The Application of BP Neural Network Algorithm in Rapid Design of the Vertical Boom of Bridge Inspection Vehicle

Jian Zhao1,*, XueLing Li1 and HongFeng Ma1

1 Jiangsu XCMG Construction Machinery Research Institute Co., Ltd, Xuzhou, 21004, China
* 2576020746@qq.com

Abstract: During the analysis of the vertical boom of bridge inspection vehicle, it is not easy for the designer to provide a good design scheme quickly. In order to find a professional CAD software which can quickly obtain the ideal design scheme, the BP neural network algorithm is adopted to obtain the design solution by means of mapping. The better schemes of vertical boom are selected for different types of bridge inspection vehicles. These schemes are used as sample data to train the BP neural network for obtaining weights and thresholds. The trained neural network is used for the rapid design of the vertical boom of bridge inspection vehicle. As long as the design parameters are input, the design scheme of the vertical boom can be output directly.

1. Introduction

The bridge inspection vehicle is a kind of special vehicle which provides operation platform for the bridge maintenance and repair workers[1]. The vehicle is mainly composed of rotating platform, connecting rack, vertical boom, telescopic boom and so on[2]. It is an important bearing component for vertical boom, connecting rotating platform and operation platform of bridge inspection vehicle. It is directly related to the life safety of operators for the performance of vertical boom.

During the analysis of the vertical boom of bridge inspection vehicle, it is not easy for the designer to provide a good design scheme quickly. Due to the long product development cycle, it can’t respond quickly to market demand. In order to find a professional CAD software which can quickly obtain the ideal design scheme, the BP neural network algorithm is adopted to obtain the design solution by means of mapping. The better schemes of vertical boom are selected for different types of bridge inspection vehicles. These schemes are used as sample data to train the BP neural network for obtaining weights and thresholds. The trained neural network is used for the rapid design of the vertical boom of bridge inspection vehicle. As long as the design parameters are input, the design scheme of the vertical boom can be output directly that provides a reference for the designer.

2. BP neural network algorithm

BP neural network algorithm is one of the most commonly used neural network algorithms. Due to its simple structure and strong plasticity, the algorithm has strong nonlinear mapping capabilities. The three-layer BP neural network can fit any nonlinear continuous function with arbitrary precision. When training a BP neural network, a tutor learning mechanism is used to automatically extract the relationship between input and output data. And the learning content is adaptively memorized in the network's weights and thresholds. The BP neural network algorithm is suitable for solving the nonlinear rapid design problems of professional machinery.
2.1 Three-layer BP neural network model

BP neural network is a kind of multilayer feedforward artificial neural network with error back propagation mechanism. As shown in Figure 1, the three-layer BP neural network consists of an input layer, a hidden layer, and an output layer. Layers are connected to each other, and nodes in each layer are not connected. The forward propagation of network learning is to receive the input signal $X_i$ at the input layer, then process the data from the input layer through the hidden layer and pass it to the output layer to output the result. The result of the output is called the predicted output. In the sample data, the comparison with the predicted output is called the expected output. The sign of the end of the neural network training is that the error between the predicted output and the expected output meets the requirements; otherwise, it goes to back propagation and corrects the weights and thresholds of each layer[3].

![Figure 1. Structure of a three-layer BP neural network](image)

2.2 BP neural network algorithm

The BP network changes the weights and thresholds of each neuron according to certain rules during the learning process.

The specific steps of the algorithm are as follows[4]:

1. Forward propagation: First, normalize the sample data. The normalization method is calculated according to Eq. (1).

   $X_{rl} = \frac{X_{rl} - X_{\text{min}l}}{X_{\text{max}l} - X_{\text{min}l}}$

   \[ (1) \]

   Then, the input of the hidden layer can be calculated according to Eq. (2).

   $I_j = \sum_{i=1}^{n} V_{ij} X_{ri} - V_{oj}$

   \[ (2) \]

   The output of the hidden layer can be calculated according to Eq. (3).

   $y_j = f(I_j) = f\left(\sum_{i=1}^{n} V_{ij} X_{ri} - V_{oj}\right)$

   \[ (3) \]

   The input of the output layer can be calculated according to Eq. (4).

   $I_k = \sum_{j=1}^{m} U_{jk} y_{rj} - U_{ok}$

   \[ (4) \]

   The output of the output layer can be calculated according to Eq. (5).
The error of the k-th neuron in the output layer can be calculated according to Eq. (6).

\[ e_{rk}(T) = d_{rk}(T) - z_{rk}(T) \]  

The overall network error follows Eq. (7). When \( E(T) < \varepsilon \), the calculation ends, where \( \varepsilon \) is the calculation accuracy. Otherwise, error back propagation is performed.

\[ E(T) = \frac{1}{2} \sum_{k=1}^{q} e_{rk}^2(T) \]  

Where \( n \) is the number of neurons in the input layer, \( i \) is one of neurons in the input layer, \( p \) is the number of neurons in the hidden layer, \( m \) is the number of neurons in the output layer, \( k \) is one of neurons in the output layer, \( r \) is the number of groups of sample data, \( X = (X_1, X_2, ..., X_r, ..., X_q) \), \( D = (D_1, D_2, ..., D_r, ..., D_q) \) is the expected output, \( v_{ij} \) is the weight between the input layer and the hidden layer, \( \mu_{jk} \) is the threshold of the hidden layer, \( I_j \) is the input of the hidden layer, \( y_j \) is the output of the hidden layer, \( I_k \) is the input of the output layer, \( Z_k \) is the output of the output layer. The activation function is calculated according to Eq. (8).

\[ f(x) = \frac{1}{1+e^{-x}} \]  

Weight correction is calculated according to Eq. (9)-(14).

\[ \Delta u_{jk}(T) = -\eta \frac{\partial E}{\partial u_{jk}} = -\eta \frac{\partial E \partial I_k}{\partial I_k \partial u_{jk}} = -\eta \delta_k y_j \]  

\[ u_{jk}(T + 1) = \alpha u_{jk}(T) + \Delta u_{jk}(T) \]  

\[ \delta_k = \frac{\partial E}{\partial I_k} = \frac{\partial E}{\partial Z_k} f'(I_k) = (d_{rk} - z_{rk}) z_{rk}(1 - z_{rk}) \]  

\[ \Delta v_{ij}(T) = -\eta \frac{\partial E}{\partial v_{ij}} = -\eta \frac{\partial E \partial I_j}{\partial I_j \partial v_{ij}} = -\eta \delta_j x_{rj} \]  

\[ v_{ij}(T + 1) = \alpha v_{ij}(T) + \Delta v_{ij}(T) \]  

\[ \delta_j = \eta \sum_{k=1}^{m} (d_{rk} - z_{rk}) z_{rk}(1 - z_{rk}) y_j(1 - y_j)x_{rj} \]

\[ = \eta \sum_{k=1}^{m} \delta_k u_{jk} y_j(1 - y_j)x_{rj} \]  

\[ = \eta \sum_{k=1}^{m} \delta_k u_{jk} y_j(1 - y_j)x_{rj} \]
Where $\Delta u_{jk}$ is the correction amount of the weight between the hidden layer and the output layer, $\delta_k$ is a feedback factor, $\Delta v_{ij}$ is the correction amount of the weight between the input layer and the hidden layer, $\eta$ is the learning rate between 0.01 and 1, $\alpha$ is the momentum factor ranging from 0 to 1.

3. Network structure and characteristics of bridge inspection vehicle vertical boom

3.1 Construction of BP network of vertical boom

There are five design parameters of the vertical boom, which are the length of the working platform $x_{r1}$, the weight of the working platform $x_{r2}$, the moment of the working platform's weight and uniform load $x_{r3}$, the end load of the telescopic boom $x_{r4}$, and the moment of the end load to vertical boom $x_{r5}$. Therefore, there are five nodes in the input layer of the network. The expected output is the better scheme of vertical boom for training the neural network. There are 12 parameters in the expected output, which are the length of the whole boom $d_{r1}$, length of the outer surface of the vertical boom $d_{r2}$, the width of the outer surface of the vertical boom $d_{r3}$, the length of the main chord member $d_{r4}$, the width of the main chord member $d_{r5}$, the thickness of the main chord member $d_{r6}$, and the length of the diagonal web member $d_{r7}$, the width of the diagonal web member $d_{r8}$, the thickness of the diagonal web member $d_{r9}$, the length of the horizontal web member $d_{r10}$, the width of the horizontal web member $d_{r11}$, the thickness of the horizontal web member $d_{r12}$. Therefore, there are 12 nodes in the output layer. The number of nodes in the hidden layer can be obtained according to Eq.(15), and the number of nodes in the hidden layer is 11. As shown in Figure 2, a three-layer BP neural network with vertical boom is constructed.

$$p = \sqrt{n + m + 7}$$

Where $p$ is the number of nodes in the hidden layer.

![Figure 2. Structure of the vertical boom network](image)

3.2 Selection of sample data

There are four types of bridge inspection vehicles with spans of 16m, 18m, 20m, and 22m. These four types of bridge inspection vehicles are loaded by uniform load and boom end load respectively. In this way, eight training samples can be obtained. The specific loading method is shown in Table 1.

| Span (m) | Uniform load (KN) | Boom end load (KN) |
|---------|------------------|-------------------|
| 16      | 5.5              | 0                 |
| 16      | 0                | 2.5               |
| 18      | 6                | 0                 |
| 18      | 0                | 3                 |
| 20      | 7                | 0                 |
| 20      | 0                | 3.5               |
| 22      | 7.5              | 0                 |
| 22      | 0                | 3.85              |
4. **algorithm implementation**

4.1 **Rapid Design Software Development**

The software is developed on the platform of windows by using a object-oriented programming language. The better scheme of vertical boom is selected for different types of bridge inspection vehicles. These schemes are used as sample data to train the BP neural network for obtaining weights and thresholds. The trained neural network is used for the rapid design of the vertical boom of bridge inspection vehicle. As long as the design parameters are input, the design scheme of the vertical boom can be output directly that provides a reference for the designer.

Figure 3 shows the software initialization interface. Click "Rapid Design" to enter the rapid design interface, as shown in Figure 4.

![Figure 3. Initialization interface](image)

![Figure 4. Rapid design interface](image)

There are three major functions in the rapid design interface, which are training of BP neural network, the output of design scheme, and output of command flow for secondary development of HyperMesh. Click "BP Algorithm" to train BP neural network. When the BP neural network is trained, the trained weights and thresholds will be displayed in the "Weight and Thresholds" area of the interface.

In the "Design Parameter" area of the rapid design interface, enter the design parameters of the vertical boom and click "Rapid Design". And the design results will be immediately displayed in the "Result" area. The designer can adjust the scheme according to the results to get the final design scheme. Finally click "Output HM" to output the command stream for secondary development of HyperMesh. HyperMesh is used to check the correctness of the design scheme. Figure 5 shows the HM command output interface.

![Figure 5. HM command interface](image)

4.2 **Modeling example**

Taking a certain model of bridge inspection vehicle vertical boom model as an example, input design parameters, where the length of the working platform is equal to 22m, the weight of the working platform is equal to 24.5e3N, the moment of the working platform's weight and uniform load is equal to 1.755e8 N/mm, the end load of the telescopic boom is equal to 3.85 e3N, the moment of the end load to vertical boom is equal to 8.833e7 N/mm. And the design results will be immediately displayed in
the "Result" area. The designer can adjust the scheme according to the results to get the final design scheme. Finally click "Output HM" to output the command stream for secondary development of HyperMesh. The finite element model is established automatically by using HyperMesh to execute the HM command. And the Optistruct solver file is output. The Optistruct solves the file and outputs the analysis results. As shown in Figure 6, the maximum tensile stress of the model is 243.7Mpa, the maximum compressive stress is 229.3Mpa, and the maximum displacement is 70.3mm.

Figure 6. Stress diagram (a) and Strain diagram (b)

5. Conclusion
The conclusion is as follows:

(1) The trained neural network is used for the rapid design of the vertical boom of bridge inspection vehicle. As long as the design parameters are input, the design scheme of the vertical boom can be output directly that provides a reference for the designer.

(2) Due to its simple structure and strong plasticity, the BP neural network algorithm has strong nonlinear mapping capabilities. The three-layer BP neural network can fit any nonlinear continuous function with arbitrary precision. The algorithm is suitable for the rapid design of the vertical boom of bridge inspection vehicle.

(3) It is a feasible method to obtain the parameters of non-standard products by using the mapping method to build a rapid design module. It explores a new idea for the development of CAD software for bridge inspection vehicles.

Reference
[1] Zheng Z P, Zeng M. (2012) Finite element analysis and optimization for rotating platform of bridge inspection vehicles based on ANSYS. J. Sci. Commun., 3: 105-107.
[2] Li W, Zhang H. (2018) Cause analysis of deformation and experimental study on the vertical truss of bridge inspection vehicles. J. Sci. Commun., 11: 110-111.
[3] Hu M X. (2012) Intrusion detection algorithm based on BP neural network. J. Sci. Commun., 38: 148-150.
[4] Wang J Q, Wang F L, Qiu L C. (2011) Prediction of total power in agriculture machinery based on BP neural network. J. Sci. Commun., 42: 11-12.
[5] Liu X Y, Liu H. (2008) Artificial Neural Networks and Particle Swarm Algorithm Optimization. Beijing University of Posts and Telecommunications Press, Beijing.