Proceedings of the 34th Chinese Control Conference
July 28-30, 2015, Hangzhou, China

An Effective Tracking Control for Robotic Fish: Implementation and Application

Xiang Pan[1], Liang Li[2], Shi-Ming Chen[3], Guangming Xie [4]

1. School of Electrical and Electronic Engineering, East China Jiaotong University, Nanchang 330013 P. R. China
E-mail: pan_xiang050827@163.com

2. Intelligent Control Laboratory, College of Engineering, Peking University, Beijing 100871, P. R. China
E-mail: liatli@pku.edu.cn

3. School of Electrical and Electronic Engineering, East China Jiaotong University, Nanchang 330013 P. R. China
E-mail: chen1977318@163.com

4. Intelligent Control Laboratory, College of Engineering, Peking University, Beijing 100871, P. R. China
E-mail: xiegming@pku.edu.cn

Abstract: Developing an effective tracking controller for the robotic fish is quite difficult because of the limited kinematic motion and the heavy disturbance of water wave. In this paper, to implement the basic pose-to-pose task for the robotic fish, we applied a tracking controller proposed by Kanayama. The detail implementation of the controller is introduced. And experiments conducted in a water tank verify the effectiveness of the controller for the task. Further, The application of the tracking controller in the robotic fish school shed a new light on the research of the collective behaviour.

Key Words: Robotic fish, tracking controller, pose-to-pose control, collective behaviour

1 Introduction

Bio-inspired robotics have been, and still are the challenging field of science, as the gap between manmade machine and creature is still large [1]. Robotic fishes, for example, have drawn a heavy interest of both roboticists and biologists[2–4], since the first robotuna has been made in Massachusetts Institute of Technology (MIT) [5]. One of the significant problems to be solved in the field of robotic fish is how to control the robotic fish from one posture (including position and direction) to another posture effectively. In this paper, we mainly focus on these issues based on a carangiform robotic fish.

Comparing to the wheel robot moving on the land, the robotic fish swimming in the water is affected by the water wave and cannot swim backward or laterally. Therefore, the tracking control of the robotic fish is more difficult than the wheel robot, although the kinematic model of the robotic fish is similar to the unicycle model. Previous researches on these problems are based on the limit cycle approach [6], the fuzzy control method [7], and sliding-mode control [8]. Most of them can only implement the point-to-point problem, that is, the controller ignores the direction of robot.

In this article, we develop a powerful tracking controller based on the Kanayama model [9]. This is the first application of this kind controller in the aquatic robots, as the underwater robots are endowed with fewer locomotion ability and suffer more disturbances than land robots. For example, the robotic fish can only swim forward and turning right or left, thus limiting the power of controller. Moreover, when fish swim near the boundary, the backward waves will also effect the posture of the robotic fish. The effectiveness of the controller is proved both by simulation and real experiments. The comparisons between these two results show that the real tracking control is more difficult than the simulation one, and by adding the disturbances of the water, the controller needs more time to converse.

Further, we applied the whole robot system to the researches on the collective behaviour, a popular research field in the biology [10, 11]. Although the development of the research is quick and powerful, the limitation of the field lies in the verifications by theoretical modeling or simulation. To the knowledge of the author, few collective behaviour has been applied to the field of engineering. We first explore the real experiments on the robotic fish school in a limited water tank. This environment is quite different to that in the simulation, such as larger disturbances of the water and the boundary effects. However, experiments on the real robotic fish school proved the effectiveness of the Couzin model. And the emergent phenomenon of circling and paralleling of fish school have been observed. During the process, each fish in the school takes the same rule of the tracking controller we proposed above. All of these prove that the tracking controller is efficient for the pose to pose control of robotic fish.

The remainder of the paper is organized as follows. In Section II, we present the prototype of a carangiform robotic fish and a whole tracking controller test system. The detail tracking controller we used as well as a simulink are introduced in Section III. The method of carrying out the controller in our robotic fish and the experiment results are given in section IV. In Section V, we applied the controller to the effectiveness of the collective behaviour. The results and discussions conclude our work in Section V.

2 The Prototype of Robotic Fish and Experiment Setup

In this chapter, we introduce a carangiform robotic fish including the mechanism and locomotion control. Further, we also illustrate the experiment setup.

2.1 Robotic Fish

The prototype of robotic fish we used in these experiments is made in the Intelligent Control Laboratory at Peking university according to carangiform fish [2, 12]. It consists of three parts, a rigid head, a flexible body and a caudal fin see

Fig. 1. The rigid head is designed with a streamline shape and contains a battery, control module and wireless communication module. The flexible body is made of soft rubber. Inside the skin, there are three links controlled by three servomotors. The caudal fin are designed with gradually varied stiffness that is similar to the real one. Resembling to the natural fish, the robotic fish is propelled through body undulation. The swimming mode is controlled by an AVR microcontroller inside the robotic fish.

The body undulation of the robotic fish is also controlled by a bio-inspired controller, Central Pattern Generator (CPG). CPG is composed of neural networks in the spinal cord or ganglion, and is proved to generate animals' movements, such as walking, running, swimming or flying [13–15]. Compared to the traditional trajectory approximation method [16], CPG controllers have the following advantages:

1) Complex calculations for accurate points on the trajectory of the robot are avoided, and numerous derivations of equations are eliminated.

2) Robots embedded with CPG controller can adapt to dynamic environment because their controlling parameters can be modified online.

3) CPG controller provides a smooth transition between two locomotion patterns, while trajectory approximation method needs a special consideration.

The Cartesian coordination of the fish body is defined with the origin fixed at the nose. The propulsion of the robotic fish is generated by the swapping of the three servomotors, representing three joints. As the servomotors are controlled by the Pulse-Width Modulation (PWM) signals, the goal of CPG is to form rhythmic flapping angles. Fig. 2 depicts the schematic of the controller. Since CPG controller is benefit of the simple input, we define all the input parameters are "Speed" and "Direction". The transition layer can transform the control parameter to the network input to form the oscillating outputs. Within the network inputs, CPG outputs the periodic angles values. The values are then send to AVR controller to generate the corresponding Pulse-Width Modulation (PWM) signals to drive the servomotors [17].

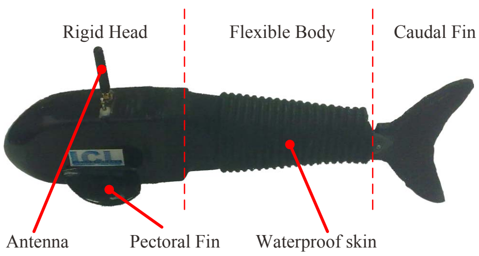

Fig. 1: Robotic fish prototype. The robotic fish consists of rigid head, flexible body and caudal fin.

2.2 Experiment Platform

The experiment platform is also developed at Peking university [18]. The whole experimental schematic is shown in Fig. 3. The robotic fish swims in a 2 $m\times$ 3 $m\times$ 0.3 m water tank. An overview global camera is fixed to record the trace of the robotic fish, sending the video to the host to analyze the posture of the robotic fish online. The tracking controller

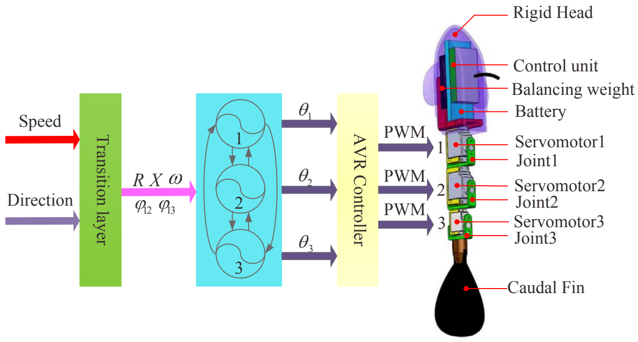

Fig. 2: Schematic of CPG controller for the locomotion control of robotic fish

is calculated in the host. And the command of the speed and direction is sent to the robotic fish with a radio frequency (R-F). There is a recognition period of the system depending on the whole system from video capture of the camera to image recognition to command sending. The period is determined by many factors such as the effectiveness of the recognition algorithm, the calculation ability of the host computer, and the complexity of the tracking controller.

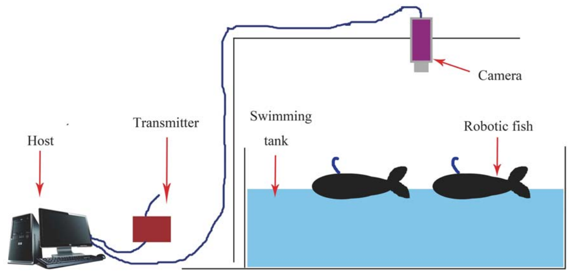

Fig. 3: The experiment platform. Robotic fish is controlled by the host after receiving the posture information of robotic fish.

3 The Tracking Controller

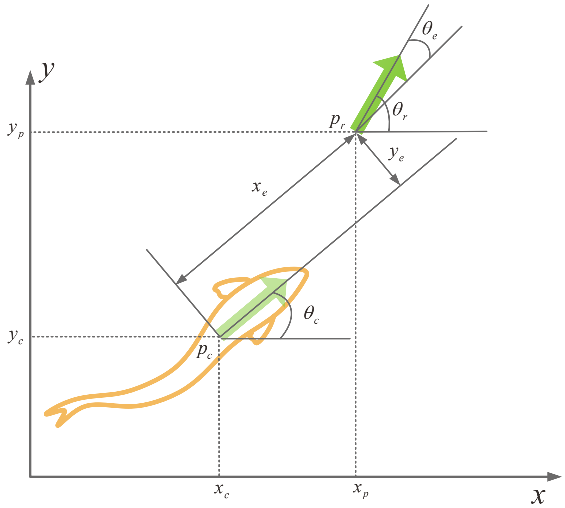

Fig. 4: Error posture calculation.

As the robotic fish swims on the water, regarding as moves on a 2D plane. The Cartesian coordinate system is defined

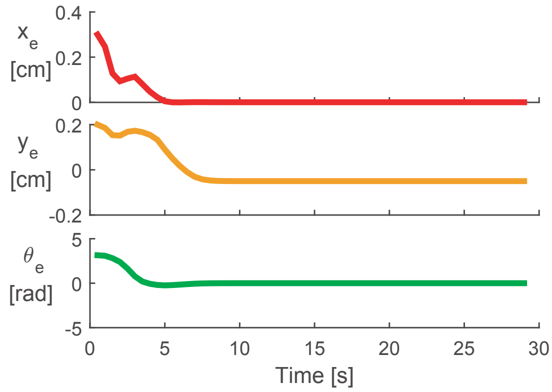

Fig. 5: Simulation in the MATLAB verifies the effectiveness of the controller.

as shown in Fig. 4. We define a specific posture by three degrees of freedom,

$$p = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \tag{1}$$

The target posture is denoted as (x_r, y_r, θ_r), then the error posture is calculated as

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{2}$$

The error posture calculation is shown in Fig. 4, in the fish body coordinate system.

A stable tracking controller proposed by Kanayama is applied to the control of the motion of robotic fish [9]. The detail control rule is defined as

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} v_r \cdot \cos\theta_e + k_x \cdot x_e \\ \omega_r + k_y \cdot y_e + k_{dir} \cdot \sin\theta_e \end{bmatrix} \tag{3}$$

Where k_x, k_y and k_{dir} are three constants and determine the performances of the controller. v_r and ω_r are the speed and angular speed of the reference posture. The stability of the controller is proved in [9] theoretically. Fig. 5 shows a simulation results of the controller using the simulink in MATLAB. The errors of three variables decrease to zero, resembling the final posture corresponds to the reference one. However, the disturbances in the model is generated by the algorithm, thus well perform of the controller. In the following chapter, we will test the controller in the real robotic fish swimming in the water tank.

4 Experiments in a Water Tank

In this chapter, we applied the stable controller to our robotic fish to implement a referenced posture from any initial posture.

4.1 Discretization of the Controller

As the robotic fish is controlled by a CPG controller embedded in a digital microcontroller, the discritization of the tracking controller is needed.

$$\begin{bmatrix} v(k) \\ \omega(k) \end{bmatrix} = \begin{bmatrix} v_r \cdot \cos\theta_e(k) + k_x \cdot x_e(k) \\ \omega_r + k_y \cdot y_e(k) + k_{dir} \cdot \sin\theta_e(k) \end{bmatrix} \tag{4}$$

Where k denotes the step of the update of the controller. And the average step time is about 47 mm, determined by the whole period of recognition system (see the description above in chapter 2). Moreover, the outputs of the controller have saturations to protect the actuators.

4.2 Parameter Determination

For a physical robotic fish, the locomotion ability is limited. And in order to reduce the disturbance caused by the shaking head of the robotic fish, we slow down the swimming speed. So, we defined the maximum input speed about half maximum swimming speed of robotic fish, that is 20 cm/s. The maximum turning velocity is $2/3\pi\ rad/s$. Further, as one of the challenging step of the tracking controller in the robotic fish, the thresholds of control parameters should be defined to make the control parameters workable (as shown in Tab. 1). And as a critical dynamic model of the robotic fish swimming in the water is difficult to be built, all the thresholds are defined through large experiments on the real robotic fish.

The thresholds are defined according to the following. The reference error of position is larger than that of the direction, thus lager position adjust controller value than the direction. Moreover, through enormous experiments we find that among the three control parameters, k_x is significant and

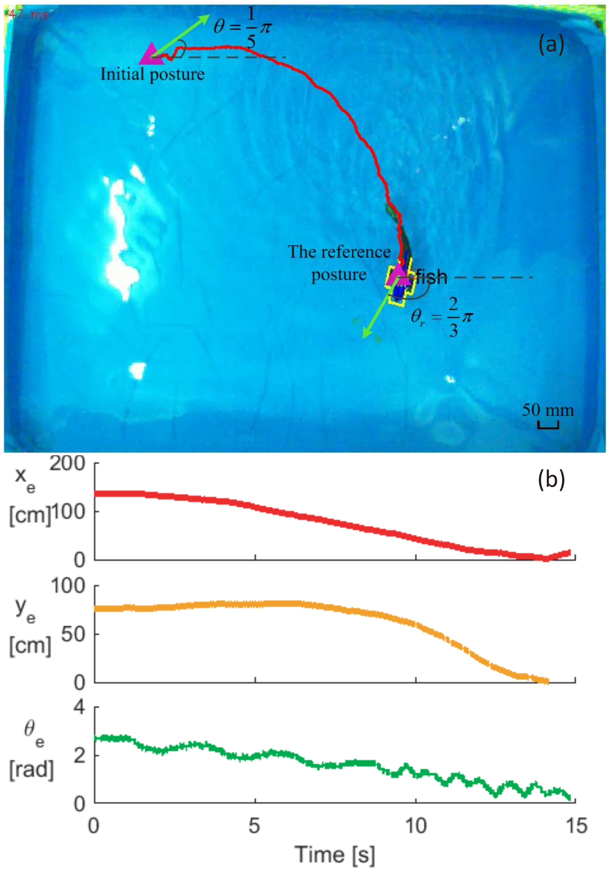

Fig. 6: The results of the experiments on the real robotic fish. (a) The trace (red line) of the robotic fish swimming from a posture to a reference posture. The angle of the start is $1/5\pi$ (the up green arrow), and the final angle is $2/3\pi$ (see the bottom). (b) The error of the posture during the tracking control.

Table 1: Definition of the thresholds of the control parameters

control variable	threshold of the variable
k_x	[0.02, 0.06]
k_y	[0.15, 0.35]
k_{dir}	[25, 60]

determine the converse speed. And larger k_y will lead an oscillating control of robotic fish, thus need fine tuning during the experiments. The control variable k_{dir} mainly control the swimming direction and is easily affected by the shaking head. Further, different initial posture or the reference posture will lead to different best control parameters. This is quite reasonable that each group of the control parameters can only control a limited problem. However, through enormous experiments with the robotic fish, we find the best control parameters are, $k_x = 0.04$, $k_y = 0.25$, $k_{dir} = 48$.

4.3 Experiment Results

An experiment on a robotic fish has been carried out by applying the tracking controller. The target of the control is to make robotic fish swim from the posture $(512,\ 240,\ 1/5\pi)$ to the reference posture $(186,\ 58,\ 2/3\pi)$ Fig. 6 (a) shows the control target and the track. From the figure, we can find the track is smooth and converse to the reference posture, proving the effectiveness of the controller. Fig. 6 (b) shows the errors of the posture, which converse to zero. And the time of the converse is about 10 s.

Compared to the simulation results 5, we find the experiments on the real robotic fish need more time to converse to stable posture and import larger disturbances. The process of the angle conversion is undulation and seems to be over controlled. The reason of this is due to the special propulsion of the robotic fish, by body undulation accompanying the shaking head. This is quite different to other robots in the land or the aquatic. Another difficulty for the tracking control of the robotic fish is that robotic fish has none barking system thus none stop when conversing to the reference position.

5 An Application on the Collective Behaviour

To further verify the effectiveness of the controller and develop the application of the whole robotic system, we apply the robotic system to the verification of the collective behaviour.

Many collective behaviour rules are deduced by simulations and have few experimental verifications or applications. We first verify the Couzin model in the robotic system. The couzin model has been extended in many models since Iain Couzin first proposed the model [19, 20]. Whereas, most were verified through simulations.

Although using simulations is convenience, the disadvantages are also clear. (a) The disturbances are generated by algorithms, and thus they are pseudo-disturbances. (b) Most models ignore the physical dynamics. (c) Few consider the problem of body cross-over. Here, we applied the robotic fish school to verify the effectiveness of the model.

The Couzin model is simply described as following. The view of a robotic fish is divided into three parts, zone of repulsion, zone of orientation and zone of attraction. In the

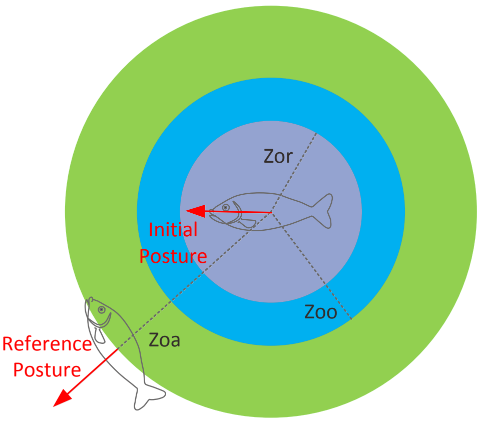

Fig. 7: Schematic of the zones where fish recognitions its neighbours and take the corresponding actions. Zor (Zone of repulsion): chose opposite direction, Zoo (Zone of orientation): chose the same direction of the neighbours', Zoa (Zone of attraction): swim toward the direction of the position of neighbours.

three zones (as shown in Fig. 7), different rules are applied to individual robotic fish. (a) In the zone of repulsion, robotic fish should control itself to avoid the others. (b) In the zone of orientation, robotic fish swims with its neighbors and adjusts its direction according the orientation of neighbors. (c) In the zone of attraction, robotic fish swims toward the position direction of the robotic fish in order to living in the groups.

The tracking controller is applied as show in Fig. 7, where the neighbour of the central fish is in the zone of attraction. Therefore, the focal fish should swim toward the position of the neighbour and in the direction of the position, that is the reference posture. And the initial posture in the tracking controller is the same as the current posture.

Fig. 8 depicts the experiment results by embedding the tracking control to robotic fish school. Here, we choose three typical values for the radius of the three zones, "Zor = 80", "Zoo = 120","Zor = 180". All the initial posture of the Couzin model are random. And the boundary effects of the robotic fish school are also quite different to simulation-

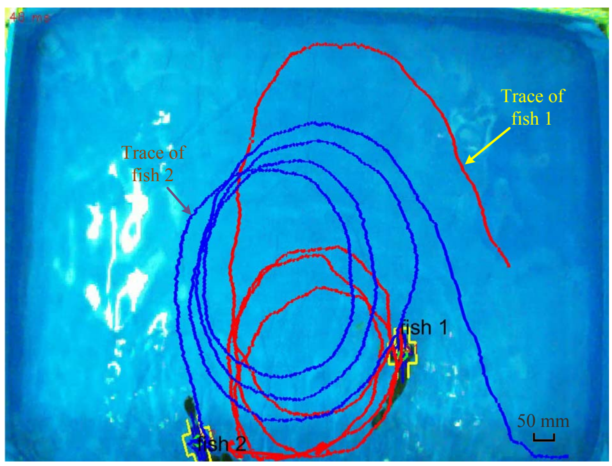

Fig. 8: The experiments of the verification of the Couzin model by robotic fish school.

s where most consider fish swim in an infinite space or a periodic space. Although we did none modification of the Couzin model for the boundary, the special phenomenons of circling robotic fish school are still observed in the experiments.

6 Conclusion and Future Work

We first apply a tracking controller to the robotic fish and prove the effectiveness of the controller by both simulation and experiments. The main difficults of the tracking controller for the robotic fish are (a) limiting motion ability of each individual, (b) strong disturbances of the environments. Further, we applied the whole robotic fish system in the field of collective behaviour, where most researches focus on the simulation works. The Couzin model, for example, is verified by our robotic fish school embedded the developed tracking controller.

There are many future work to be extended based on the work. As the robotic fish swim forward as well as shake head, which directly lead the angle controller oscillate. Therefore, a smoother is needed before the feedback of the angle variable. As robotic fish swims in a limited water tank, the boundary effect is unavoidable. A more powerful tracking controller considering the boundary is a following work of what we will do. On the other hand, the effectiveness of the collective behaviour is very limited. More work, such as larger group robotic fish, the transition between several motion modes, will be focused by using the robotic fish school equipped with more powerful tracking controller.

References

[1] A. J. Ijspeert, "Biorobotics: Using robots to emulate and investigate agile locomotion," *Science*, vol. 346, no. 6206, pp. 196–203, 2014.

[2] J. Shao, L. Wang, and J. Yu, "Development of an artificial fish-like robot and its application in cooperative transportation," *Control Engineering Practice*, vol. 16, no. 5, pp. 569–584, 2008.

[3] J. Yu, M. Wang, M. Tan, and J. Zhang, "Three-dimensional swimming," *IEEE Robotics and Automation Magazine*, vol. 18, no. 4, pp. 47–58, 2011.

[4] J. Yu, M. Wang, Z. Su, M. Tan, and J. Zhang, "Dynamic modeling of a cpg-governed multijoint robotic fish," *Advanced Robotics*, pp. 1–11, 2013.

[5] M. S. Triantafyllou and G. S. Triantafyllou, "An efficient swimming machine," *Scientific American*, vol. 272, no. 3, pp. 64–70, 1995.

[6] d. Zhang, L. Wang, J. Yu, and M. Tan, "Coordinated transport by multiple biomimetic robotic fish in underwater environment," *IEEE Transactions on Control Systems Technology*, vol. 15, no. 4, pp. 658–671, 2007.

[7] J. Yu, X. Hu, and R. Ding, "Fuzzy logic pid based control design for permanent magnet synchronous motor servo system," in *International Conference on Intelligent Computation Technology and Automation*, vol. 2, 2009, pp. 728–731.

[8] J.-X. Xu, X.-L. Niu, and Z.-Q. Guo, "Sliding mode control design for a carangiform robotic fish," in *12th International Workshop on Variable Structure Systems (VSS)*, Jan 2012, pp. 308–313.

[9] Y. Kanayama, Y. Kimura, F. Miyazaki, and T. Noguchi, "A stable tracking control method for an autonomous mobile robot," in *Proceedings of IEEE International Conference on Robotics and Automation.*, 1990, pp. 384–389 vol.1.

[10] S. Camazine, J.-L. Deneubourg, N. R. Frank, J. Sneyd, G. Theraulaz, and E. Bonabeau, *Self-Organization in Biological Systems*, ser. Princeton studies in complexity. Princeton University Press, 2003.

[11] I. D. Couzin and J. Krause, "Self-organization and collective behavior in vertebrates," in *Advances in the Study of Behavior*. Academic Press, 2003, vol. Volume 32, pp. 1–75.

[12] J. Shao, L. Wang, and J. Yu, "Development of multiple robotic fish cooperation platform," *International Journal of Systems Science*, vol. 38, no. 3, pp. 257–268, 2007.

[13] F. Delcomyn, "Neural basis of rhythmic behavior in animals," *Science*, vol. 210, no. 4469, pp. 492–498, 1980.

[14] C. Wang, G. Xie, L. Wang, and M. Cao, "Cpg-based locomotion control of a robotic fish: Using linear oscillators and reducing control parameters via pso," *International Journal of Innovative Computing Information and Control*, vol. 7, no. 7B, pp. 4237–4249, 2011.

[15] L. Li, C. Wang, and G. Xie, "Modeling of a carangiform-like robotic fish for both forward and backward swimming: Based on the fixed point," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2014, pp. 800–805.

[16] Y. P. Ivanenko, R. Grasso, V. Macellari, and F. Lacquaniti, "Control of foot trajectory in human locomotion: Role of ground contact forces in simulated reduced gravity," *Journal of Neurophysiology*, vol. 87, no. 6, pp. 3070–3089, 2002.

[17] L. Li, C. Wang, G. Xie, and H. Shi, "Digital implementation of cpg controller in avr system," in *Proceedings of the 33rd Chinese Control Conference*, 2014, pp. 8293–8298.

[18] L. Shao and G. Xie, "Real-time tracking of moving objects on a water surface," in *Proceedings of IEEE International Conference on Mechatronics and Automation*, 2012, pp. 2114–2119.

[19] I. D. Couzin, J. Krause, R. James, G. D. Ruxton, and N. R. Franks, "Collective memory and spatial sorting in animal groups," *Journal of Theoretical Biology*, vol. 218, no. 1, pp. 1–11, 2002.

[20] I. D. Couzin, J. Krause, N. R. Franks, and S. A. Levin, "Effective leadership and decision-making in animal groups on the move," *Nature*, vol. 433, no. 7025, pp. 513–516, 2005.