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Review of Biomimetic Underwater Robots Using Smart Actuators

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KEYWORDS: Biomimetic, Underwater robot, Smart actuator, Shape Memory Alloy (SMA), Ionic Polymer Metal Composite (IPMC), Lead Zirconate Titanate (PZT)

In this paper, biomimetic underwater robots built using smart actuators, e.g., a shape memory alloy (SMA), an ionic polymer metal composite (IPMC), lead zirconate titanate (PZT), or a hybrid SMA and IPMC actuator, are reviewed. The effects of underwater environment were also considered because smart actuators are often affected by their external environment. The characteristics of smart actuators are described based on their actuating conditions and motion types. Underwater robots are classified based on different swimming modes. We expanded our classification to non-fish creatures based on their swimming modes. The five swimming modes are body/caudal actuation oscillatory (BCA-O), body/caudal actuation undulatory (BCA-U), median/paired actuation oscillatory (MPA-O), median/paired actuation undulatory (MPA-U), and jet propulsion (JET). The trends of biomimetic underwater robots were analyzed based on robot speed (body length per second, BL/s). For speed per body length, robots using an SMA as an actuator are faster than robots using an IPMC when considering a similar length or weight. Robots using a DC motor are longer while their speeds per body length are similar, which means that robots using smart actuators have an advantage of compactness. Finally, robots (using smart actuators or a motor) were compared with underwater animals according to their speed and different swimming modes. This review will help in setting guidelines for the development of future biomimetic underwater robots, especially those that use smart actuators.

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1. Introduction

New tools for underwater tasks are under development by many researchers owing to increased needs related to oceanographic engineering, e.g., cables, pipelines, gas drilling, and environmental awareness.[1,2] Such demand has led to the development of underwater robots. However, a key issue in underwater robots is providing appropriate movement for the prescribed operating conditions under environmental limitations.[3] However, the movement of an underwater animal is not easy to achieve since several requirements need to be fulfilled, such as high speed, rapid acceleration, and a small hovering radius. To realize the movement of underwater animals, a biomimetic approach is an effective method as animal locomotion in nature tends to be optimized to the creature's living environment.

Many researchers have attempted to fabricate underwater robots using traditional actuators, multiple motors, pistons, joints, links, hinges, and so on to achieve the requirements of movement based on a biomimetic design and analysis.[4] In addition, many underwater robots have been developed using traditional actuators.[5-29] Although some robots exhibit good performance, their size is quite large as they require multiple sets of actuators or other additional parts to achieve their performance or meet certain requirements.

Smart actuators, on the other hand, are alternative actuators for underwater robots owing to their ability to perform flexible and complex movements, which give them an advantage in biological mechanisms.[30] Smart materials can themselves be used as actuators and can easily perform flexible and complex movements without the need for additional parts.[31,32] Thus, it is possible to fabricate robots with a relatively small weight and volume as compared to those fabricated using conventional motor- and piston-based actuators. Moreover, smart actuators make less noise during operation.

Biomimetic underwater robots have recently been developed and fabricated using smart actuators such as shape memory alloys (SMAs), ionic polymer–metal composite (IPMCs), or lead zirconate titanate (PZT).

Biomimetic underwater robots using smart actuators were first developed in early 2000 using an IPMC. The numbers of biomimetic underwater robots thereafter increased and their properties (particularly robot speed) improved.

In this paper, we review underwater biomimetic robots that use smart actuators. Then, their swimming modes are categorized into five different types by considering the location of the thrust generating section, e.g., the body, fin, or flap, and the movement each section generates. The underwater robots are then categorized according to the type of actuator used and then according to their five swimming mode, and a brief explanation of each robot is given. Finally, the trend of using smart actuators for biomimetic underwater robots is explained on the basis of the robot's speed per body length.

2. Smart Actuators in Underwater Robots

Smart actuators used in underwater robots can be classified into four main types: SMA, IPMC, PZT, and hybrid SMA and IPMC actuators. This section provides a brief description of each actuator and its characteristics when actuated under atmospheric and underwater conditions.

2.1 Shape Memory Alloy

SMA has thermo-mechanical characteristics due to phase transition in the material. This is related to the temperature and internal stress of the material, and a shape memory effect (SME) occurs under certain conditions. The SME process is described as follows. At a certain temperature between the austenite and martensite phases, when stress is applied, the austenite phase transforms into a deformed martensite phase, while it will have a residual stress. This process is called forward transformation. At this point, when temperature is applied during the austenite phase, deformation occurring during the forward transformation is destroyed and the material returns to its original shape, which is called reverse transformation (Fig. 1). During this process, a large amount of stress is derived, and through this process, SMA can be used as an actuator.

2.2 Ionic Polymer Metal Composite

IPMC is an actuator that uses a polymer called Nafion. When an external electric stimulation is applied to this material, a mechanical deformation occurs because of a change in the chemical structure. On the basis of this phenomenon, this material can be used as an actuator.

IPMC is composed of polymer and electrodes. When voltage is applied to both electrodes, an electric field is formed. Inside the polymer, sodium ions and water molecules will move to the cathode. Since the SO_3^- ions are fixed, the internal volume of water molecules will be unevenly distributed. A bending effect then occurs (Fig. 2). The characteristics of the actuator include flexible operation, repeatability, a large displacement driven contrast to a low working voltage, and a short response time.

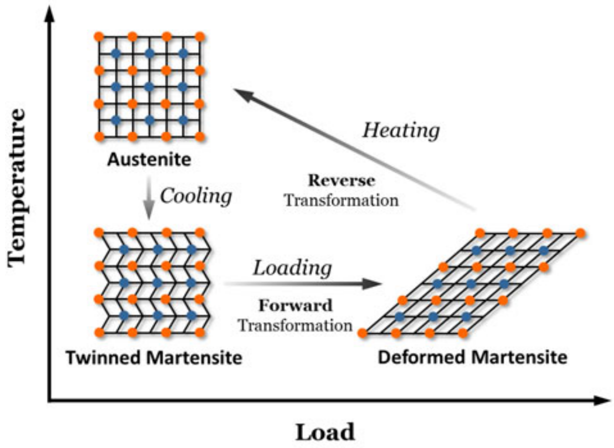

Fig. 1 Principle of shape memory alloy (SMA)

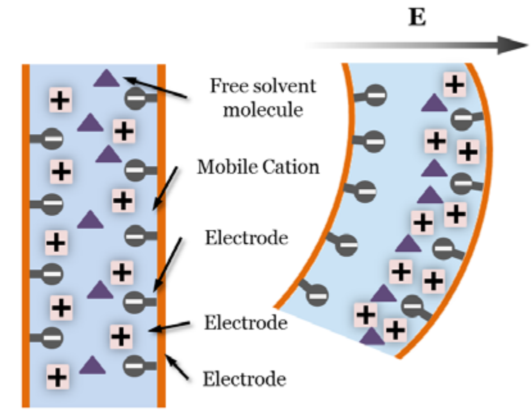

Fig. 2 Principle of ionic polymer metal composite (IPMC)

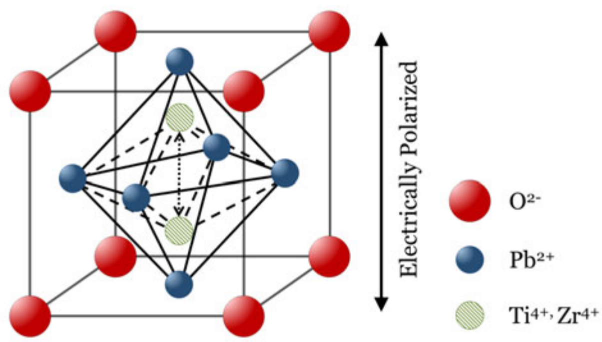

Fig. 3 Principle of lead zirconate titanate (PZT)

2.3 Lead Zirconate Titanate

PZT, which stands for the initial letters of lead (Pb), zirconate, and titanate, is an inorganic compound expressed as $Pb[Zr_xTi_{1-x}]O_3$ $(0 \le x \le 1)$ (Fig. 3). When both the surfaces of PZT are compressed by outside pressure, it generates an electric field proportional to the compression, which then produces voltage. In contrast, the shape of the PZT is deformed by an externally applied voltage. This phenomenon, called a piezoelectric effect, is how the PZT can be used as an actuator.

2.4 Comparison of the Three Actuators

Since the actuators mentioned above are driven by different principles, their actuating characteristics and performances are also

Table 1 Properties of smart actuators used in underwater robots

Characteristics	SMA[32-35,37]	IPMC[32,33,36]	PZT[32-34]
Voltage (V)	Low (>2)	Low (>1)	High (>100)
Strain (%)	Medium (>5)	Large (>40)	Small (0.2)
Stress (MPa)	Large (>200)	Low (0.3)	Large (110)
Actuation Frequency (Hz)	Slow (~1)	Fast (<100)	Very Fast (~10,000)

different. Table 1 shows a comparison of the properties of the three actuators reviewed.[32-37]

PZT requires a high voltage for actuation, and is thus not suitable for a standalone small-size underwater robot. On the other hand, SMA and IPMC require a relatively low voltage for actuation and are therefore suitable for compact underwater robots. Since SMA has a relatively low frequency, this actuator is suitable for undulatory actuation rather than oscillatory actuation. Since IPMC and PZT actuate within a broad range of speed, they are suitable for both oscillatory and undulatory actuation.

2.5 Advantages and Disadvantages of Actuating in Water

Smart actuators have different operating principles as compared to traditional actuators such as motors and pistons, and have certain advantages when operated in water. In SMA and IPMC, in particular, the external temperature and/or humidity are dominant factors affecting their behavior.

When a current is applied to an SMA, it creates a resistance such that the temperature rises sufficiently for SME to occur. If this process occurs in water, which has a relatively low temperature, the transfer of heat is faster than in the air, thus improving the cooling speed. Therefore, when an SMA is used in underwater robots, the actuating frequency can be improved by around 1 Hz as compared with normal actuating conditions.[37] When an IPMC is actuated in air, dehydration on the surface is a typical problem. However, since an underwater robot operates in water, this problem can be easily solved. The repeatability of the actuator is also improved when operating in water.[36]

3. Swimming Modes of Biomimetic Robots

Traditionally, the classification of underwater robots has been similar to that of fish.[3,38-44] According to Breder's fish classification, if a fish generates thrust by bending its body and/or caudal fin, the resulting motion is categorized as *body and/or caudal fin* (BCF) locomotion.[39] In Fig. 4, anguilliform, carangiform, and thunniform type fish such as tuna, eel, and shark can be categorized as BCF types. However, if the fish use their median fin, which includes the anal, dorsal, and pectoral fins, and/or paired fins, including the pelvic and pectoral fins, as the propulsion mechanism, the resulting swimming mode is categorized as *median and/or paired fin* (MPF) locomotion. Such rajiform and labriform type locomotions can be categorized into MPF locomotion. In addition, each locomotion mode can be divided into *undulatory* and *oscillatory* motions based on the wave frequency, which is shown from the fish movement.

Undulatory motion can be applied when a fish creates its propulsion from a wave-shaped movement. Otherwise, if the fish uses a swivel-like motion to obtain its thrust, the motion can be categorized as an *oscillatory* motion. These two classifications cannot be clearly separated, because oscillatory motion can be derived from a shorter wavelength of *undulatory* motion and vice versa. An eel typically uses its entire body to generate a wave-like motion, classified as *undulatory* motion, while a boxfish, which oscillates its caudal fin owing only to its inflexible body, can be classified as having an *oscillatory* motion.

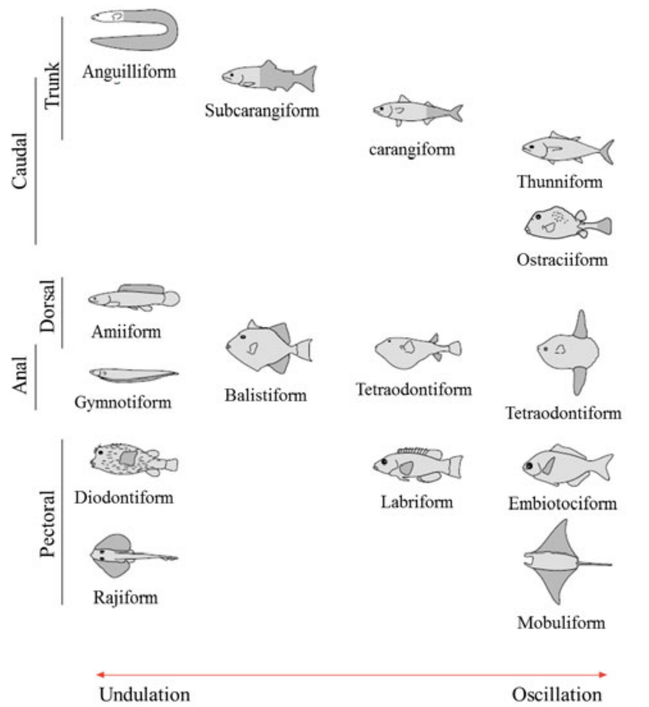

Fig. 4 Breder's fish classification based on thrust and locomotion (Reused with permission)[44]

However, in this type of fish-based categorization, a difficulty has arisen in classifying general animal species. In particular, in the field of robotics, there is no limitation in mimicking a fish-like locomotion mechanism and shape, but if the robot has a somewhat different locomotion mechanism and shape from the targeted animal, it becomes difficult to follow a traditional fish classification. Therefore, in this paper, we propose a simplified classification model specific to the robotic field. First, similar to the BCF and MPF type motion in fish classification, robots can be classified into a body and/or caudal Actuator (BCA) and median and/or paired Actuator (MPA) respectively. BCA and MPA are classified on the basis of the location where actuation occurs relative to the central axis, as referred to the propulsion direction of the robot. A BCA achieves propulsion through the actuating motion along the central axis. In an MPA, however, the actuation motion occurs off the central axis. Similar to the undulatory and oscillatory classification of fish, we set the sub-categorization as undulatory and oscillatory motion according to the motion of the robot's actuators. Just as in fish classification, undulatory motion can be described as a wave motion appearing in the actuator. In the same manner, oscillatory motion is also defined as a propulsive structure swiveling on its fixture without a wave-like shape.

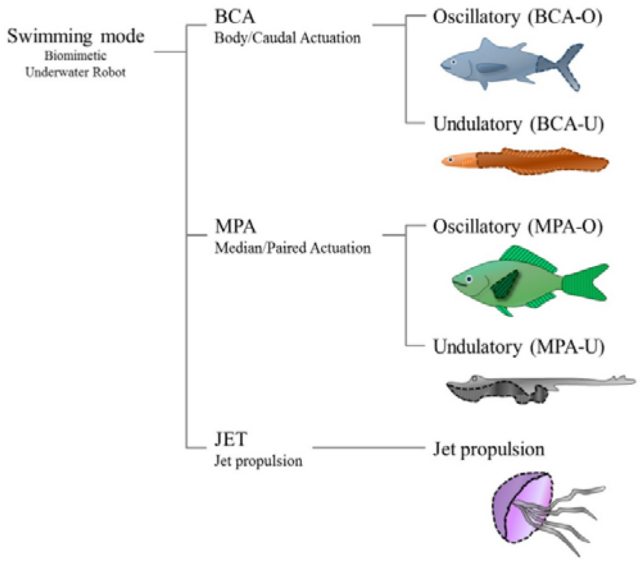

Fig. 5 Classification of swimming modes of biomimetic underwater robots (Modified and re-classified)[38]

However, to cover the various locomotion mechanisms of an autonomous underwater vehicle (AUV), it is necessary to derive other swimming modes not only from fish locomotion mechanisms but also from non-fish locomotion mechanisms such as those found in shellfish and jellyfish. From these requirements, we introduced jet propulsion as one of the swimming modes. Therefore, biomimetic underwater robots can be classified into five types based on their swimming mechanism, as shown in Fig. 5.

4. Biomimetic Robots using Smart Actuators

Table 2 summarizes robots using different smart actuators. In brief, the actuator and swimming modes are listed according to the institution that developed the biomimetic underwater robot.

4.1 SMA

A fish-robot, developed at the Harbin Institute of Technology, can achieve BCA-O swimming mode using an SMA actuator embedded into its polymer (Fig. 6).[45] The actuator was fabricated using an SMA wire with a 0.089 mm diameter embedded into the elastic substrate. The maximum deformation angle of this robot is 108° at 7.2 V. The length of the robot is 146 mm, and it has a maximum speed of 112 mm/s when actuated at 2.78 Hz.

An eel-like robot, developed at the University of Science and Technology of China and at the Nanyang Technological University, can achieve BCA-U swimming mode using an SMA wire and a flexible polyurethane-based actuator (Fig. 7).[46] The frequency range is 1/7.2–1/3 Hz, and the maximum deformation is 37 mm. The maximum speed of the robot is 8.2 mm/s when operating at 1/5.4 Hz with 1200 mA current. Furthermore, in 2002, another type of eel-like robot that uses BCA-U swimming mode was developed at the Northeastern University.[47] This robot uses the same material as the eel-like robot described above.

Table 2 A summary of biomimetic underwater robots using smart actuators

Institute	Actuator	Swimming mode	Year	Reference
AIST, Tokyo Institute of Technology, RIKEN	IPMC	BCA-U	2006	57
Chonnam National University	IPMC	JET	2009	67
College of Engineering Michigan State University	IPMC	BCA-O	2006	56
Dankook University and Korea University	IPMC	BCA-U	2003	58, 59
	IPMC	BCA-O	2003	58, 59
Harbin Engineering University and Kagawa University	IPMC	BCA-O	2008	55
Harbin Institute of Technology	SMA	BCA-O	2008	45
	SMA	MPA-U	2008	45
	SMA	MPA-O	2009	48
Kagawa University	SMA	MPA-O	2010	51
	HYBRID	JET	2007	70
	HYBRID	MPA-O	2007	69
	IPMC	MPA-O	2010	62
	IPMC	MPA-O	2003	66
Konkuk University	PZT	BCA-O	2007	68
Michigan State University	IPMC	BCA-O	2010	54
Nagoya University and Kobe University	IPMC	MPA-O	2006	4
Northeastern University	SMA	BCA-U	2002	47
Polytechnic Institute of New York University	IPMC	BCA-O	2010	53
Seoul National University	SMA	MPA-O	2011	49
Tartu University	IPMC	MPA-O	2004	61
	IPMC	MPA-U	2004	65
University of Science and Technology of China and Nanyang Technological University	SMA	BCA-U	2006	46
University of Virginia	IPMC	MPA-U	2011	63,64
	IPMC	MPA-O	2011	60
Virginia Institute of Technology	SMA	JET	2011	52

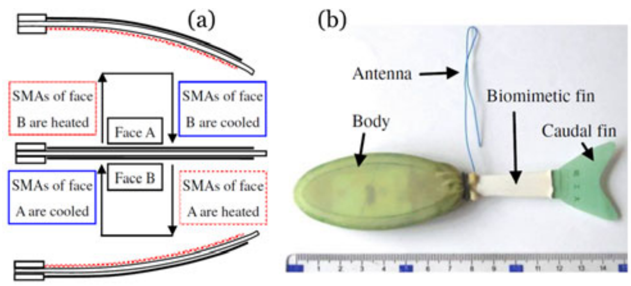

Fig. 6 Fish-like robot with a BCA-O swimming mode using SMA: (a) bending sequence of its dual-force biomimetic fin, and (b) external view of the micro robot fish with a carp-like caudal fin (Reused with permission)[45]

A micro biomimetic manta ray robot, developed at the Harbin Institute of Technology (State Key Laboratory of Robotics and System), can achieve MPA-O swimming mode (Fig. 8).[48] To fabricate its actuator, an SMA wire was embedded in a PVC sheet. The robot has a maximum speed, length, width, and height of 57 mm/s, 220 mm, 243 mm, and 66 mm, respectively.

A turtle-like swimming robot developed at the Seoul National University, (Innovative Design and Integrated Manufacturing Lab.) can achieve MPA-O swimming mode using a smart soft composite

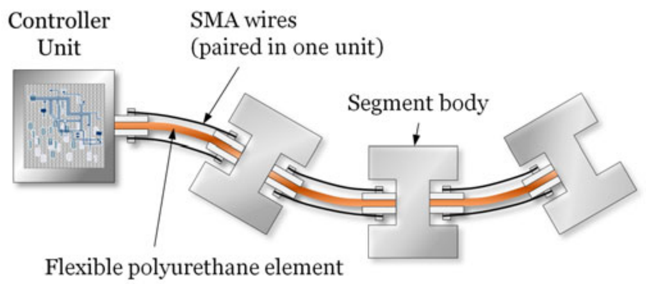

Fig. 7 Undulating three-segment body system of an eel robot with BCA-U swimming mode using SMA. SMA wires were placed on adjacent sides of a flexible segment to give sagging and hogging movement (Modified and redrawn)[46]

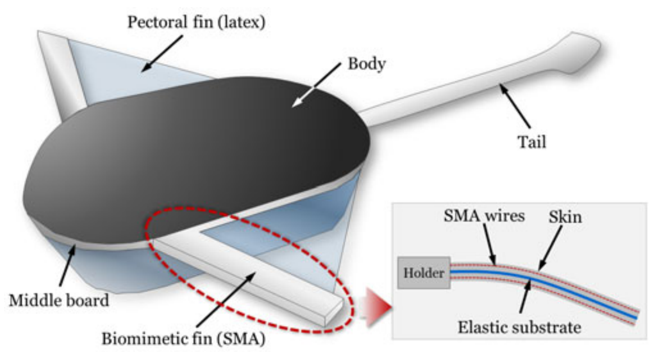

Fig. 8 Micro robot manta ray that shows MPA-O swimming mode from an SMA: the robot consisted of biomimetic fin and pectoral fin (Modified and redrawn)[48]

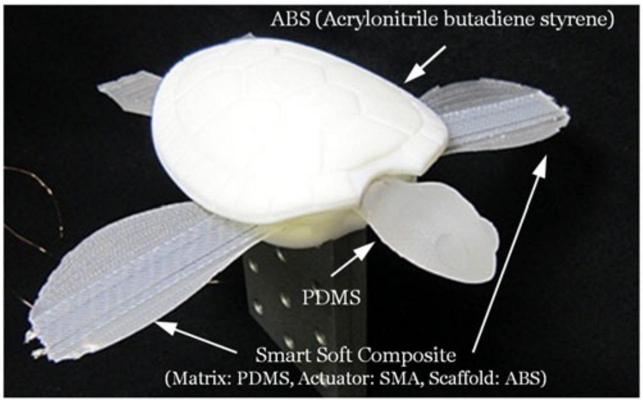

Fig. 9 Turtle-like robot that shows MPA-O swimming mode using SSC structure[49,50]

(SSC) structure which is made by 3D printing and casting processes (Fig. 9).[49,50] This SSC structure realizes coupled motions of bending and twisting in a single structure, and achieves efficient turtle-like swimming motion. The robot has a maximum speed, length, width of 22.5 mm/s, 123 mm, and 166 mm, respectively.

Another jelly-fish like robot, developed at the Kagawa University, achieves a flapping locomotion generated from an SMA-based actuator with positive spring elements.[51] The maximum speed of this robot is similar to a manta ray robot with a smaller size (63 mm in length, 35 mm in width, and 18 mm in height).

A squid-like robot, developed at the Harbin Institute of technology, achieves MPA-U swimming mode from an SMA-

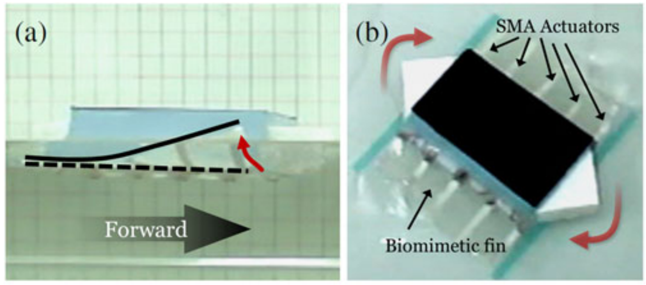

Fig. 10 Robot squid that shows MPA-U swimming mode from an SMA: (a) straight swimming motion and (b) clockwise rotation (Reused with permission)[45]

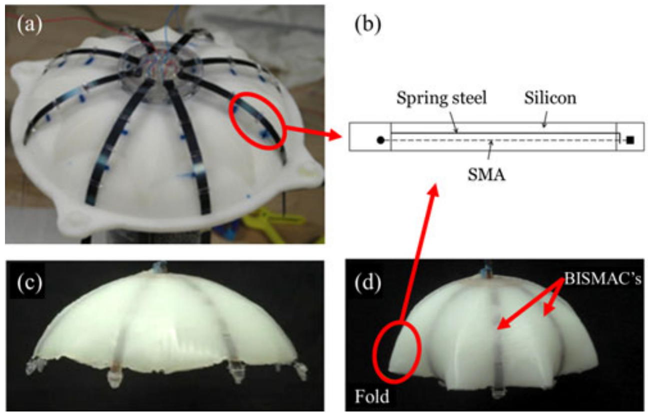

Fig. 11 Robojelly, which uses jet propulsion swimming mode from an SMA: (a) top view of the internal structure meshed with its mold, and (b) a schematic of a BISMAC actuator (Reused with permission)[52]

embedded polymer-based actuator (Fig. 10).[45] This actuator is fabricated using an SMA wire embedded into an elastic substrate. Undulating locomotion is generated by 10 SMA actuators (5 actuators on each side) with a maximum speed of 40 mm/s at 3.125 Hz. The length of this robot is 242 mm, and its width and height are 225 and 52 mm, respectively.

Robojelly, a jellyfish-like robot developed at Virginia Institute of Technology, achieves jet propulsion to generate thrust using an SMA-based actuator called a bio-inspired shape memory alloy composite (BISMAC) (Fig. 11).[52] BISMAC is fabricated using a steel spring and SMA wire embedded in silicone. The BISMAC is 110 mm long and 0.1 mm thick, while the bell is 134 mm in diameter and 82 mm in height. This robot has a maximum speed of 54 mm/s at 0.5 Hz.

4.2 IPMC

IPMC is widely used in fabricating BCA-O swimming robots. A fish-like robotic swimmer, developed at the Polytechnic Institute of New York University (Dynamical Systems Lab.), mimics the general swimming locomotion of fish, thrusting itself with its tail fin.[53] Its maximum tip displacement is 12.5 mm at 2 Hz, while its maximum speed is 12 mm/s at 0.98 Hz. Another fish-like robot, developed at the Michigan State University (Fig. 12),[54] has a mounted IPMC passive tail fin to achieve BCA-O swimming mode. The range of frequency is 0.05–10 Hz, and it has a maximum speed

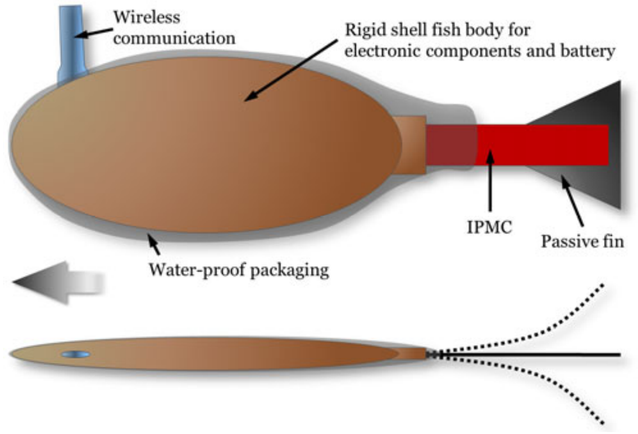

Fig. 12 Robotic fish with BCA-O swimming mode using an IPMC (Modified and redrawn)[54]

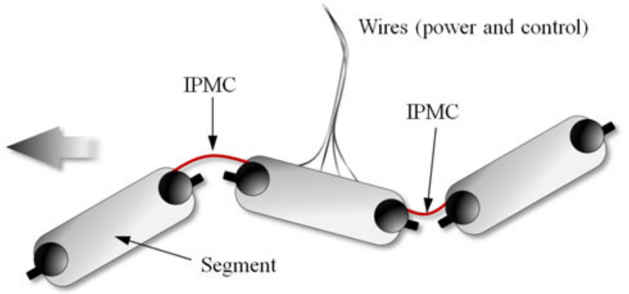

Fig. 13 Snake-like robot showing BCA-U swimming mode using an IPMC (Modified and redrawn)[57]

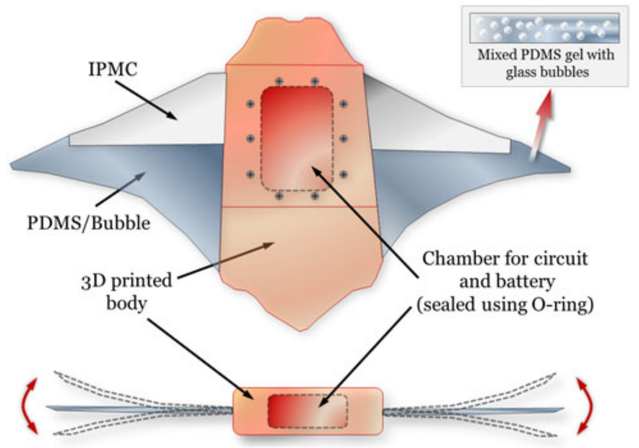

Fig. 14 Robotic cownose ray with MPA-O swimming mode using an IPMC (Modified and redrawn)[60]

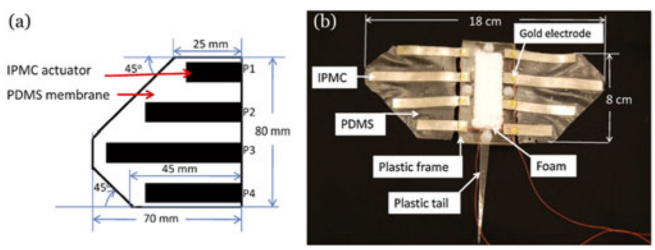

Fig. 15 Robotic manta ray with MPA-U swimming mode using an IPMC: (a) design of the IPMC membrane actuator, and (b) a top-view photograph of the robotic manta ray (without the control unit), (Reused with permission)[64]

of 22 mm/s when operated at 1.6 Hz. The robot is 200 mm long, 52 mm wide, and 63 mm tall. Another fish-like robot, developed jointly at the Harbin Engineering University and the Kagawa University, swims in BCA-O mode using an IPMC actuator.[55] The actuator (10 mm long and 8 mm wide) of this robot has 7 mm of maximum displacement at a frequency range from 0.3 to 7 Hz, and has a maximum speed of 24 mm/s (2 Hz).

A wireless biomimetic robotic fish, developed at the Michigan State University (Smart Microsystems Lab.) in 2010, also demonstrates BCA-O swimming mode with an IPMC-based actuator.[54] The length and width of this actuator are 23 mm and 15 mm, respectively. The maximum tip displacement of the actuator is 0.8 mm. Four different types of fins are mounted on its tail to optimize the robot speed related to the shape of the fin. The maximum speed of the robot is 23 mm/s at around 1 Hz.

The Navigating EAP-Controlled Module with Onboard Resources (NEMO), a robotic fish developed jointly at the Department of Electrical and Computer Engineering and the College of Engineering at the Michigan State University, also achieves BCA-O swimming mode with an IPMC-based actuator.[56] Location and environmental data can be gathered from a global positioning system (GPS), digital compass, and thermo sensor integrated with a control board. NEMO is 230 mm long, 65 mm wide, and 30 mm tall. The maximum speed of NEMO is 6.3 mm/s at 2 Hz (the operating frequency range is 0.3–3.3 Hz).

A snake-like robot was developed by the Bio-Mimetic Control Research Center, Tokyo Institute of Technology, RIKEN (The Institute of Physical and Chemical Research), and AIST (National Institution of Advanced Industrial Science and Technology). The robot mimics a real snake, and moves using BCA-U swimming mode (Fig. 13).[57] The actuator of this robot is made of an IPMC film (20 × 2 × 0.2 mm, Nafion 117® plated with gold, DuPont). The robot moves at a maximum speed of 8 mm/s at a frequency of 0.4 Hz. The complete body of the robot is made up of three parts such that it mimics the behavior of a snake. The robot moves by the actuation of the IPMC film, which is attached to the section between the joints.

Another robot, tadRob, which mimics a tadpole, was jointly developed by the Dankook University, Korea University, and Korea Institute of Science and Technology (KIST).[58] This robot also shows BCA-U swimming mode using an IPMC. The robot uses a fin made of PDMS film (54 mm long, 20 mm wide, and 0.3 mm thick). The actuating frequency ranges from 1 to 8 Hz, and it has a maximum deformation of 4 mm. Robot has the dimensions of 96 mm in length, 24 mm in width, 25 mm in height. Its maximum swimming speed in water reaches 23.6 mm/s (13.5 mm/s when oscillation).[58,59] The frequency of the robot is controlled independently using a micro control unit (MCU).

A robotic cownose ray was developed by the University of Virginia (BIER Lab.) and has MPA-O swimming mode. The actuating part of the wing consists of an IPMC, while the other part consists of a PDMS (Fig. 14).[60] This robot is 210 mm long, 330 mm wide, and 50 mm thick. Its maximum speed reaches 7 mm/s at a

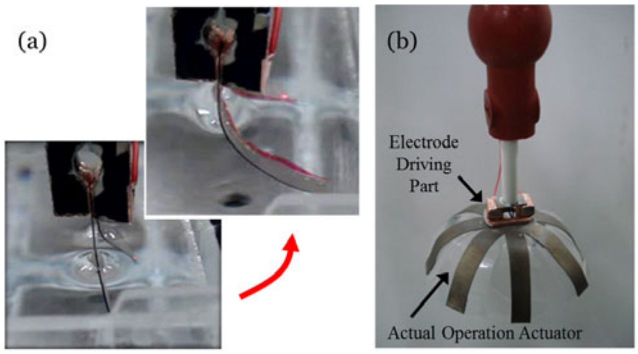

Fig. 16 Biomimetic jellyfish robot with jet propulsion swimming motion using an IPMC: (a) mobility test of two IPMC legs integrated using cellophane paper, and (b) a photograph of the fabricated jellyfish (Reused with permission)[67]

frequency of 0.157 Hz. Another robot mimicking a ray was developed at the Tartu University (Intelligent Materials and Systems Lab.), and uses an IPMC actuator to achieve a MPA-O swimming motion. The dimensions of this robot are 35 × 54 × 0.5 mm, and its maximum swimming speed is 9 mm/s.[61] Another underwater micro robot was developed jointly by the Kagawa University, Harbin Engineering University, Kansai Research Institute, and AIST. It shows MPA-O swimming mode and has moving, grapping, and buoyancy control abilities.[62] A total of 10 IPMC actuators are used, each with dimensions 12 × 3 × 0.2 mm. The overall size of the robot is 33 × 14 × 14 mm, and its reported maximum speed is 1.54 mm/s at 1 Hz and 9V. The robot can control its buoyancy, and it reaches a maximum floating speed of 7 mm/s.

The University of Virginia (BIER Lab.) has developed a pectoral-fin-mimicking manta-ray, which consists of a PDMS membrane using four IPMCs (0.28 mm in thickness) (Fig. 15).[63,64] Implementation of the undulating (MPA-U) locomotion is achieved by adjusting the four IPMCs in a continuous cycle. The maximum tip deflection of the actuator is 17.5 mm. Through their experiments, the researchers achieved a maximum speed of 4.4 mm/s at 0.4Hz. Similarly, AIST (Japan, Bio-mimetic Control Research Center), Nagoya University, and Kobe University have mimicked the wing of a ray using an IPMC and polyethylene film to achieve MPA-U swimming mode.[4] This robot is capable of swimming at a maximum speed of 18.1 mm/s at a frequency of 1.25 Hz with a maximum deformation of 2.8 mm.

A ray-like underwater robot was developed by the Tartu University (Intelligent Materials and Systems Lab). In 2004, they mimicked the pectoral fin of a ray.[65] To achieve MPA-U swimming mode, the robot uses 16 connected IPMCs (Musclesheet™) fixed on organic glass. The robot is 140 mm in length and 28 mm in width. It can reach a maximum speed of 0.005 mm/s at a wave frequency of 0.4 Hz when the IPMCs are controlled sequentially.

A biomimetic fish-like robot was developed by Kagawa University, Nagoya University, and AIST.[66] This robot generates propulsion using two actuators consisting of an ionic conducting polymer film (ICFP), which is similar to an IPMC. Through their experiments, the researchers achieved a maximum speed of 5.21 mm/s at 0.004 Hz. The ICFP actuators were attached on both sides of the robot's body to control its buoyancy. Chonnam National University also developed a jellyfish mimetic robot driven with a jet propulsion system (Fig. 16).[67] The actuator is 21 mm in length and is composed of cellophane paper and an IPMC. The maximum experimental frequency of the actuator is 16.6 Hz. The robot regulates its buoyancy using a balloon. Its maximum speed at 1 Hz is 2.3 mm/s.

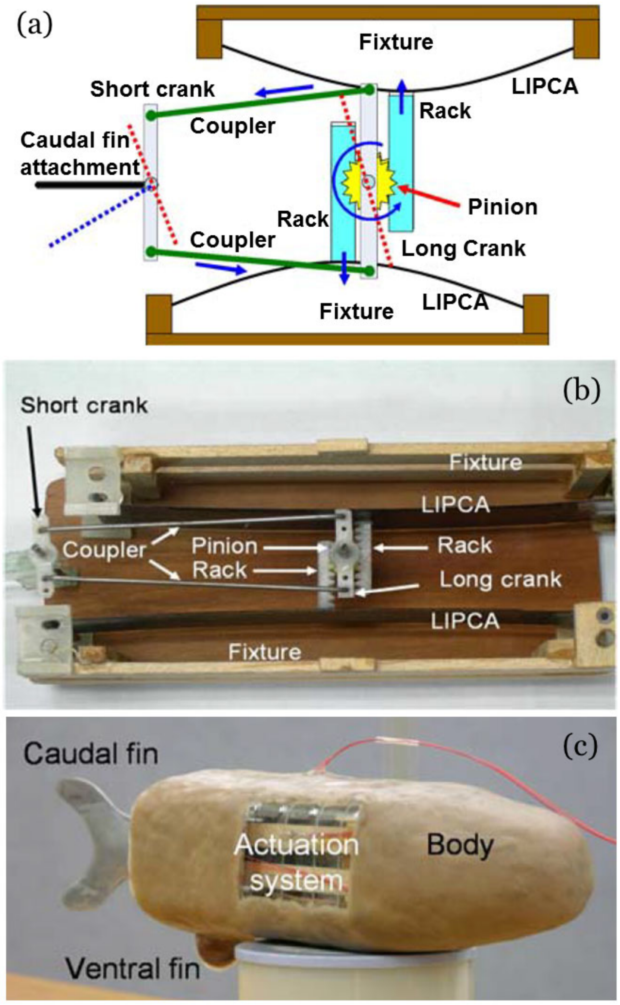

Fig. 17 Biomimetic fish robot with BCA-O swimming mode using a PZT: (a) design of the actuation system, (b) the actuation system itself, and (c) the final assembly of the biomimetic fish robot (Reused with permission)[68]

4.3 PZT

A biomimetic fish robot that is driven with a BCA-O swimming motion using a caudal fin was developed by the Artificial Muscle Research Center, Konkuk University (Fig. 17).[68] The researchers used a ceramic actuator called a lightweight piezocomposite actuator (LIPCA), which is a unimorph piezoceramic encapsulated with glass/epoxy and carbon/epoxy. To simulate the motion of the fin, a crank, rack, and pinion structure is used. Because an additional device is required to achieve locomotion, the size of the robot is increased (1000 × 500 × 400 mm). Its maximum speed is 25.16 mm/s at an operating frequency of 0.9 Hz with 300 V_{pp} as the operating voltage.

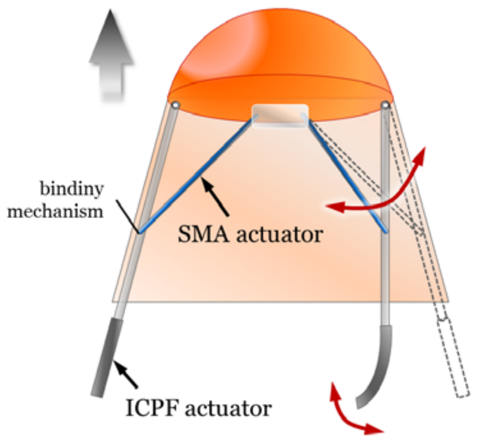

Fig. 18 Jellyfish-like micro robot that achieves MPA-O swimming mode using a hybrid actuator (right side: SMA and ICPF actuators when both are electrified and dashed line: when released (Modified and redrawn)[69]

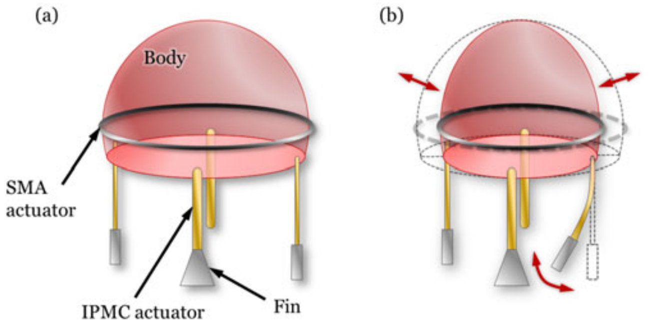

Fig. 19 Jellyfish-type underwater micro robot that achieves jet propulsion swimming mode using a hybrid actuator: (a) structure of the micro robot, and (b) when electric is applied (Modified and redrawn)[70]

4.4 Hybrid

A jellyfish-like micro robot using a hybrid actuator was developed by the Harbin Engineering University and Kagawa University (Fig. 18).[69] This robot consists of four actuators, each of which was fabricated by combining an SMA (10 mm × ϕ 1 mm) with an ICPF (15 × 8 × 0.3 mm) to achieve a MPA-O swimming motion. The maximum frequencies of the SMA and ICPF are 0.5 and 2 Hz, respectively. Unlike a real jellyfish, this robot generates thrust through the bending movement of the actuators.

Another robot using a hybrid actuator was developed by the Kagawa University (Guo Lab., Fig. 19).[70] This is a jellyfish mimetic robot propelled using jet propulsion. The actuator was fabricated by combining an SMA, an ICPF, and a rubber material. Its length in the moving direction is 46.1 mm, and the diameter of the cross section is 36.3 mm. The robot has a maximum speed of 6 mm/s at an operating frequency of 0.6 Hz.

5. Comparisons of Biomimetic Underwater Robots

Motor-propelled underwater robots were compared as a reference, which showed that such robots are significantly faster

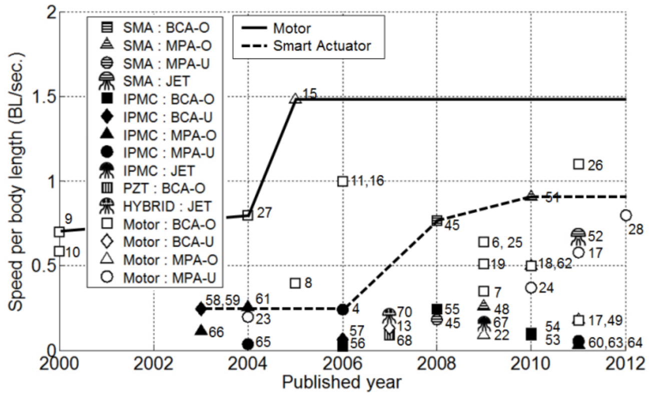

Fig. 20 Speed comparison of motor- and smart-actuator-based biomimetic underwater robots

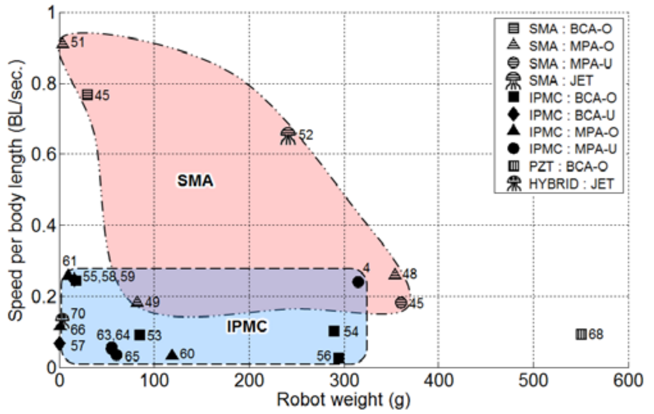

Fig. 21 Comparison of robots using different actuators (speed per body length vs. robot weight)

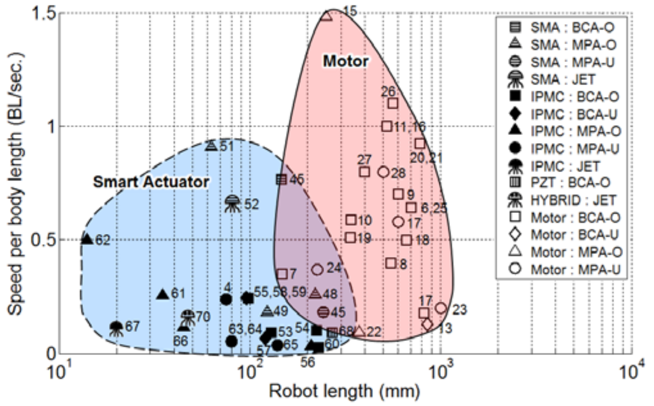

Fig. 22 Comparison of motor based robots and smart-actuator based robots (speed per body length vs. robot length)

than robots that use smart actuators. The speed based on body length of the developed biomimetic underwater robots was increased until 2010, and the maximum speed achieved was 57 mm/s (0.9 BL/s) (Fig. 20).[51]

In the early stage of biomimetic underwater robot design using smart actuators, most of the actuators used were made of an IPMC. Since 2005, researchers began using an SMA with/without the use of an IPMC or other smart actuator type to improve the speed. Since 2008, robots with the fastest speed have used an SMA as an actuator.

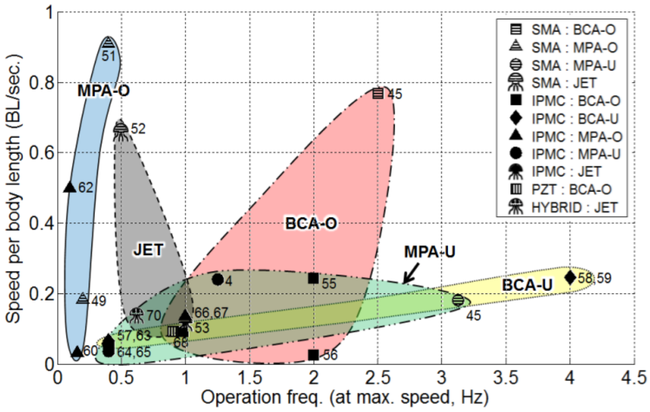

Fig. 23 Comparison of robots operating in different swimming modes (speed per body length vs. operation frequency (at maximum speed))

Robots actuated using an SMA show a faster speed than other robots in all swimming modes (Figs. 21 and 22). By increasing the robot length, the speed per body length was decreased. Although the capabilities of robot may increase with a larger body size, a limitation in the propulsion of the actuator itself remains. Therefore, considering the robot length, the speed tends to decrease with an increase in robot size. The smallest-sized biomimetic robot in this review was developed at the Kagawa University with a 14 mm length, and it is operated using an IPMC.[62] The speed of this robot is 7 mm/s (0.5 BL/s).

An SMA wire is usually embedded in the composite structure and the material actuates based on the eccentricity principle owing to its short range of actuation (~5% strain). Still it is needed to be longer than IPMC actuator to perform enough deformation. This may be one reason why small robots less than 50 mm in size are actuated by an IPMC or a hybrid and not by an SMA alone.

PZT generates a relatively high stress (110 MPa) and small displacement (0.2%) compared with other actuators. Because of these characteristics, to operate PZT for the desired locomotion, it is necessary to construct an additional mechanism (Fig. 17). As shown in the graph, additional mechanisms make the robot size bigger than other robots that use an SMA, IPMC, or hybrid. Motor-based robots tend to be larger and faster than smart-actuator-based robots on average. The length of the smallest motor-based robot is 148 mm (0.35 BL/s), which is still longer than most smart-actuator-based robots.

We can see the differences between swimming modes based on the operation frequency at the maximum speed of each robot (Fig. 23). In the left area in the figure, which indicates MPA-O swimming mode, the robot uses an SMA or IPMC as an actuator, and operates below 0.5 Hz at maximum speed. Similar to MPA-O, jet propulsion and BCA-O have operation frequency in certain range. For BCA-O, which is shown in the middle region, the speed per body length and the operating frequency tend to be proportional. We can find the similar phenomenon in the research that explains about the relationship between caudal fin which has similar function in actuator of BCA-O swimming robot's frequency and speed.[76]

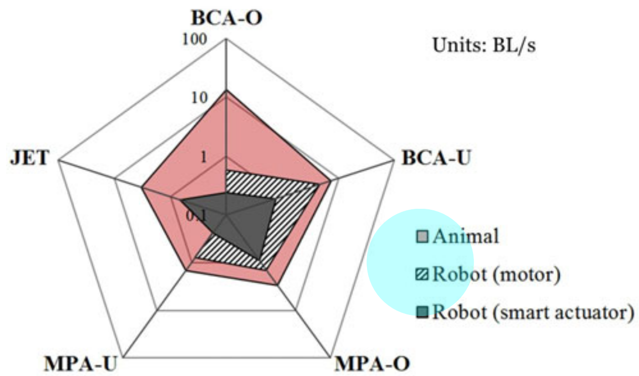

Fig. 24 Maximum speed comparison among animal, motor based robot, and smart actuator based robot[71-75]

6. Where are we now?

Robot speeds (motor- and smart- actuator-based robots) were compared with animal speeds to show the current status of robot technology (Fig. 24). Each axis represents the fastest animals and robots following particular swimming modes. The bluefin tuna[74] which swims in BCA-O swimming mode, has the fastest speed (72 km/h) among all swimming modes. On the other hand, the fastest animal using BCA-U swimming mode, the European eel,[75] almost matches a robot using a motor as an actuator. Smart-material-based MPA-O robots, which show the fastest performance compared to robots using other swimming modes, have almost the same speed as motor-based robots. Jet propulsion (Octopus vulgaris[72]) swimming mode shows a faster speed than MPA-U[73] but robots using a motor with this swimming mode are not reported. However, robots using a smart actuator can achieve jet propulsion swimming mode.

7. Conclusions

Biomimetic underwater robots were reviewed in this paper based on their actuators and swimming modes. The results show that speed per body length was increased over time, although robots using smart actuators are, in general, slower than robots using motors. A robot using PZT as an actuator was the largest and heaviest among all robots using smart actuators, since a PZT actuator requires an additional mechanism owing to a poor displacement. In addition, motor-based robots tend to be longer for a similar reason. On the other hand, robots using smart actuators such as an SMA, IPMC, or a hybrid have an advantage in terms of compactness. A comparison of robots with similar length or weight showed that robots using an SMA, IPMC, or a hybrid are faster than other robots in terms of speed per body length. However, robots using smart actuators are still the slowest compared with other robot types or underwater animals, despite their advantages in reduced size and weight, biomimetic actuation, noise reduction, and so on.

As the first review of biomimetic underwater robots using smart actuators, this paper may be used as a guide or map for researchers developing smart-actuator-based robots.

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