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# PRESENT RESEARCH SITUATIONS AND FUTURE PROSPECTS ON BIOMIMETIC ROBOT FISH

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***Abstract- As mankind steps into the 21st century, the exploration of the ocean also enters a new phase. In the recent decades, the research on biomimetic robot fish has attracted scientific communities' attention increasingly. With its character of high flexibility and intelligence, biomimetic robot fish have become one of the research focuses in the field of underwater robots in recent years. This paper mainly describes the classification of propulsion modes and the corresponding characteristics, the international research situation, the open problems and future research issues for biomimetic robot fish.***

**Index terms**: Biomimetic Robot Fish, Propulsion Modes, Sensor, Aquatic Environment

## 1. Research Significance of Biomimetic Robot Fish

Fish is the most ancient vertebrate, and they are almost all inhabiting in the aquatic environment on the earth. Throughout 5 hundred million years of natural selection, fish have evolved an astonishing level of swimming abilities. It not only could maintain both low power consumption and high efficiency in the sustained swimming, but also can achieve high-velocity mobility in the outbreak swimming. A variety of fish has their own numerous unique swimming patterns [1], and they are significantly better than the Unmanned Underwater Vehicle (UUV) in terms of mobility, acceleration ability, and boost efficiency. As mankind step into the 21st century, the exploration of the ocean is also entering a new phase. In the recent decades, the research on biomimetic robot fish has drawn scientific communities' attention increasingly. With its character of high-performance of flexibility and intelligence, biomimetic robot fish have become one of the research focuses in the field of underwater robots in the recent years [2].

Researching biomimetic robot fish has a lot of practical significance, and these fish can simulate the principles of fish swimming realistically. It makes the motion of biomimetic robot fish more coincident than the existing UUVs in the fluid mechanics principle and have better abilities of swimming, drifting, accelerate, balance and steering. Utilizing biomimetic robot fish, people could not only do exploration of underwater resource and test quality of water area and find out contaminated area, people can also do the exploration of bottom topography and underwater archeology and military reconnaissance. What is more, through the manufacture of the experimental platform of biomimetic robot fish, researchers could simulate and study the movement principle of fish and fluid mechanics principle the fish attached to, which is significant. In addition, the biomimetic robot fish achieve a low noise movement when advancing. Generally speaking, their structure is much simpler than the normal UUVs, while the cost of production is also lower. When given the same electrical energy, the biomimetic robot fish can travel much farther than the normal UUVs, and operate for longer time continuously. They can be miniaturized without life-support safeguard equipment and have no danger to mankind. Furthermore, biomimetic robot fish have bright development prospects in the fields of entertainment and athletics, such as water polo and aquarium exhibitions. Application fields of biomimetic robot fish include fish exhibition, exploration, salvage assistance and related scientific fields with other underwater devices [3].

## 2. Propulsion Modes Classification and Corresponding Features of Biomimetic Robot Fish

Based on the propulsive structures employed for locomotion, the swimming of biomimetic robot fish can be classified into two categories at the present stage. The first and most common kind of biomimetic robot fish, takes Body and/or Caudal Fin (referred to as BCF) swimming model as its bionic prototype, such as the UPF-2001 as shown in Figure 1 of Japan National Maritime Research Institute (NMRI), the Vorticity Control Unmanned Undersea Vehicle (VCUUV) of MIT and Draper Laboratory, etc.[4]. Due to the large body stiffness, fluctuations are mainly concentrated in the posterior portion, and caudal fin with certain stiffness mainly provides swimming propulsion. Its propulsion velocity and propulsive efficiency are relatively high. The main driving motivation force of lateral displacement is provided by neck and caudal fin, about 90% of propulsion force is caused by caudal fin, and the 2/3 of fish body maintains rigidity. At this stage, there are large number of research on biomimetic robot fish that utilizing this propulsion mode. The anterior portion and caudal fin can be made of some materials with certain stiffness, while the tail could be made of some elastic materials or rigid materials, which is driven by the motors to wiggle. The different biomimetic robot fish have different structures in terms of complexity. The simple ones can realize swimming directly by a rigid rod-shaped tail driven by the motor, while the complex ones' tail can be made into multi-joint or elastic tail, and driven by one or more motors cooperatively or be made of shape memory alloy. Meanwhile, when using rudder to control, biomimetic robot fish displays a considerable swimming velocity and propulsive efficiency in the cruise movement, while its mobility needs to be improved. For instance, the UPF-2001, made by NMRI, was regarded high-performance and multi-objective as its design goals at that time. Since the designed structure was still full of limitations just at that time, the UPF-2001 did not fully attain the swimming level compared with the real fish. The structure of UPF-2001 is shown in Figure 2.


Figure 1. UPF-2001.

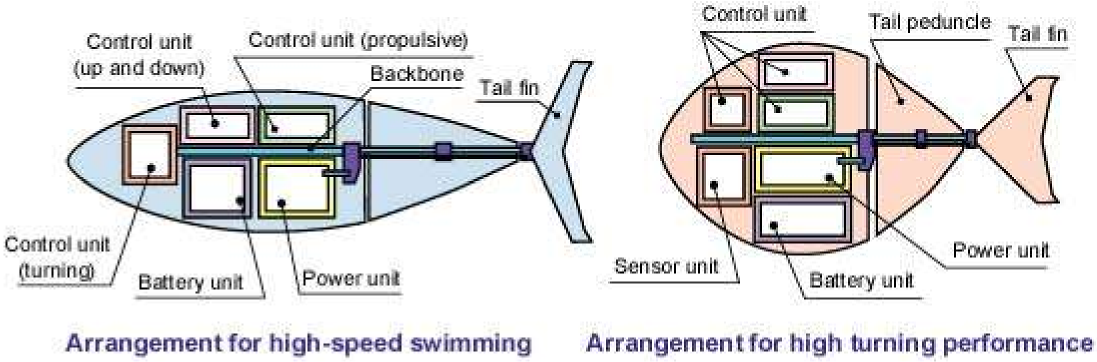


Figure 2. Structure of UPF-2001.

The other kind of biomimetic robot fish, takes Median and/or Paired Fin (MPF) swaying model as its bionic prototype. The MPF mode is general employed at slow speeds, offering greater maneuverability. Recent reviews provide thorough investigations on advances in morphology, kinematics, and hydrodynamics of swimming fish. For example, the artificial Black Bass, manufactured by Kato Laboratory and Tokai University of Japan, mainly imitates the propulsion mode of the real black bass, and the propulsion was provided by means of swaying or undulation of pectoral fin. The majority of fish improves maneuvering characteristics or propels swimming with auxiliary power in this way. Therefore, the mobility of these biomimetic robot fish has been tremendously improved. Nonetheless, the propulsion and propellant efficiency of pectoral fin mode are the lowest, swimming velocity and mechanical efficiency is also not outstanding. The less research on such biomimetic robot fish is reported. Most of these research mainly use the piezoelectric ceramic or ion exchange membrane, by changing the input voltage frequency to change their micro-displacement, and control the rigid fins swaying to produce propulsion.

BCF mode shows the more outstanding performance of high-velocity and high efficiency, while MPF mode achieves good stability. Both types of the propulsion modes have been studied in detail.

## 3. Research Survey on Biomimetic Robot Fish

### 3.1 Research Survey on the Theory

Researchers initially focused the research work on the establishment and experimental analysis of the hydrodynamic model. In 1960, according to Lighthill's work, the movement of the biomimetic robot fish can express as

$$y_{body}(x,t) = [c_1 x + c_2 x^2][\sin(kx + \omega t)]$$

Where $y_{body}(x,t)$ is the transverse displacement of the biomimetic robot fish along the $x$-axis at time $t$ (dorsal fin and ventral fin), $x$ is the axial displacement of body (head and tail axis), $c_1$ and $c_2$ are the linear coefficient and the quadratic coefficient of the body wave amplitude envelope of fish respectively, $k = 2\pi/\lambda$ is multiples of the body wave and $\lambda$ is the wave length, $\omega = 2\pi f$ is the body wave frequency of fish and $f$ is the propelling frequency [5].

The caudal fin of fish simultaneously involves in two motions: the pitching and heaving motions. The phases of the two motions are dissimilar. Therefore, the motion of the biomimetic robot fish is divided into two parts: the body undulation and the heaving and pitching motions of the caudal fin. Depend on the original formula, the movement of the biomimetic robot fish is discretized about time $t$ and expressed in body undulation equation and caudal fin oscillation equation, described as

$$y_{body}(x_i) = [c_1 x_i + c_2 x_i^2][\sin(kx_i - 2\pi \frac{n}{M})]$$

$$\begin{cases} y_{tail}(x_{i+1}) = y_{tail}(x_i) + L_{i+1} \times \sin\theta \\ \theta = \theta_{max} \bullet \qquad x_i - 2\pi \frac{n}{M} + \phi) \end{cases}$$

Where $x_i$ denotes the displacement of each Joint along $x$-axis respectively, and

$y_{tail}(x_{i+1})$ is the transverse displacement of the caudal fin along the $y$-axis, which consists of heaving motion ($y_{body}(x_i)$) and pitching motion ($L_{i+1} \times \sin\theta$), $\theta_{max}$ is the maximum attack angle, *M* is defined as a discrete number that divides a period into small intervals, *n* counts from 0 to *M*−1, while $\phi$ represents the phase difference between the heaving and the pitching motions.

As early as 1926, some scholars had begun the study on the mechanism of fish swimming and made a variety of related theories. In 1960s, the fish-movement model close to the actual fish movement was constructed by the scholars represented by M.J.Lighthill [5]. After then, M.J.Lighthill firstly proposed Physical Model of Carangiform Swimming based on the "small-amplitude potential theory", and in 1971, the "large-amplitude elongated -body theory" was proposed further with the "elongated-body theory" used to the hydrodynamic analysis of Carangiform fish [6]. The physical model of Carangiform Swimming is shown in Figure 3. In 1977, based on the "large-amplitude slender-body theory", the "two-dimensional resistance theory" was proposed by M.G.Chopra and T.Kambe [7]. Considering the biomechanical properties of fish and the dynamic characteristics of the structure, and supposing the longitudinal bending stiffness of fish is constant, in allusion to the fish that body length is wee Compared with Lateral amplitude, Hess and Videler proposed the "thin-body theory" in 1984[8]. In 1994, Cheng and Blickhan proposed the "wave-plate theory"[9]. In 1998, Cheng proposed the "dynamic beam theory". These theories had laid a firm theoretical foundation for the continuous development of biomimetic robot fish.

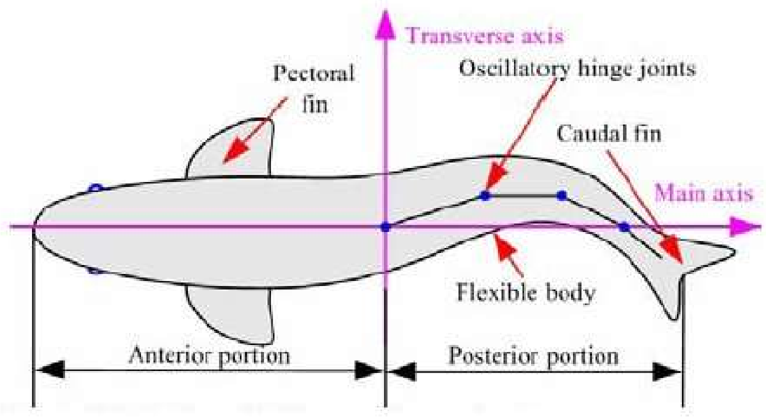


Figure 3. Physical Model of Carangiform Swimming.

3.2 Manufacture Situation of Biomimetic Robot Fish

With the continuous development of bionics, structural mechanics, automatic control technology, image processing and other fields, many countries have made a lot of progress on the research of biomimetic robot fish at present. The United States and Japan have got the most research achievements in the area of biomimetic robot fish among these countries.

3.2.1 Research Survey of the Unites States

The well-known RoboTuna, developed by Triantafyllou and co-workers in MIT in 1994, is the first robot fish. Its length is about 1.2m, constituted by 2,843 component parts, spine made out of articulated aluminum alloy, ribs made by hollow polystyrene, skin made up of polyurethane elastic fiber yarn. The major structural component of the robot fish is a segmented backbone made up from 8 discrete rigid vertebra connected with low friction ball bearing joints. These 8 vertebras are driven through an elaborate system of pulleys and cable tendons by 6 brushless DC servo motors mounted outside the fish above the waterline inside the carriage support structure. These tendon drives are the mechanical analog of the biological fish's muscles. The structure of RoboTuna is shown in Figure 4. Under the control of the multi-processor machines and advanced propulsion systems, RoboTuna can simulate the real fish swimming by swaying of the body and the tail and its velocity may reach to 2m/s [10]. At the same time, MIT had proved that the propulsion efficiency of biomimetic robot fish was more efficient than the existing UUVs [2] [11].

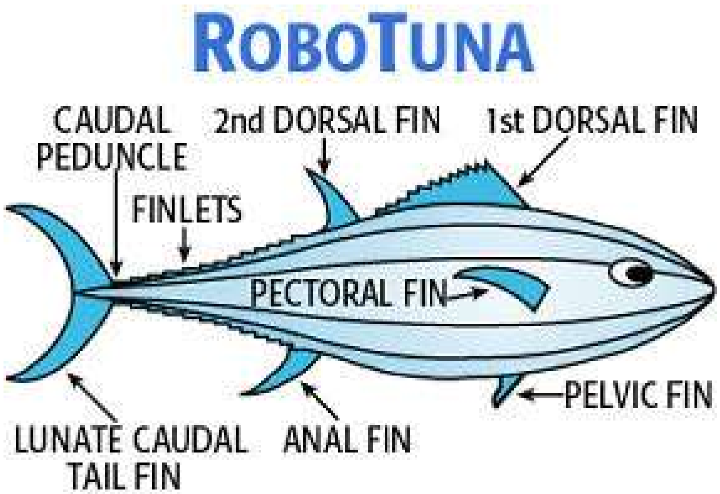


Figure 4. Structure of RoboTuna.

The second year, MIT and Draper Laboratory had developed RoboPike as shown in Figure 5, an improved version of RoboTuna, the research aimed to explain the well-known Gray Paradox—dolphins do not seem to possess such muscle power to swim so fast. The body length of RoboPike is 32 inches, and its displacement is 8 pounds, body made by fiberglass. Anal and dorsal fins are constructed using stainless steel wire and Skin Flex (TM). Skin Flex (TM) is a castable rubber, which will allow the fins to bend during turning and swimming. This Flexible structure make it can resist the tremendous impact when swimming, and its intension could sufficiently withstand water pressure. The main servo, not having to flex the body very much, is implemented with a scotch yoke and linkage to the two main bulkheads of the fish. The caudal tail fin is the main source of propulsion in a fish. It provides thrust by having an angle of attack with the oncoming water. This pitch angle is very important, and is controlled separately by its own servo. This means that the tail fin servo controls a hinge which the caudal tail fin is attached to. The pectoral fins are controlled by miniature model airplane servos. These servos are mounted to a waterproof box, which redirects the axis of movement outside the hull of the fish. The fins are mounted on the output shaft of the servo [12]. The successful manufacture and experiment had demonstrated that RoboPike possessed outstanding ability of static steering and acceleration.

Figure 5. RoboPike.

Based on the previous research, in 1998, MIT manufactured a kind of VCUUVs, the supreme version of RoboTuna. After that, MIT had done the research of flapping wings in depth. In addition, the department of zoology in University of California (UC) and the department of mathematics in Lafayette College constructed mathematical model of fish propulsion successfully. Northeastern University (NU) also carried out some research projects on anguilliformes propulsion of biomimetic robot fish. In 2002, the University of Central Florida (UCF) manufactured "MERIF", a kind of micro robot fish, whose drive system was wholly constituted by the shape memory alloy and could truly realize noise-free drive.

3.2.2 Research Survey of Japan

From 1991 to 1994, Nagoya University manufactured a miniature underwater floating robot of imitation pectoral fins mode by using piezoelectric ceramics (PZT) and miniature wave body underwater vehicle of body undulation mode with shape memory alloy (SMA).In 1996, Kato Laboratory and Tokai University of Japan manufactured an artificial Black Bass, which proved that highly mobile pectoral fin propulsion mode has full of high maneuverability [13]. And then, they manufactured a kind of biomimetic robot fish by using Ionic Conducting Polymer Film (ICPF) as the driving element of the tail fin, and could control its swimming velocity by changing the input voltage frequency in the year of 1998.

In the same year, the Nation Marine Center (NMRI) of Japan started to research on biomimetic robot fish. Since then, in order to research the different characteristics of fish swimming, the NMRI manufactured a variety of types of biomimetic robot fish. Among them, there is a PF-60 whose body length is 60cm and it is designed to research the propulsion of linear motor, which can simulate the fish movement with high velocity and high acceleration [14]. There is a PF-550, which is designed for the purpose of the research on the quick dive movement. Its body length is 57cm and has a chunky streamline appearance. It achieves the dive movement rely on the mode of complexor propulsion. PF-700, whose body length is 70cm, it is designed for the purpose of the research on the high- velocity propulsion, is manufactured by simulating saury and can engender the swaying frequency of 10Hz. Besides, the maximum swimming velocity of PF-700 can achieve to 0.7m/s. Afterwards, regarding high-performance and multi-purpose as the design objectives, the NMRI manufactured UPF-2001 successfully, whose body length is 57cm and its maximum swimming velocity is

0.97m/s. UPF-2001 is an experimental platform with high-performance, it simulate tuna and has two joints, realizing floating and diving movement by using the elevator. The modular design method has been taken in the manufacture of UPF-2001 [15].

3.2.3 Research Survey of China

As early as 1980s, University of Science and Technology of China (USTC) had done a lot of related research on three-dimensional wave plate theory (3DWPT). In 1994, Huazhong University of Science and Technology (HUST) manufactured the propulsion machinery of flexible caudal fin propulsion and the fish-shaped structure. Afterwards, Beijing University of Aeronautics and Astronautics (BUAA) had developed the robotic eel successfully in 1999, and had expanded research on control and coordination in 2001 together with the Institute of Automation of Chinese Academy of Sciences, preliminarily establishing the multi-robofish collaboration platform. In August of 2004, cooperating with the Institute of Automation of Chinese Academy of Sciences, BUAA had manufactured a practical biomimetic robot fish as shown in Figure 6, which participating in underwater archaeological studies and exploration of Koxinga's ancient warships. This underwater exploration was identified as the first case of experimental investigation of biomimetic UUV on the international plane by the related experts [16].

Figure 6. Biomimetic Robot Fish Manufactured by BUAA.

## 4. The Existing Problems at This Stage

Biomimetic robot fish is considered as a research field including a number of cross-disciplines. Biomimetic robot fish will face a nondeterministic and complex environment when swimming in the aquatic environment. Navigation control technology in the nondeterministic environment of biomimetic robot fish has become a key technology. In the research on the navigation control theories and methods of underwater biomimetic robot fish, there have already been a mass of research and application achievements on the control methods in the deterministic environment. The scholars have also carried out some research on the control theories in the nondeterministic environment, and put forward several methods too. Nevertheless, a unified and impeccable architecture has not been established yet, and there are a number of significant theories and technical issues need to be solved and improved. These issues mainly include environmental modeling technology, localization technology, learning and optimization of navigation controller, fault diagnosis, online motion planning and control and so on. There has been less prior knowledge of biomimetic robot fish in nondeterministic underwater environment, and the prior knowledge relates to environmental cognition, optimization decision, knowledge representation and knowledge acquisition and some other significant issues.

The research on the hardware and control theory and method of biomimetic robot fish in the nondeterministic aquatic environment, will promote the development and research of cognition science, pattern recognition, nonlinear control and other frontier disciplines. Meanwhile, the related research would further promote the development and melioration of autonomous mobile robots' own hardware and control systems in the fields of aerospace, ocean , military, architecture, transportation, industry and service industry and so on, it could lay the theoretical and technical foundation for the military and abyssal adhibition of autonomous mobile robots such as unmanned underwater detectors, unmanned underwater rescue robots and unmanned vehicles [17]. At the present stage, the existing issues faced by the research on biomimetic robot fish include several following aspects.

### 4.1 The Velocity and Efficiency Issues

The realization of high-efficient and sustainable cruising propulsion mode of biomimetic robot fish mainly depends on the control of vortex. Hence, the swimming velocity and efficiency of the biomimetic robot fish obtaining propulsive power by the swing of caudal fin is the supreme among all kinds of biomimetic robot fish. While, through the current research, researchers could only observe the vortex when biomimetic robot fish swims, and utilize the energy of vortex to achieve the movement of biomimetic robot fish. However, how to regulate the velocity and orientation of biomimetic robot fish by means of control the vortex has not been solved yet. Therefore, there has not been an optimalizing control system of caudal fin, which can effectively control the vortex and reduce resistance, enhance propulsion and improve propulsive efficiency when the biomimetic robot fish swims [18]. In addition, the research on the shape of caudal fin has shown that the propulsive efficiency of crescent and fork-shaped caudal fin is much more excellent than any others [19].

### 4.2 The Stability Issue of Design

Stability is a significant attribute can never be overlooked when biomimetic robot fish swims in the aquatic environment. In order to improve the stability of biomimetic robot fish in the design, it requires that anterior portion is heavy, that is to say, the barycenter should shift forward, especially in the design of multi-joints biomimetic robot fish [20]. In the meantime, when controlling velocity, it will lead to the situation that biomimetic robot fish sways and resonates in a specific frequency, and it might have effects on the stability and propulsion of biomimetic robot fish seriously.

In addition, at present the control of biomimetic robot fish is principally based on the simplified body undulation equation and caudal fin oscillation equation of M.J.Lighthill's elongated-body theory, which is actually an idealized model and does not take into account the fluid resistance and viscous resistance in the aquatic environment. In practice, the actual swimming posture of biomimetic robot fish does not entirely fit the posture of theoretical assumption because it existing water resistance when fish swims. It is significant to enhance the stability of biomimetic robot fish by the ways of exterminating the difference between the two postures and then according this to meliorate the control of biomimetic robot fish.

### 4.3 The Image Processing and Color Discrimination Issues

It is the responsibility of visual image processing system that service for making strategic decisions by means of extracting effective image information collected by the camera located in the head part of robot fish. Image processing systems are mainly based on color information at this stage. Processors receive the image information relied on the YCbCr color space, and the color threshold value can be obtained by the way of off-line sampling. Both visibility and illumination conditions in the underwater environment are different from on the land actually, and the quality of the images collected is influenced by the wave interference and other unknown factors. Hence, it is difficult to achieve precise position control because of the nondeterminacy and complicacy in the aquatic environment. When the biomimetic robot fish swims, because of the complexity and nondeterminacy of the underwater environment, the light intensities from different positions are also dissimilar in the process of real-time collecting image. The changes of illumination have effects on the surface color of the imaging objects because of the refraction underwater, so that it cannot distinguish the attribution of color type through a group of unitary RGB threshold values. Therefore, it also cannot ensure the system's robustness of color discrimination programs [21]. Color of image might be precarious because of the noise caused by visual image processing system when the system collects image. It has already been an issue urgently to be solved.

### 4.4 The Failure Diagnosis and Fault Tolerant Control (FTC) Issues

In the nondeterministic underwater environment, mechanical components and control systems of biomimetic robot fish are probable to break down, while the operators cannot intervene the operating biomimetic robot fish directly with a less cost. If the failure is not be detected or disposed in time, the biomimetic robot fish will be operating in an unpredictable and dangerous way. It not only shortens robot fish's working life and could not operate in the scheduled way, but also may even lead to some serious results, for instance, it might damage the precious historical relics when doing underwater archaeological exploration and so on. Hence, it has become an urgent research task to research fault diagnosis and FTC technology and improve the safety and reliability of biomimetic robot fish in the nondeterministic underwater environment. [22]

The scholars have done some extensive and systematic research on failure diagnosis and FTC technology for a long time, and the ways of failure diagnosis mainly include multi-model method [23], state identification and fault diagnosis method based on particle filter [24], fault diagnosis and repair method of sensors based on information fusion [25] and so on.

Classical FTC methods can be divided into passive FTC and initiative FTC, but it is necessary that the system need nondeterminacy of model and robustness to external disturbances [26]. At present, the research on failure diagnosis and FTC methods still remains in the computer simulation or experiment stage, while the research on fault diagnosis and FTC methods of biomimetic robot fish in the nondeterministic underwater environment has just started. The difficult issues need to be resolved urgently include robustness, multi-fault diagnosis, soft-fault diagnosis, efficiency, self-diagnosis and self-repair, etc. For this purpose, the trends of fault diagnosis and FTC technology include several following aspects. Firstly, researchers could use the method combining qualitative reasoning with quantitative reasoning, combining qualitative model and mathematical model to establish the high level architecture (HLA) of diagnosis and FTC system. Secondly, they can improve the algorithm of particle filter and overcome failure miss-diagnosis issue, in order to improve efficiency further. Thirdly, these researchers might integrate model knowledge and empirical knowledge, and then make the diagnosis, fault tolerance, modeling, and learning into integration organically. Fourthly, they may comprehensively research on the mechanical, electronic, electrical system, sensors, communications, computers and software subsystems, and then design fault-tolerant hardware and software platform.

## 5. Future Prospects

The technology of biomimetic robot fish represents the cutting-edge development of many advanced technologies, integrating the development achievements of some different disciplines. Jian Song, the former president of the Chinese Academy of Engineering, had once pointed out, "the progress and application of robotics is the most convincing achievement of automatic control fields in the 20th century and the contemporary supreme sense of automation" [27]. Biomimetic robot fish could not only play an important role in the fields of military, research, archeology and life increasingly, but also become the effective instrument and experiment platform which would research the generation of complex intelligent behavior and explore the biological motion patterns. The research on intelligent biomimetic robot fish has recently drawn attention of many researchers including the scholars of traditional control fields, mathematicians, physicists, biologists and so on[28]-[30].

The research on intelligent biomimetic robot fish is still in the developmental stage, and a plenty of theories and techniques also need to be further improved. Meanwhile, in practical work, the application of these theories and techniques also need to be constantly practiced and accumulated. This paper mainly describes some international research situation of biomimetic robot fish, while there are plenty of broad prospects need to research further in many fields. At the present stage, these several following aspects will have broad prospects of the research on intelligent biomimetic robot fish.

## 5.1 The Environment Perception Technology

In the complex underwater environment, only by using the own sensors of the intelligent biomimetic robot fish, robot fish can collect the information of the external environment, which could further guide their behavior. Otherwise, the biomimetic robot fish can only swim blindly in this environment. On this account, it is one of the significant issues of the research and development on biomimetic robot fish that how to collect and analyze environmental information. The improvement of the efficiency and accuracy of robot fish is growing up and reinforcing together with the development of sensor technology. Beside this, they are complemented each other. The sensor technology and environmental cognition are included in the environmental perception technology. These two aspects are described as follows in detail.

### 5.1.1 The Sensor Technology

The sensors of biomimetic robot fish can be divided into two major categories, internal sensors and external sensors. The former usually consists of velocity sensors, position sensors and angle sensors, which mounting inside the robot fish itself and perceiving its own status, in order to correct and control the operation of robot fish. While the latter, mainly including image sensor and vidicon, is used to obtain information from the underwater environment around and the state characteristics of the target objects for the robot fish, so that the robot fish can interact together with the environment around. Consequently, the robot fish could gain the self-correcting and self-adaption capabilities to the environment. At this stage, visual sensors and velocity sensors are in the practical application of intelligent biomimetic robot fish. However, many problems about sensor technology currently are still open, and there will be a large developmental space in the future.

With the automatic and intelligentized development of measurement and control system of biomimetic robot fish, the sensors not only should be high-accurate, high-reliable and good-stable, but also have the certain data-handling capability and own the abilities of self-diagnosing, self-correcting and self-compensation. Traditional sensors can actually measure only one parameter. While for the robot fish, the sensors need to simultaneously measure multiple parameters in many occasions, and these sensors should be highly integrated and small. Now scientists from different countries have paid much attention to this direction and have manufactured a number of multi-functional sensors.

5.1.2 Environmental Cognition

The integration of underwater environmental information is a process modeling the perceived information, and environment modeling is closely related to self-positioning of biomimetic robot fish. The accuracy of the environmental models relies on the positioning accuracy, while the positioning cannot realize without the environmental models. The positioning methods existing of the underwater robots mainly include dead reckoning, integrated positioning and perceptual positioning [31]. An appropriate environment model will be beneficial to the understanding on environment of biomimetic robot fish, and reduce the calculated amount when the system makes decision and path planning.

Despite the Artificial Intelligence (AI) has made a great progress on the robotic reasoning, but it has still been in a relatively low level in terms of environmental cognition and comprehending. Moravec, the pioneer of robotics, once pointed out that “artificial robots’ ability on reasoning and thinking could be same as adults in some intelligent activities, while their ability on perception and understanding might even be worse than one year-old baby. This is not only limited by the existing sensors, computers and other hardware, but also limited by the not-in-depth comprehending on the mechanism of environment cognition and the incomplete methodology of environmental cognition and other reasons"[32]. To research on biomimetic robot fish in the nondeterministic underwater environment, it is indispensable that the researchers should simulate the conscious cognitive methods and unconscious reaction mechanisms forming in the process of the real fish interacting with the environment. It is a significant methodology about environmental cognition that the scholars research the representation and properties of environmental knowledge with the constraints of time and space and transforms the discrete, one-sided and incomplete spatial information perceived from the sensors into the forms of knowledge which could apply to decision programming.

5.2 The Multi-sensor Information Fusion Technology

Sensors in the control and navigation system of the biomimetic robot fish play a pivotal. The robot fish gains information from these sensors, and then analyses and processes the information, in order to achieve the accurate path planning or carry out certain missions [33].

The purpose of multi-sensor information fusion is not only improving system reliability, robustness and expanding the observation range on the time and space; but also increasing the trustworthiness of data and enhancing the resolving power of system. Beside this, it is particularly suitable for the underwater robots when they travel in the complex nondeterministic environment or make the local environmental modeling in special missions [34], and it is also fit for the global environmental modeling [35] [36], localization and path planning navigation. There are many methods on information fusion, such as the pixel-level fusion, feature-level fusion and decision-level fusion [37]. The specific technologies include Bayes estimation method [38], D-S evidence theory [39] [40], Kalman filtering [41], integrated average method, fuzzy logic method, neural networks method, expert system approach, maximum similarity-based estimation algorithm, etc.

Currently, there are a lot of problems in information fusion technology, and these issues will directly affect the performance of biomimetic robot fish after information fusion. The information fusion technology in the dynamic environment and initiative sensor information fusion technology are the main research contents of sensor information fusion technology in the nondeterministic underwater environment. Because the environment is dynamic and the information obtained from the sensors maybe nondeterministic, so how to reduce the nondeterminacy of information and build the reasonable nondeterministic model is an important future research direction of information fusion in the future. Accordingly, it is full of significance that improving the instantaneity of information fusion, reducing the error rate when information fuses and establishing and consummating the evaluation mechanism on the quality of information fusion [42].

The achievement of three-dimensional modeling and obstacle avoidance of biomimetic robot fish is based on the information fusion from range-finding sensors and visual sensors, while the achievement of positioning is relied on the information fusion from different range-finding sensors [43]. The research on these methods has always been the focus of research for the scholars, and will also be the focus and hot spot of future research. There are a variety of different sensors equipped in the complex hardware system of biomimetic, while how to manage and coordinate these sensors will be an issue urgently to be solved in future research. The purpose of managing and coordinating these sensors is to make full use of the limited sensor resources and the internal space and to provide the information more accurate, more reliable and more exact for the fish for the control and navigation of the robot fish [44]. The core issue of managing and coordinating these sensors is how to select the operating mode and optimization strategy of sensors based on the environment. This series of questions has broad research prospect, which is worth further study. To collect more detailed and accurate results, more sensors such as pressure sensors, accelerometer and 3-D obliquity detectors will be integrated in the sensing system.

### 5.3 The Research on Self-learning of Behavior

From the point of view of biological evolution, the intelligent behavior of animal presented in the environment realizes the evolution in the interaction with the environment. Brain and nervous system, the material basis of intelligence, stimulated constantly by the environmental information, are continuously enriched and completed. The behavior of animal is becoming intelligent gradually in the purposeful movement process in the environment. How to achieve the learning and evolution of the spatial cognition behavior is a new research direction which realizing controls navigation and path planning through the ways of neurology, cognitive Science and even psychology.

Perception depends on the past knowledge and experience, and perception information is the consequence caused by the actual stimulated sensory information interacting together with memory information. The cognitive subject not only runs in the environment, but also can exert influence on the environment. The cognition process consists of the process of information obtaining and information processing (i.e., the process of thinking), also includes the process of changing the knowledge or generating subjective information (i.e., the accumulation of knowledge and experience). The interaction of autonomous cognitive systems with the environment will be able to combine the active create of the environment and the maximum use of the natural environment, and then achieve the cognition of the unknown environment. So the focuses and hot spots of future research include: how could the biomimetic robot fish gain the necessary information as much as possible, in order to comprehend accurately and comprehensively the unknown environment in which it resides; and how to the robot fish get the evolutionary learning ability in the self-adaption way.

The idea of self-adaption plays a significant role in robotic science, while the immediate artificial intelligence presented by Brooks is the adaption to the natural environment. And the site cognitive is a task that researches on the information processing and behavior in the environment. Therefore, the further research on this field is full of significance for the environmental cognition of autonomous biomimetic robot fish [45]. Simplifying the design process is the main advantage of the biomimetic robot fish's control navigation system based on evolutionary learning and self-adaption. It is one of the effective ways on realizing the low-level reactive control and high-level decision-making that making the design results have certain robustness [46]. There will have a prodigious promoting effect on the understanding of the cognitive processes of the robot fish's biomimetic system by means of the Research on this direction.

There have made a lot of research results on the development of biomimetic robot fish so far. But there has still existed certain issues urgently to be solved and the existing performance of biomimetic robot fish is far from the ideal requirements. However, with the continuous development of bionics, materials science, sensor technology, intelligent control and image acquisition technology, we should believe that the biomimetic robot fish which can be accurately controlled and is high efficiency, high-velocity, energy saving, low noisy and stable must be manufactured in the future. And this kind of robot fish will play an important role in the future UUVs, and further step into people's daily life [47-54].

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