ASBTRACT
This research aims at modeling the thermotaxis behavior of *C.elegans* which is a kind of nematode with full clarified neuronal connections. Firstly, this work establishes the motion model which can perform the undulatory locomotion with turning behavior. Secondly, the thermotaxis behavior is modeled by nonlinear functions and the nonlinear functions are learned by artificial neural network. Once the artificial neural networks have been well trained, they can perform the desired thermotaxis behavior. Last, several testing simulations are carried out to verify the effectiveness of the model under different environments. The testing results reveal the essence of the thermotaxis of *C. elegans* to some extent, and theoretically support the research on the navigation of the crawling robots.

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Introduction
In nature, the microorganism and the microscopic organism have the capability to find the optimum temperature (thermotaxis) and chemical concentration (chemotaxis). These behaviors are vitally important for their surviving, such as finding food and avoiding the harmful environment. In single cell microorganisms, these taxis behaviors are controlled by chemical receptor protein, which make it move toward the expected temperature and chemical concentration. For higher level animals, they have sensory neurons and neural networks that control their movements. These neurons and neural network can help organisms to find the isotherm line and equipotential line owing equal chemical concentration.

The perception of neural network in higher level animals includes external environment and internal states. *C. elegans* is an excellent research model since the nematode has a simple structure, with transparent body and fully understandable neuronal connections. It is about 2 millimeters long and can live about 3 days at 20 degrees Celsius. In the field of developmental biology, it widely used for basic research work. In the cell differentiation research field, it is the first multicellular organism with the completed genome sequence. The nematode has 302 neurons, about 8000 synapses, and its connectome of nervous system has been clearly understood by neuroscientist. Thus, to simulate the nervous system of *C.elegans* is more practical significant than to simulate the mammals. With the nervous system, the nematode can perform these behaviors, such as thermotaxis, chemotaxis, mechanical perception, permeability avoidance, etc. In engineering aspect, the researchers mostly are interested in the first 2 kinds of behaviors, for which the navigation strategy and the movement mechanism could be adopted to construct the bio-inspired crawling robots. The crawling robots can achieve at least 4 tasks: 1) rescuing survivors in complex areas where human cannot enter; 2) checking the inner side of the industrial equipment pipes; 3) crawling on the ground, under water, or inside the pipes for military utilities; 4) checking the stomach, blood vessels, or intestine for clinical use.

Up to now, the research on *C.elegans* mainly involves the fields of biology, medical science, genetics, neurology, etc. However, the research on *C.elegans* in engineering aspect is new and the outcomes are limited.

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From our survey, the research about *C. elegans* started from 1963 and there are more than 20,000 academic literatures that have been published. In China, there are about 120 papers and mostly all of them are based on the research of biology, medical, genetics, etc. Among them, very limited research works are based on the chemotaxis\(^1\) of *C. elegans*. The object of this study is modeling the thermotaxis of *C. elegans* to perform the undulatory locomotion. Some relative works started from 20 years ago and these works are divided into 4 groups. The first group is Niebur et al. They provided the first movement model of nervous system based on *C. elegans*. The model paid close attention to how the movement wave spread in the nematode’s nerve cells.\(^2\) The second group is Conhen et al. They constructed a nervous-mechanical model which can generate the forward undulatory locomotion.\(^3\) The third group is Suzuki et al. They modeled and simulated the undulatory locomotion behavior of *C. elegans* by means of nervous control. They explored the head turning, directional control, forward and backward locomotion under touching perception.\(^4\) The fourth group is Lockery et al. They investigated the chemotaxis behavior of *C. elegans* by using a 3 layers dynamic neural network to implement the capability of finding food.

### Results

We construct the neural network in this paper to simulate the information transfer process from sensory neurons to motor neurons via interneurons in *C. elegans*. By following the biological essence,\(^5,6\) the neurons in the hidden layer should not be too many. The neuron number for the hidden layer is increased from 2 tentatively. From our experiment, 3 hidden layer neurons can achieve the satisfactory results, and it is the same to the model in\(^5\), in which it also obtains 3 hidden layer neurons.

The error diagram for 500 test data is shown in Fig. 1. From Fig. 1, we can observe that the errors is relatively low, even though the test data is not used for training. Then, we use the well trained neural network to achieve the thermotaxis behavior by performing the undulatory locomotion.

The experiment in this paper is carried out in the MATLAB environment. The temperature environment is simulated by a coordinate system in our testing and follows the Gaussian distribution in Eq. (1). Time period in Section 4.3 is divided into 2 situations.

One is half of motion period (k = 4) and the other is quarter of motion period (k = 2).

In the experiment, we first consider the situation that time period is half of motion period. As shown in Fig. 2, the thermotaxis motion process is acquired by means of nonlinear function, and as shown in Fig. 3, the thermotaxis motion process is acquired by means of BP neural network. In each figure, the simulated *C. elegans* starts from 3 different points. The three initial points are located as (0, 0), (0, 160), (120, 160). The initial angle is set to be 0 with positive direction of X axis in our experiment.

In Fig. 2 and Fig. 3, the small circles at the coordinates (80, 80) show the maximum temperature, and the solid circles represent the isothermal lines, and the
dotted circle represents the optimum temperature line. According to Fig. 2, from 3 different initial points, the nematode arrives at the optimum temperature line smoothly and moves around there. According to Fig. 3, BP neural network is used instead of the nonlinear function. We can observe that the nematode finally arrives at the optimum temperature line smoothly and moves around there, which indicates that the BP neural network can approximate the nonlinear function well.

Secondly, under the situation that time period is a quarter of motion period, as shown in Fig. 4 and Fig. 5, thermotaxis motion process is acquired repeatedly by means of nonlinear function and BP neural network respectively. The initial condition is the same to the situation that time period is one half of motion period.

From Fig. 2 to Fig. 5, we can observe that when the initial points are (0, 160) and (120, 160), the nematode can arrive at the optimum temperature line smoothly. However, as shown in Figure 4 and Fig. 5, under the condition that the initial point is (0, 0), the nematode cannot arrive at the optimum temperature line, which means the thermotaxis behavior is failed. Here we analyze 2 behaviors, one for Fig. 2 with initial point (0, 0) and the other for Fig. 4 with initial point (0, 0). As shown in Fig. 6 and Fig. 7, the variations of \( \Delta C \), \( \Delta C_0 \) and \( \phi \) over time are recorded. Fig. 6 shows the thermotaxis behavior process in Fig. 2. Figure 7 shows the process in Fig. 4.

From Fig. 6 and Fig. 7, we can observe that the lines in Fig. 7 are more fluctuated than those in Fig. 6. The reason to yield the more fluctuations is that the time period for the direction decision in Fig. 7 is every quarter of period time, compared with that the time period for the direction decision in Fig. 6 is every half period time. If the decision making happens at every quarter of time period, the temperature gradient direction is not parallel to the motion direction, which may not guide the correct direction. However, when the decision making happens at every half of time period, the temperature gradient direction is in accordance with the motion direction, which could guide the correct direction. From the results of our experiment, we may infer that the time of direction decision making could be half of time period for undulatory locomotion

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**Figure 3.** Thermotaxis motion process by using BP neural network.

**Figure 4.** Thermotaxis motion process by using nonlinear function.

**Figure 5.** Thermotaxis motion process by using BP neural network.
nematode, which is consistent with the biological experiment result in 7. Furthermore, this result would provide an effective way for the navigation strategy of the worm-like robot or snake-like robot.

**Discussion**

The thermotaxis behavior of *C. elegans* based on the undulatory locomotion is explored in this paper. We model the temperature distribution by using Gaussian distribution and then design the whole muscle structure of *C. elegans* by using a multi-joint rigid link system. The kinematic model is constructed and the nonlinear functions are designed to simulate the thermotaxis behavior of *C. elegans*. To manipulate the thermotaxis behavior, we adopt the BP neural network to learn the nonlinear function. The well trained BP neural network can implement the thermotaxis behavior by navigating itself toward the optimum isotherm. In the experiment part, we test our model by using different decision time periods in several initial situations. From the experiment result, we can observe that the proposed model achieves the thermotaxis behavior effectively, which reveals the essence of the thermotaxis of *C. elegans* to some extent. In future work, the crawling robot will be explored based on the theoretical results for clinical use, such as the capsule robot or endoscope equipment for blood vessels or intestine inspection.

**Methods**

**Environment model**

To test the thermotaxis of *C. elegans*, this paper constructs a coordinate system to simulate the temperature environment where *C. elegans* lives. In our model, we assume that the temperature distribution follows the Gaussian distribution. The model is shown in Eq. (1).

\[
C(x, y) = C_{\text{max}} \exp \left( -\frac{(x-a)^2 + (y-b)^2}{S} \right)
\]  

(1)
In Eq. (1), \((a, b)\) is the center point of Gaussian distribution. In this paper, \(a = 80\) and \(b = 80\). \(C_{\text{max}}\) is the maximum temperature in the environment model. In this paper, we set \(C_{\text{max}} = 100\) degree centigrade. \(S\) is the variance of the distribution. \(C(x, y)\) shows the temperature of the coordinate \((x, y)\). The model is shown in Figure 8.

**Muscle structure model**

The body of *C. elegans* is cylinder, and the body wall muscles can be classified into 4 quadrants, as shown in Fig. 9, these 4 quadrants are dorsal-left (DL), ventral-left (VL), ventral-right (VR), and dorsal-right (DR), respectively.

As is shown in Fig. 10, based on the muscles structure, the body can be divided into 11 muscle segments. The center of each muscle segment is depicted as a joint. For example, muscles denoted as 3 and 4 in each quadrant form the second segment. Muscles from 21 to 24 (21 to 23 for VL quadrant) form the last segment, because anatomically these 3 or 4 muscles in each quadrant are controlled by the same motor neuron. In addition, 2 joints (0 and 12) stand for the head and the tail, respectively. Above all, the whole body is represented by 13 nodes. The 13 nodes are connected by 12 links. Thus, the body of *C. elegans* is represented by a multi-joint rigid link system.\(^9,10\)

According to the multi-joint rigid link model in Fig. 10, the movement shape of *C. elegans* in our study forms a sinusoid wave with 1.5 periods, as shown in Fig. 11.

**Kinematic model**

*C. elegans* feels the external temperature through the sensory neurons in the head, and then the interneurons compute the deflection angle. Finally, the motor neurons adjust the shrink of the corresponding muscles based on the deflection angle, achieving the deflection movement. The deflection angle is acquired based on the temperature for the sensory neurons at different time. The deflection movement is acquired by the first node (node 0 in Fig. 10) moving round the

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**Figure 8.** Environment model.

**Figure 9.** The structure of body wall muscles.

**Figure 10.** Multi-joint rigid link model.
second node (node 1 in Fig. 10) when the second node is located at the time of \( t = k^*T/8 \) \((k = 0, \ldots, n)\). One deflection movement process is shown in Figure 12.

The coordinate of head node at time \((k-1)^*T/8\) is \( A(x_a, y_a) \). If the nematode does not turn, the coordinate of the first node at time \( k^*T/8 \) (that is, at time \( t \)) is \( C(x, y) \), and meets these Eqs. (2)-(3).

\[
x = \omega t \\
y = A^*\sin(\omega t + B)
\]

(2)\hspace{1cm}(3)

The Eqs. (2)-(3) are the equations for the motion of \textit{C.elegans} at time \( t \). \( \omega \) is the angular velocity, \( t \) is the time, \( A \) is the amplitude of the kinematic waves, and \( B \) is the phase lag.

If it turns the angle of \( \phi \), the coordinate of head node at time \( t \) is \( B(x_b, y_b) \), which is acquired by \( C(x, y) \) turning the angle of \( \phi \) clockwise based on the point of \( A(x_a, y_a) \).

As we known, when a point \( C(x, y) \) in Cartesian coordinates turns an angle of \( \phi \) clockwise based on the point of \( A(x_a, y_a) \), the new point \( B(x_b, y_b) \) is acquired as follows.

\[
x_b = (y_a - y)\sin \phi + (x_a - x)\cos \phi + x \\
y_b = (y_a - y)\cos \phi - (x_a - x)\sin \phi + y
\]

(4)\hspace{1cm}(5)

The model of deflection angle

Considering at time \( t-1 \) and \( t \), the head of \textit{C.elegans} passes 2 points \((x(t-1), y(t-1))\) and \((x(t), y(t))\), respectively. The deflection angle for the next step is determined by 2 parts. One is the temperature difference of the head node at time \( t-1 \) and \( t \). The other is the difference between current temperature and the optimum temperature. Based on above conception, we design a set of functions to approximate the logic of thermotaxis behavior. These functions are shown in Eqs. (6)-(10).

\[
C(t) = C(x(t), y(t)), \\
C(t-1) = C(x(t-1), y(t-1)), \\
\Delta C = C(t) - C(t-1), \\
\Delta Co = C(t) - Co, \\
\phi(t) = \frac{1}{m^*(1 + \exp(a^*(\Delta C^*\Delta Co + b)))}.
\]

(6)\hspace{1cm}(7)\hspace{1cm}(8)\hspace{1cm}(9)\hspace{1cm}(10)

In the Eqs. (7–10), \( C(t-1) \) and \( C(t) \) are the temperatures at time \( t-1 \) and \( t \), respectively. \( Co \) is the optimum temperature. \( \Delta C \) is the temperature difference at time \( t-1 \) and \( t \). \( \Delta Co \) is the difference between the temperature at time \( t \) and the optimum temperature. The movement situation can been classified into 3 categories.

When \( \Delta Co < 0 \), that is, the temperature of the head area is less than the optimum temperature. Under this condition, \( \Delta C < 0 \) means the nematode is deviating from the optimum temperature, so it should deflect.
Otherwise, $\Delta C > 0$ means it should go along the original direction. When $\Delta Co > 0$, that is, the temperature of the head area is higher than the optimum temperature. $\Delta C < 0$ means the nematode go toward the optimum temperature, so the nematode should go along the direction of the original. $\Delta C > 0$ means the nematode should deflect. When the nematode is under the optimum temperature, it should not deflect.

Base on the $C(t-1), C(t), \Delta Co$ and $\Delta C$, the deflection angle $\phi$ is obtained by Eq. (11). In Eq. (11), $m$, $a$ and $b$ are constants. The nonlinear function Eq. (11) is shown in Figure 13.

Based on the characteristic of the biased turning mechanism of *C. elegans*, this paper assumes that the biased turning is toward the right side, which is corresponding with the clockwise deflection movement in our model in Section 4.3.

**Artificial neural network**

Artificial neural network simulates the cognition mechanism of the human brain and is a kind of powerful system to achieve some functions such as classification, pattern recognition and so on. The artificial neural network is composed of a large number of layered information process units (neurons), which owns the learning and parallel computing capabilities. Naturally, the movement of *C. elegans* is controlled by its nervous system. So in this study, we adopt the artificial neural network to be the control system to implement the thermotaxis behavior. Based on the strong learning capability, the neural network can approximate the nonlinear function efficiently. Once the neural network has learnt the nonlinear function well, it can realize the thermotaxis behavior.

For our neural network model, $\Delta C$ and $\Delta Co$ are 2 inputs and $\phi$ is the output. The relation between inputs and output follows the nonlinear function Eq. (11). In this paper, we use BP neural network to approximate it. BP neural network is one kind of multilayer feedforward neural network. Its signal transmits forward, and error transmits backward. The BP neural network used in this work is shown in Fig. 14, which consists one input layer, one hidden layer and one output layer. The first layer includes 2 input neurons with linear activation function. The second layer is the hidden layer with the sigmoid activation function. The third layer is the output layer with linear activation function. The number of neurons in the hidden layer is determined in experiment.

According to the probable range of $\Delta C$ and $\Delta Co$ in Section 4.1 and the Eqs. (7)-(11) in Section 4.4, 2500 input-output datasets are constructed. Among them, 2000 sets are randomly selected to be the training data and the rest 500 sets are regarded as the test data. Before training, all data should be normalized.

**Disclosure of potential conflicts of interest**

No potential conflicts of interest were disclosed.

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