

Parallel Control and Management System for Biomimetic Robotic Fish Based on ACP Approach

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Abstract—This paper deals with the management and control of a biomimetic robotic fish within a control framework of artificial systems, computational experiments, and parallel execution (ACP). Without the need of precise hydrodynamic modeling and control implementation, we firstly built a functionally equivalent artificial robotic fish by using the Agent technology. When performing a specific task, network-stored control strategies and environment models can be downloaded for computing, testing, and optimizing purposes. By parallel execution, the optimal algorithm can be transferred to the physical robotic fish, where error feedback signals serve to seek the optimal solution in the network. Furthermore, the optimized control strategies, environment models, as well as the newly learned knowledge will be uploaded to the network after accomplishing the mission. At last, we demonstrate this ACP-centered control method through pushball experiment on robotic fish.

I. INTRODUCTION

NATURAL selection has ensured that the mechanical systems evolved in fish are highly efficient with regard to the habitats and modes of life for each species [1]. The cruising performance, high maneuverability, and acceleration ability are beyond the capabilities of current underwater vehicles. With the development of the bionics and robotics, it has become one of hot topics in the field of Autonomous Underwater Vehicle (AUV) to improve the ways that man-made systems operate in and interact with the aquatic environments. It will bring about a profound revolution to the nautical techniques.

The biomimetic robotic fish is a multidisciplinary field that mainly involves hydrodynamics-based control, mechanics, electronics, image processing, and control theory, which is complex and challenging [2]. In order to develop robotic fish as agile as real fish, researchers in the world have begun to study the robotic fish for many years [3].

At present, there are so many control algorithms have been presented. Li *et al.* presented an iterative learning control (ILC) method which is applied to a two-link carangiform

robotic fish in real time and achieved precise speed tracking performance [5]. Hu *et al.* studied a numerical method for parameter synthesis of a central pattern generator (CPG) network to acquire desired locomotors patterns [6]. Wang *et al.* proposed a two-phase CPG-based control architecture to improve the maneuverability and adaptability of robotic fish in water [7]. Li *et al.* applied fuzzy logic method to the dynamic modeling and improved swimming control efficiency of a robotic fish [8]. Wai *et al.* introduced a new bio-inspired wire-driven robotic fish, which based on Lighthill's elongated body theory. Their developed robotic fish can sway its caudal fin to establish forward motion as well as ascending motion [9]. The above-mentioned control algorithms are mostly based on the hydrodynamic mechanism of fishlike swimming. However, there are some weaknesses for the hydrodynamic models such as a huge computational burden and application complexity.

In general, research on the motion control based on the fluid mechanics model and simplified hydrodynamic model. It is hard to predict the precise location of the robotic fish in the water because of the inaccurate mathematical model. With the development of the computing and information technology, the development of simulation software has become the important research direction. The frequently-used representative software involves NPSAIS, MVS, DVECS, CADCON [10], experimental robotic fish system [11], [12] and multiple robot fishes cooperation system based on global vision [13]. The conventional simulation process usually adopted the off-line programming, which was independently from the actual execution system. Most of them also lacked of real-time feedback and strategy optimization.

In response to solving problems of complex systems, Wang *et al.* proposed the parallel system theory based on artificial system, computational experiments, and parallel execution (ACP) [14]–[18]. The emphasis is on illustrating the difference between the proposed system expansion schemes for parallel control through cyber-physical social interaction and the traditional divide and conquer methods for parallel computing through concurrent task execution. The theory of parallel control comes directly from the ACP approach, where artificial systems are used for modeling and representation, computational experiments are utilized for analysis and evaluation, and parallel execution is conducted for control and management of complex systems. Studies of this new control approach have been presented and discussed in transportation [19], ethylene [20], economy [21], and

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social management [22], [23].

This new control approach is applied to build a parallel control and management system for robotic fish to achieve precise control. An agent-based method is taken to cultivate an artificial robotic fish system, which is equivalent to the actual system. When performing a specific task, the relevant control strategies and environment models will be downloaded in the network for analysis and evaluation by computational experiments, and then the optimal algorithm is transferred to the actual system, where error feedback signals will be solved by seeking the solutions in the network. During the computational experiments the controllable and uncontrollable factors will also be considered. Finally, the optimized control strategy, environment model, and the newly learned knowledge which are uploaded to the network as guidance.

The rest of the paper is organized as follows. Section II, an overall framework is described in detail. The basic architectures of the parallel control and management system for robotic fish will be introduced. The artificial robotic fish system, computational experiments, and parallel execution are illustrated in Section III, IV, and V respectively. Section VI explains the ACP-based method by a pushball experiment of robotic fish. Finally, Section VII summarizes the research progress and future work.

II. FRAMEWORK OF THE CONTROL AND MANAGEMENT SYSTEM

The parallel control and management system for robotic fish based on ACP approach consists of artificial system model, computational experiments, as well as parallel execution. The framework of the system is shown in Fig. 1.

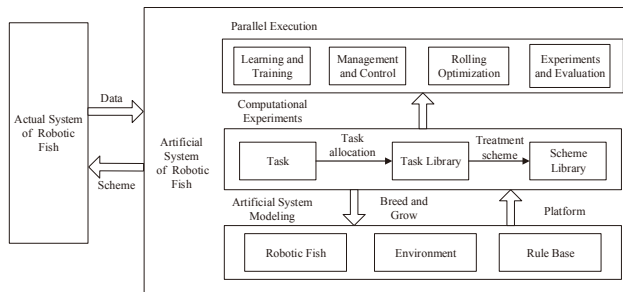


Fig. 1. Framework of the parallel control and management system

The overall research includes the following three parts:

- 1) The artificial system model is made up of robotic fish, environment, and rule base, which are affected and interacted each other. The bottom-up Agent-based method as the key way is used to cultivate the artificial system which is equivalent to actual system.
- 2) Computational experiments are used to test the relevant control strategies and models, which are downloaded from the network. The experimental results will be stored in the scheme library.
- 3) Parallel execution has the function to apply the optimal strategy to actual system on the one hand and to feed back the error signals to the artificial system on the other

hand.

There are three application modes to realize the parallel control and management system for robotic fish:

1) Learning and Training

The parallel control and management system is developed for learning and training operations for operators and robotic fish.

Not only can the manipulator use the system to learn how to operator the robotic fish, but also the robotic fish learns the new algorithms and intelligence technologies.

2) Experimentation and Evaluation

By computational experiments, we analyze and evaluate how to keep the status under large perturbations, such as rapid maneuvering, power-efficient swimming, and trajectory planning and tracking. The system is designed to reduce cost, improve the efficiency, and verify rationality of a variety of algorithms.

3) Control and Management

In this mode, using the method of interaction between virtuality and reality to accomplish the assigned work quickly and accurately and to realize co-evolution between artificial system and actual system.

III. ARTIFICIAL SYSTEM MODELING OF ROBOTIC FISH

It is the foundation for parallel control and management system to create artificial system models, which show several possible versions of the actual system flexibly based on multi-dimensional world rather than approach the relative real system. This section introduces the artificial robotic fish system modeling and models credibility validation.

A. Agent-Based Modeling Method

Following the principle of simplicity and consensus, the artificial system of robotic fish is built. There have been many methods about modeling, such as Agent [24], Petri net [25], cellular automaton [26] [27], fuzzy logic, and neural network [28]. The module is required to have the ability of autonomy, interactivity, self-learning, and self-adaption. Besides these common characteristics, the agent method and programming technology have the distinct individuality characteristic, like interaction and communication among them. So the agent method and programming technology are chosen as the preferred modeling approach. Fig. 2 describes the main components of the artificial system of robotic fish.

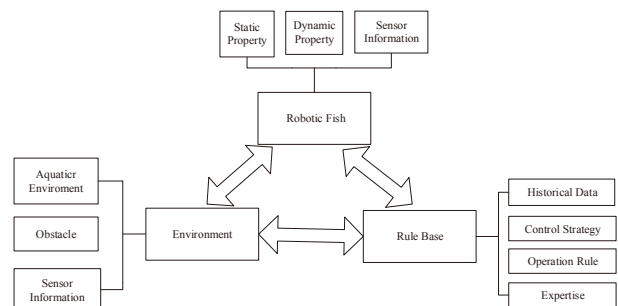


Fig. 2. The main components of the artificial system of robotic fish

The main models of artificial system consist of robotic fish,

environment, and rule base.

Robotic fish models are made up of static attribute, dynamic attribute, and sensor information.

The static attribute means the geometrical body parameter of the physical robotic fish such as size, mass, center of gravity, center of buoyancy, joint numbers, scale of swing joint, the parameters of pectoral fin, and tail fin (shape, chord length, span length, plan form area, angle of attack, and so on).

The dynamic attribute means movement parameters of the physical robotic fish that takes into account the maximum speed, oscillation frequency, torque, driving mode, communication mode, and so on.

The sensor information refers to the information which is on-boarded on the physical robotic fish, such as obstacles in surroundings, visual information, and the battery level.

As is shown in Fig. 3, the robotic fish is composed of a rigid head housing a camera, a four joint soft body, a crescent caudal fin, and a pair of independent pectoral fins. The basic technical parameters of the robotic fish prototype are described in Table I.

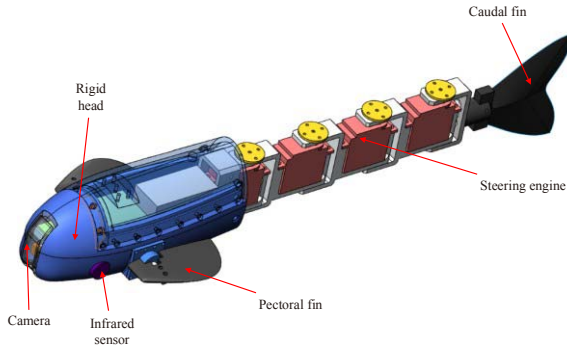


Fig. 3. Prototype of the robotic fish

Symbol	Quantity
Dimension ($L \times W \times H$)	$\sim 517 \text{ mm} \times 160 \text{ mm} \times 78 \text{ mm}$
Mass	$\sim 1.3 \text{ kg}$
Number of joints	4
The length of pectoral fins	8 cm
Maximum turning radius	$\sim 0.4 \text{ BL}$
Maximum speed	$\sim 1.2 \text{ BL/s}$
Working voltage	7.4 V
Control mode	Radio control
Drive mode	DC servomotor
Maximum torque	3.2 kgf.cm
Operation time	$\sim 2 \text{ h}$
On-board sensors	camera, infrared sensor

The environment agent mainly involves the aquatic environment which contains the density of water, obstacle, visual information of environment, and so on.

The general form of production rules is condition - action means using IF-THEN to express rules. The historical data, control strategies, operating disciplines, and expertise of each

agent are used to form all kinds of rules, and then these rules are stored to database. For example, infrared sensors are installed around the robotic fish, we can get the rule of obstacle avoidance on the base of the relationship between the information and the motor skills.

B. Modeling Credibility Validation

In order to bring the artificial system into correspondence with the actual system, it is necessary to validate the equivalence of models. Modeling credibility validation consists of reasonable structure verification and behavior consistency verification.

Reasonable structure verification means the terminal agent is fully consistent with the actual equipment, in order to ensure the availability and reasonability of the artificial system, the truthful data of real robotic fish system is taken to modify parameters of corresponding system agents in order to roll optimization and modify parameters of artificial system.

The artificial system and actual system will achieve equivalence after using these two methods.

IV. COMPUTATIONAL EXPERIMENTS OF PARALLEL SYSTEM

The created artificial system of robotic fish in Section III is equivalent to a vast network, in which the relevant data, knowledge, and algorithms interact each other.

Some computational experiments will be done by means of the platform. Software robotic fish can be used to verify the feasibility of control strategies, the influence of controllable factors and uncontrollable factors on the movement precision of robotic fish. The network architecture of computational experiments is shown in Fig. 4.

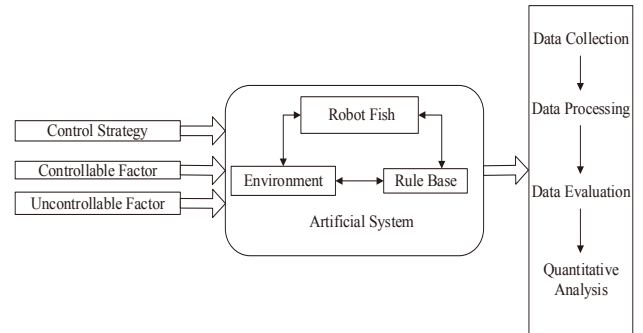


Fig. 4. Network architecture of computational experiments

When performing a special task, the relevant control strategies will be downloaded to test and evaluate. The controllable factors and uncontrollable factors will also be taken into account at the same time.

After collecting, handling, and analyzing the result of computational experiments, the optimal algorithm will be chosen.

The computational experiments of parallel system mainly discuss the following aspects of content:

- 1) Trajectory planning: the point-to-point (PTP) control, which means how to make the robotic fish move continuously and steadily from an initial point to a final one, is one of the basic problems concerning the robotic

controllability. Waves occur when a robotic fish moves, which affects the movement of the robotic fish and others even in static state. Since it is very difficult to establish the hydrodynamic model of fish like swimming using analytical method. So the software robotic fish can be used to correct deviation adaptively after many experiments.

- 2) Optimize control strategies: many control-oriented swimming modeling have been carried out, such as Lagrangian model, kinematic model, CPG-based swimming control, closed-loop method, fuzzy logic method, and so on. Different control strategies should be taken to deal with different tasks and different environment. It is unwise to test every control strategy on the physical robotic fish, so the software robotic fish can be used to do some computational experiments quickly. For the different environment and tasks, we can choose the optimized control strategy.
- 3) Coordination of multiple biomimetic robotic fishes: cooperative task of multiple robots under a complex and dynamic aquatic environment has great significance. According to the requirements of task, robotic fish is required to play different roles. Trajectory of each fish is planned. During the movement, each robotic fish is required to avoid some static obstacles and other moving robotic fish. According to the demand of the system's task and the restriction of its work environment, trajectory of each robotic fish will be test and evaluate, through computational experiments the software robotic fish will get the optimal control algorithm to achieve the task.
- 4) Responding to emergencies: unexpected situations will be existed during the operation like low battery, communications disruption, and so on. The emergency plans must be provided and evaluated by computational experiments to prevent these problems. For example, the software robotic fish may estimate whether it can accomplish the task in the remaining quantity of battery based on the computational experiments.

V. PARALLEL EXECUTION

On the basis of artificial robotic fish system and computational experiments, parallel execution will be built to accomplish the assigned work effectively and accurately. The framework of overall parallel execution is shown in Fig. 5.

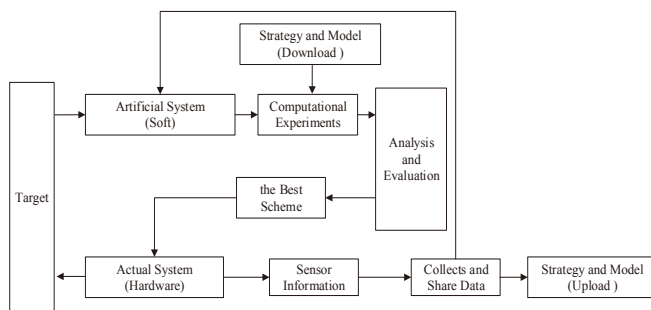


Fig. 5. The framework of overall parallel execution

There are several mainly steps to achieve parallel execution:

- 1) When performing a special task, the optimal method is chosen by computational experiments and transferred to the physical robotic fish to deal with the task. At the same time, parallel control and management system will deliver the real-time sensor information of the actual system to the artificial system.
- 2) According to the accompanied error between physical robotic fish and the software robotic fish, the solution which is searched in the network to revise the parameters of software robotic fish and then to optimize and evaluate again. If the solution does not work or there does not exist the solution, the robotic fish will ask human for help. The software robotic fish will store the newly learned knowledge.
- 3) After completing the mission, the optimized control strategy, environment model of the actual system, and the newly learned knowledge of the software robotic fish will be uploaded to the network database.

Through transforming the optimized algorithm to the physical robotic fish, at the same time collecting the real-time and dynamic information feed back to the network. By this way realize the interaction between software robotic fish and physical robotic fish.

VI. CASE ANALYSIS

A pushball experiment of robotic fish, which is shown in Fig. 6, is established to facilitate understanding of the parallel control and management system for robotic fish.

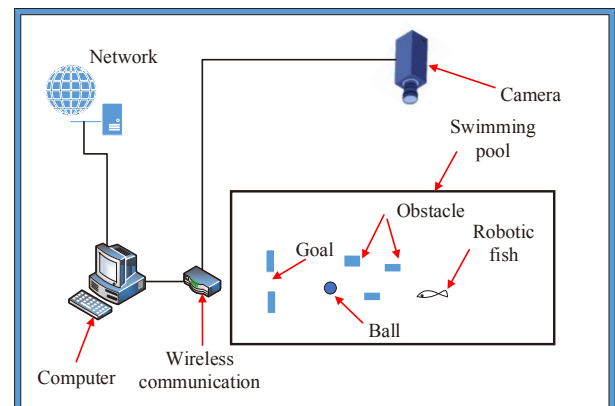


Fig. 6. Experimental platform for pushing ball control of robotic fish

The purpose of the task is that driving the robotic fish to push a ball to the goal and avoid obstacles at the same time. A CCD camera is handed over a swimming pool, which is utilized to capture the information about fish and surrounding and identify obstacles in surrounding and the motion status information of robotic fish, including the posture, velocities, and accelerations. The processed information will be sent to the computer that connects with the network which collects, stores, and shares data independent of specific robotic fish. The computer downloads some relevant information and sent control commands to the robotic fish through a wireless radio transmitter

The undulatory motion of robotic fish is assumed to take the form of a traveling wave which is suggested by Lighthill has been successfully applied on Robo Tuna. For simplicity and feasibility in engineering design, the desired motion for the multilink is expected to approximate the so-called body wave to get generation forward thrust [29].

$$y_{body}(x, i) = (c_1 x + c_2 x^2) \sin(kx \pm \frac{2\pi}{M} i) \quad (1)$$

where y_{body} represents the transverse displacement of the fish body, i denotes the i th variable of the spline curve sequence, x denotes the displacement along main axis, c_1 is the linear wave amplitude envelope, c_2 is the quadratic wave amplitude envelope, M is called body-wave resolution that represents the discrete degree of the overall traveling wave, which is restricted by the maximum oscillating frequency of actuators.

The processes of parallel control and management system experiment is described as follows:

- 1) The artificial system of the parallel system based on the parameters of physical robotic fish, information of sensors, and the rule base of control theory and motion rules is built. The property of the physical robotic fish have been shown in Table I, Yu *et al.* [30] proposed the collision avoidance rules for robotic fish. The motional characteristics such as *move-to-goal* (), *obstacle-avoidance* (), *push-ball* (), and so on have been presented extensively in [30].
- 2) In terms of experimental requirements, some current information like path planning, collision avoidance control, will be searched and downloaded by software robotic fish. During the experiments, robotic fish, the ball, and obstacles are marked with specified colors, all of the dynamic parameters are delivered to the software robotic fish. After computational experiments the optimized control strategy is chosen and sent to the physical robotic fish. The physical robotic fish will execute commands involved trajectory planning, obstacle avoidance.
- 3) It is unavoidable that there are some uncontrollable factor. For example, the fish may lose the ball because the ball is too light to remain stationary. Because of these uncontrollable factors, the software robotic fish will find solutions in the network to make up the deviation. If the network does not exist, the system will ask people for help. We can control the robotic fish to save the question or supplement the rule. At the same time, the software robotic fish will store the newly learned knowledge. At the end of task performance, the software robotic fish shares the acquired knowledge by uploading it to a distributed database.
- 4) After that, another robotic fish is asked to do the same task. After creating the artificial system of the second robotic fish, downloading the information which uploaded by the first robotic fish. Although there are difference between the two robots and environment, the downloaded information would provide guidance on how the second robotic fish deal with the uncontrollable factor. When the second robotic fish successfully performs its task, it will upload the new knowledge to the network again.

With more robotic fish downloading the relevant information and uploading the newly learned knowledge to the network, it will become more reliable and fulfilled.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have presented a novel parallel control and management system for robotic fish based on ACP approach. The artificial systems, computational experiments, and parallel execution are described thoroughly. Artificial systems are used to cultivate the equivalent software robotic fish, computational experiments are utilized for analysis and evaluation, parallel execution is conducted for control and management of complex systems. After finishing the task, the optimized control strategy, environment model, and the newly learned knowledge will be uploaded to the network to collect and share. Finally, we create a pushball experiment of robotic fish to demonstrate the parallel control and management system. This system opens up a new path for the research of robotic fish.

In the near future, we will pay more attention to the development of coordinately evolved artificial and physical robotic fish systems.

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