chen X, Sellier M. Design, fabrication and swimming performance of a free-swimming tuna-mimetic robot. *J Robot*. 2014;**2014**: 1–7. doi: 10.1155/2014/687985.

48 Afolayan MO, Yawas DS, Folayan CO, Aku SY. Mechanical description of a hyper-redundant robot joint mechanism used for a design of a biomimetic robotic fish. *J Robot*. 2012;**2012**: 1–16. doi: 10.1155/2012/826364.

49 Shintake J, Ming A, Shimoj M. Development of flexible underwater robots with caudal fin propulsion. In: *Proceedings of the International Conference on Intelligent Robots and Systems (IROS 2010), Taipei, Taiwan*. IEEE/RSJ; 2010. p. 940–945.

50 Zhang Y, Liu G, Li H. Development of a micro swimming robot using optimised giant magnetostrictive thin films. *Appl Bionics Biomech*. 2006;**3**(3):161–170. doi: 10.1533/abbi.2006.0025.

51 Zhang R, Shen Z, Wang Z. Ostraciiform underwater robot with segmented caudal fin. *IEEE Robot Automat Lett*. 2018;**3**(4):2902–2909. doi: 10.1109/LRA.2018.2847198.

52 Qian Z, Liu H, Bi Z. Design and experiment of miniaturized and low-cost robotic fish with customized electromagnetic actuation. In: *New Developments in Mechanics and Mechanical Engineering, Recent Advances In Mechanical Engineering Series, Vienna, Austria*. 2015. p. 9–15.

53 Shin BH, Lee K-M, Lee S-Y. A miniaturized tadpole robot using an electromagnetic oscillatory actuator. *J Bionic Eng*. 2015;**12**(1):29–36. doi: 10.1016/S1672-6529(14)60097-4.

54 Wang Z, Hang G, Li J, Wang Y, Xiao K. A micro-robot fish with embedded SMA wire actuated flexible biomimetic fin. *Sens Actuators A Phys*. 2008;**144**(2):354–360. doi: 10.1016/j.sna.2008.02.013.

55 Li S, Li J. A robot fish of autonomous navigation with single caudal fin. In: *Proceedings of the 2nd International Conference on Robotics and Automation Engineering (ICRAE 2017), Shanghai, China*. IEEE; 2017. p. 276–279.

56 Nakabayashi M, Kobayashi R, Kobayashi S, Morikawa H. A novel propulsion mechanism using a fin with a variable-effective-length spring. In: *Proceedings of the International Conference on Robotics and Biomimetics (ROBIO 2009), Bangkok, Thailand*. IEEE; 2009. p. 1515–1521.

57 Kodati P, Kinkle J, Winn A, Deng X. Microautonomous robotic ostraciiform (MARCO): Hydrodynamics, design, and fabrication. *IEEE Trans Robot*. 2008;**24**(1):105–117. doi: 10.1109/TRO.2008.915446.

58 Lachat D, Crespi A, Ijspeert AJ. Boxybot: a swimming and crawling fish robot controlled by a central pattern generator. In: *Proceedings of the 1st International Conference on Biomedical Robotics and Biomechatronics (BioRob 2006), Pisa, Italy*. IEEE/RAS-EMBS; 2006. p. 643–648.

59 Wang W, Xie G. CPG-based locomotion controller design for a boxfish-like robot. *Int J Adv Robot Syst*. 2014;**11**(6):1–11. doi: 10.5772/58564.

60 Liu B, Guo Z, Liao B. Hydrodynamic performance study on a dual-caudal fin. In: *Proceedings of the International Conference on Mechatronics and Automation (ICMA 2017), Takamatsu, Japan*. IEEE; 2017. p. 620–625.