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CPGs control method using a new oscillator in robotic fish

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A new oscillator is presented in this paper based on our pervious oscillator (Zhang's oscillator). Using this new oscillator, a bionic neural control system, the central pattern generators (CPGs) control system, is built. This control system has a two-level form. To validate the function of this new oscillator and the control system, simulations and experiments were both carried out, a simple robotic fish was built with three joints, and the results showed that the new oscillator can be used in startup and stop control mode, angle offset control mode and amplitude changing control mode. The new oscillator can be used in bionic CPGs control area with a simple form, and may be a new progress in bionic control.

CPGs control, oscillator, robotic fish

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1 Introduction

In recent years, designing and controlling of underwater robots have been hot topics all over the world [1]. Lots of studies have been carried out by scientists and engineers, and they focus not only on the hydrodynamics mechanism and bio-inspired practice of fishlike swimming, but also on the control of the robotic fish [2]. There are two main ways to control the robotic fish, one is the traditional method, which can be defined as non-biomimetic way, and the other one is called biomimetic way [3].

Biomimetic control is a new way in modern control area. From the studies of real fish, the movement of fish is called rhythmic movement [4]. The rhythmic movement, such as swimming, walking, running and flying are produced by central pattern generators (CPGs), which are neural circuits that produce coordinated oscillatory signals in the absence of sensory input or descending inputs from higher cognitive elements [5]. In this paper, we put forward a new oscillator model based on Zhang's oscillator [6], which can produce oscillatory signals. Using this new kind oscillator, we can realize some kinds of fish movement. The validity of this new oscillator in control of robotic fish locomotion is proved not only by the simulation results but also by experiments. In the experiments, we designed a two-level control system, which was inspired by Rybak [7].

The organization of this paper is as follows: Section 2 presents the design of the new oscillator and the analysis of the new oscillator's characteristics. The control system of CPGs is also built in Section 2. Section 3 details the simulation and analysis of robotic fish movements, experiments are carried out in Section 4, and conclusions are given in Section 5.

2 Design of CPG model

2.1 Oscillator model

The most fundamental CPG model using the neural oscil-

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lator was proposed by Brown [8]. It consists of two neurons, which contact each other by reciprocal inhibition. After that, a number of neural oscillators were proposed. Wilson and Cowan [9] proposed a famous oscillator in 1972, which has been widely adopted in bionic robot control [10]. Matsuoka [11] also proposed a particular artificial neural oscillator composed of four neurons to imitate the symmetry inhibitory properties.

Our group has also proposed an artificial neural oscillator (Zhang's oscillator) based on a sine-cosine model [12], which is shown in Figure 1.

The dynamic model of Zhang's oscillator can be described by the following differential equations:

$$\begin{cases} \dot{u} = \omega v + f(x) + p_u(t), \\ \dot{v} = -\omega u + f(x) + p_v(t), \end{cases} \tag{1}$$

where u denotes the activity of excitatory neuron, v denotes the activity of inhibitory neuron, ω is the strength of mutual connections, P_u and P_v denote the external inputs composed of descending commands and sensor feedback, which are also the start signals, and $f(x)$ is a nonlinear self feedback function. In the differential equations of Zhang's oscillator $f(x)$ is described as

$$f(x) = k\left[-\frac{x}{r} + \frac{4}{\pi}\tan^{-1}\left(\frac{x}{r}\right)\right], \tag{2}$$

where k denotes the convergence speed to limit cycles, and r denotes the oscillatory amplitude control parameter. From the expression of the function, it contains a trigonometric function, which makes the self feedback function a little complex. In this paper, different from Zhang's nonlinear function, another new nonlinear function is chosen, whcih is described as

$$f(x) = kx(1 - rx^2), \tag{3}$$

where k and r denote the same meanings as Zhang's. This expression only contains a polynomial function, which makes the whole expression of the oscillator compact. So the dynamic model of the new oscillator can be described as follows:

$$\begin{cases} \dot{u} = \omega v + ku(1 - ru^2) + p_u(t), \\ \dot{v} = -\omega u + kv(1 - rv^2) + p_v(t). \end{cases} \tag{4}$$

The self feedback function and the limit cycles of the new oscillator are shown in Figures 2 and 3, respectively.

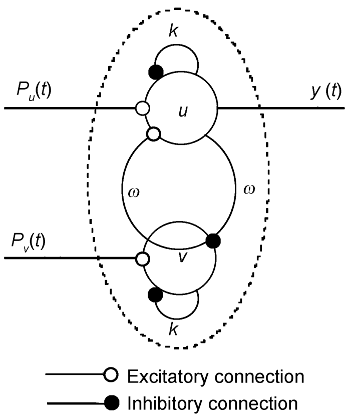

Figure 1 The novel artificial neural oscillator described by Zhang (Zhang's oscillator).

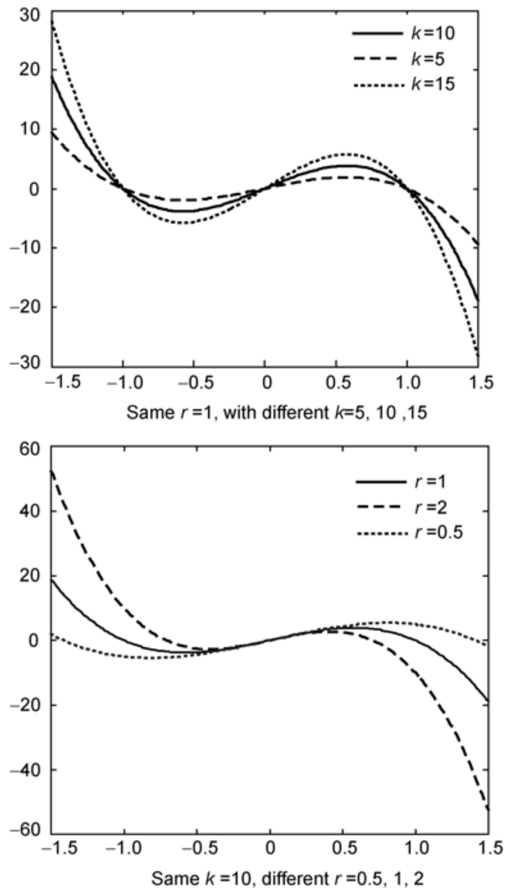

Figure 2 Different k and r of the self feedback function.

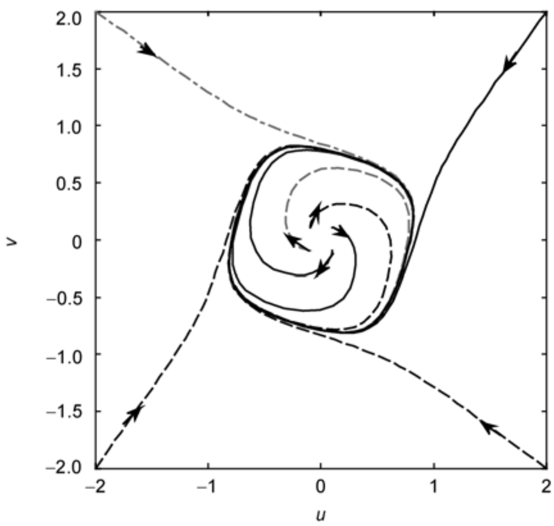

Figure 3 Limit cycles of the oscillator.

From Figure 3, we can see that different start points will converge to the same stable cycle. It has the same characteristics as Zhang's.

The output of the new oscillator u can be seen in Figure 4. From the figure, the output of the oscillator has a periodic shape, and the period and amplitude can be adjusted by k and r. Since the output u has such a periodic characteristic, it may be used as the control signal.

2.2 CPGs control system

The CPGs control system is built up by groups of oscillators. Each oscillator controls one group of muscles, output u or v means the flexor and the extensor of real muscles, the active and inhibit signals can control the joints [13–15].

As mentioned above, our CPGs control system is inspired by Rybak. We design a two-level CPGs control system, which can be seen in Figure 5.

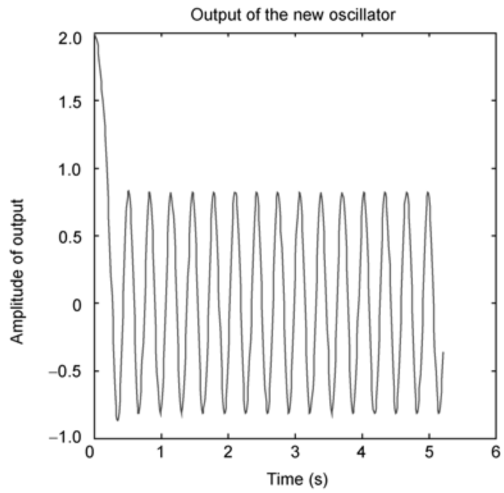

Figure 4 The output of the new oscillator.

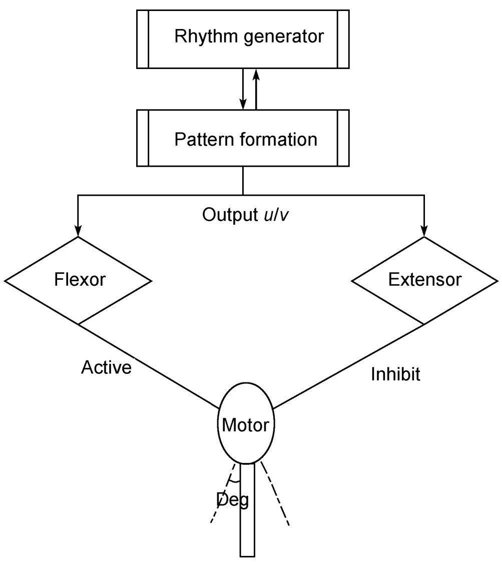

Figure 5 CPGs control system.

In Figure 5, the rhythm generator is the output of the oscillator, and the pattern formation can adjust some parameters of the oscillator, and control the period and amplitude of the output. The output of the oscillators u and v means the flexor and the extensor, just like the human muscles. The active and inhibit of the muscle can drive the target motor.

The dynamics of the CPGs control system are described by following equations:

$$\begin{cases} \dot{u} = \omega v + ku(1-ru^2) + p_u(t), \\ \dot{v} = -\omega u + kv(1-rv^2) + p_v(t), \\ y = u, \end{cases} \tag{5}$$

where P_u and P_v denote the same meanings as in eq. (1), and without them the oscillator will not begin to work. y denotes the output signal of the oscillator. To make it simple, the CPGs control system can be predigested as Figure 6.

In a robotic fish, the joints are driven by servomotors. The dynamics of the joint is given as

$$J\ddot{\theta} + D\dot{\theta} + k_s\theta = \tau, \tag{6}$$

where θ is the joint angle, $\dot{\theta}$ is the angular velocity, $\ddot{\theta}$ is the angular acceleration, J is the rotating inertia, D is the damping coefficient, k_s is the restoring force, and τ is the driving moment of the actuator.

Let the output of the oscillator u control the motor's angle, and this is the smallest segmental of CPGs control system, and it is also the fundamental of the robotic fish.

3 Simulation results

3.1 Startup and stop mode

The startup of the locomotion is actually to activate the oscillator and make it have an output. We impose a short time width pulse in eq. (5). The startup signals, P_u and P_v are given as

$$\begin{cases} \begin{cases} q_u(t) = \text{step}(t-t_s) - \text{step}(t-t_s-t_d), \\ q_v = 0, \end{cases} \\ \begin{cases} \text{step}(t) = 0, & t \leqslant 0, \\ \text{step}(t) = 1, & t > 0, \end{cases} \end{cases} \tag{7}$$

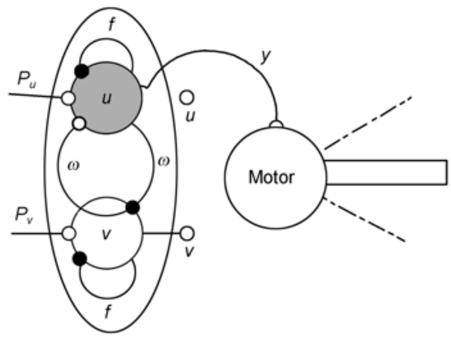

Figure 6 Simple form of the CPGs control system.

where t_s is onset time and t_d is the time width of the pulse. The output of the oscillator can be seen in Figure 7.

From the figure, we can see that given an stimulate to the oscillator, the output can persist a sine wave for a long time. It is one of the CPG's characteristics.

The stop process is to weaken and cease oscillation of the oscillator. Usually, to cease the oscillation, a direct way is let the oscillation neurons stop oscillation, that is, set the neurons to zero. This method neglects the transition from locomotion to stillness and may destroy the propeller hardware. We instead using a descending function which is applied to the oscillator to modulate the oscillation amplitude, described as

$$P_u(t) = r_0[1 - \int_{t=0} \mathrm{step}(t - t_c)\mathrm{d}t], \tag{8}$$

where r_0 is the original amplitude, t_c is the time of stop and k_c is the parameter to control amplitude descending speed. The output of the joint's angle can be seen in Figure 8.

From Figure 8, we can see that when the stop command

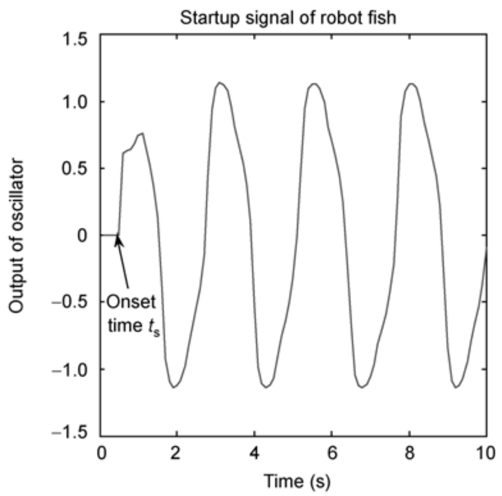

Figure 7 Startup signal of robotic fish.

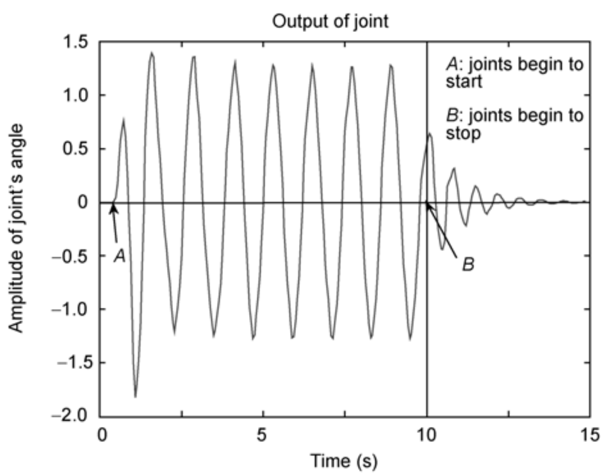

Figure 8 The whole output of the robotic fish, including startup and stop.

comes at time t_c which is point B in the figure, the joint begins to decrease its amplitude and lasts for a few seconds before really to stop. This characteristic makes the joints of the robot with less impact than sudden stop.

3.2 Angle offset mode

The robotic fish can turn right or left with an offset to the joint's angle. To realize the turning, we should make the single joint oscillate at an offset angle. So we add an offset to the output of the oscillator. The dynamics can be described as follows:

$$\begin{cases} \dot{u}_\theta = \omega v + k u_\theta (1 - r u^2{}_\theta) + p_u(t), \\ \dot{v} = -\omega u_\theta + k v (1 - r v^2) + p_v(t), \\ u_\theta = u - \theta, \\ y = u, \end{cases} \tag{9}$$

where θ is the offset angle in the output of the oscillator, and the value of θ determines the amplitude of the turning angle. The limit cycles of the new oscillator will converge to point $A(\theta, 0)$, which can be seen in Figure 9. The output of the joint also will be changed, because of the effect of the offset angle, as can be seen in Figure 10.

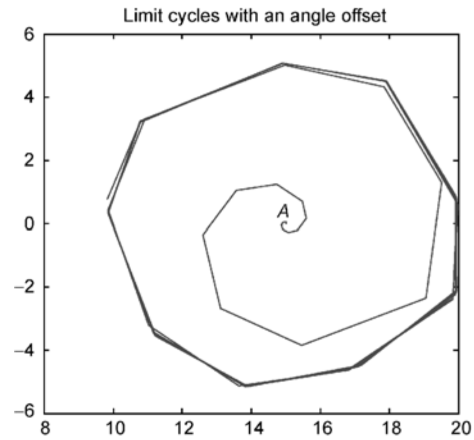

Figure 9 The limit cycles when adding an angle offset; in this figure, θ=15.

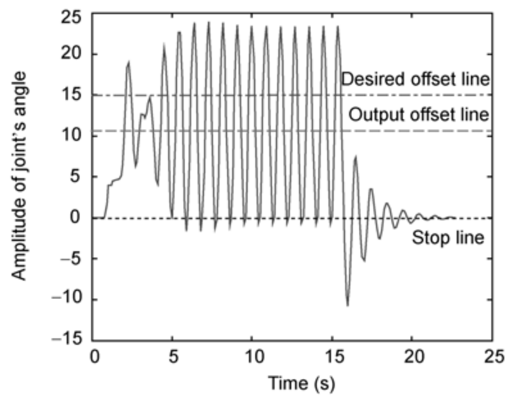

Figure 10 The output of the joint when there is an offset angle to the oscillator.

3.3 Amplitude change mode

The robotic fish can swim in different situations with different speeds.

To realize this kind movement, the robotic fish should swing the joints with different amplitudes. To do this, we just change some parameters of the function of the new oscillator. In eq. (4), r is the parameter to determine the amplitude of the output of the oscillator, as shown in Figure 11.

The amplitude change mode has an important use in modern biomimetic control. With the development of the new sensor, the robotic fish can feel the pressure and direction of the water, and change its oscillatory amplitude to get the best swimming performance, just like a real fish.

The control system is designed into two parts, just like the CPGs control system in Figure 5. We use a computer as the pattern formation to control the amplitude and the period of the oscillator; the Infineon 16-bit Xc164cs microcontroller is used as the oscillator, which also can be called the rhythm generator.

Structurally, our control system has two independent parts. This structure is more intelligent, since the upper controller can modify the parameters without affecting the lower controller, as can be seen in Figure 12.

To validate our control system, we designed a simple robotic fish, which consisted of three joints, each driven by a servomotor. The dynamics of each joint is given by eq. (6). The robotic fish can be seen in Figure 13. The data of one of the joints are shown in Figure 14.

In the regular swimming mode, we just used the simulation results in the startup mode to control the joints to oscillate around zero position. The joints could oscillate regularly.

In the turning mode, we used the simulation results in the angle offset mode. We let the joints oscillate at a desired position, so the robotic fish could turn.

From Figure 15, we can see that the robotic fish does not oscillate symmetrically around zero position, it has an angle offset. Figure 16 shows the data of one of the joints.

4 Conclusions

Both the simulations and experiments have shown that the joint can be controlled well by this new kind of oscillator, and that the control system can work well.

Due to limited time, our robotic fish was not in the best state. It was only used to validate our new oscillator.

From these results, we can see that the new oscillator,

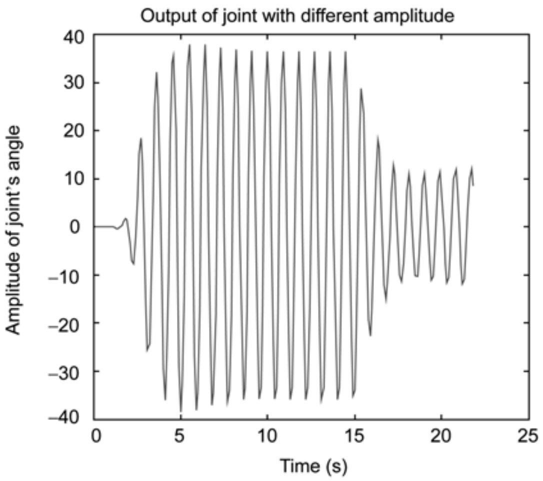

Figure 11 Output of joint with different amplitudes, where r is from 1 to 2.

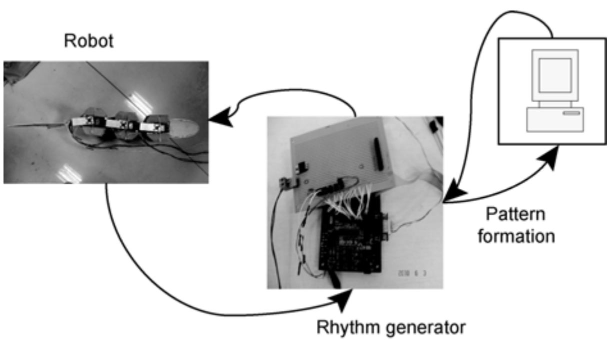

Figure 12 The two-level CPGs control system.

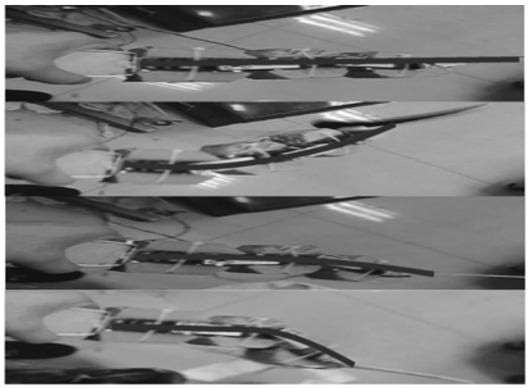

Figure 13 Robotic fish in startup mode.

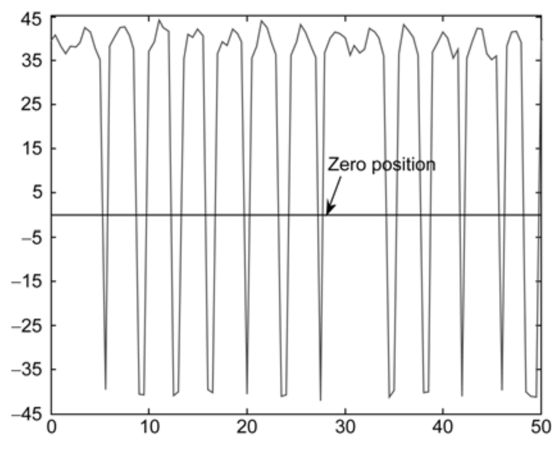

Figure 14 Data acquired form one of the joints in startup mode.

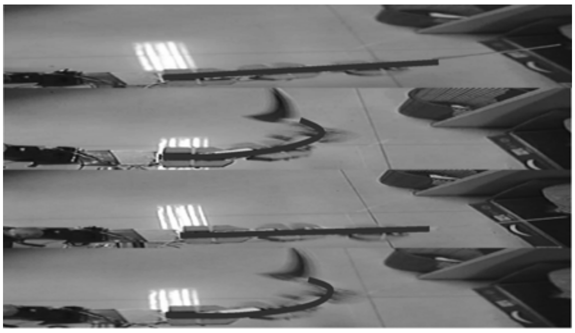

Figure 15 Robotic fish in the turning mode.

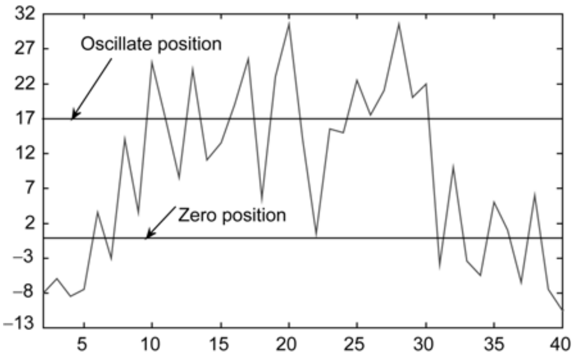

Figure 16 Data acquired form one of the joints in turning mode.

which has a self feedback nonlinear function that is different from Zhang's oscillator, can be used to control the robotic fish movement. By adjusting some parameters of the oscillator, the output will change its period or amplitude. Using these characteristics of the oscillator, the robotic fish can realize turning and swimming movement.

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