Computer Modeling and Topology Analysis of Controllable Metamorphic Ship Welding Manipulator

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Abstract: A new controllable metamorphic ship welding manipulator based on multi loop coupling structure is designed and its structure is modeled by computer. The topological analysis is carried out by using bichromatic topological graph and adjacency matrix, and then we can obtain the metamorphic principle of its closed-chain mechanism, and reveale the configuration evolution process. The modified Grübler-Kutzbach formula is used to analyze the degree of freedom in different configurations. Then obtained the corresponding effective configurations, which are suitable for free welding, local welding, horizontal welding and vertical welding respectively. Based on metamorphic principle and the process of configuration evolution, the kinematic chain topology of multi-degree-of-freedom controllable metamorphic mechanism can be obtained by computer software analysis. This kind of variable topology mechanism can also provide reference for the innovative design of other construction machinery.

1. Introduction

Ship welding is one of the most important aspects of labor cost in shipbuilding. Welding accounts for about one third of the total cost of building a ship, and welding consumes about seven-tenths of the total labor time in shipbuilding [1-2]. Taking the ship welding robot as an example, the main function of the ship welding robot is to complete the welding work in the process of ship building from plane segment to curved surface segment, the parts of hull erection stage, small closure, middle closure and large closure of curved outer plate and abutment. Accordingly, the path tracking control method of wheeled mobile welding robot based on dynamics [3], the dynamic system of shipbuilding welding machinery [4], and the related optimization design [5] have attracted more and more attention in the field of shipbuilding welding machinery. However, most of the existing researches focus on the trajectory tracking, control method and system path planning of welding robot. The research on the structure of its actuator, especially the combination of metamorphic mechanism [6-7], controllable mechanism [8], series-parallel hybrid mechanism and other mechanism research frontiers are rarely reported.

For this reason, a kind of mechanism configuration of controllable metamorphic ship welding robot based on multi-loop coupling structure is designed. The mechanism metamorphism principle is obtained by topological analysis of the robot using bichromatic topology diagram and adjacency matrix. The modified Grübler-Kutzbach formula [9] is used to analyze the degree of freedom under different configuration, and obtain the corresponding effective configurations.

2. Configurations

Aiming at the actuator of the ship welding robot, a new type of controllable metamorphic ship

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welding manipulator is designed by retaining the attitude adjusting mechanism of the end welding torch. The manipulator is shown in Figure 1.and the diagram of its metamorphic source mechanism is shown in Figure 2. The closed-chain mechanism is composed of several components which are hinged each other, among which BD = CD, AB = EF, CE = AF = OK, OB = EK and KJ = IJ satisfy the link length relationship. The quadrilateral KPQS is parallelogram, and the components 3, 7, 9 and 11 are three pairs of components. The components 2, 5, and 12 are three groups of driving arms driven by three servo motors which are mounted on A, F and G of rack 1. When I and K, B and C coincide, the two groups of five-bar linkages can be connected by electromagnetic relay to form a new compound hinge. Therefore, the metamorphic source mechanism has 4 combined configurations.

3. Topological analysis and degree of freedom computation

3.1 Free Welding Configuration (Metamorphic Source Mechanism)

The topological structure of the mechanism is represented by a bichromatic topological diagram in which A, B, D, E, C, F, O, P, K, Q, R, S, J, I, H and G represent the kinematic pairs 13, 14 … 28, respectively. As shown in Figure 3, the kinematic pairs 14 and 21 in the metamorphic mechanism can be visually seen as compound hinges according to the bichromatic topological diagram and the components 1, 2, 7 and 10 are components with three motion pairs. There are 12 components and 15 kinematic pairs. It can be seen that 1 - 7 components constitute a kind of double closed five - bar linkage with inner sub chains.

The mechanism diagrams of metamorphic mechanism, configuration 1, 2 and 3, and the bichromatic topology diagrams are as follows.

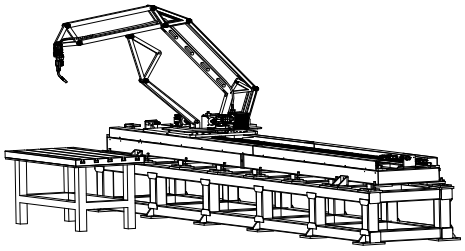


Fig. 1. The new ship welding robot of controllable metamorphic type

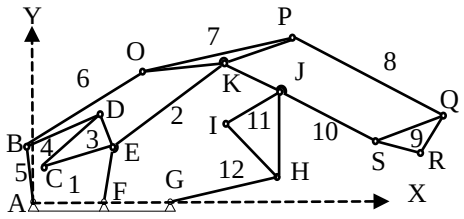
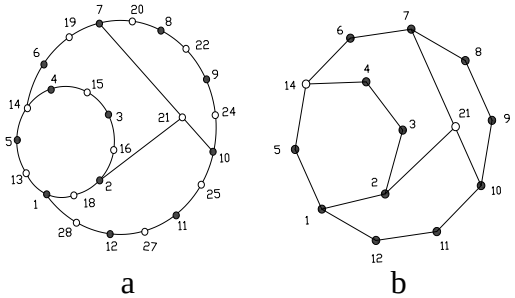


Fig. 2. Schematic diagram of metamorphic source mechanism



a b

Fig.3. bichromatic topological graph of metamorphic source mechanism

The adjacency matrix is

$$A_0 = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \end{array} \begin{array}{c} \begin{array}{cccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

The degree of freedom of the mechanism is solved by the theory of screw [14] 11-14 and the modified Grübler-Kutzbach formula.

$$\begin{aligned} M &= d\left(n-g-1\right)+\sum_{i=1}^{g} f_i+\nu-\zeta \\ &= 3(12-15-1)+15+0-0=3 \end{aligned} \tag{1}$$

Where, M represents number of degrees of freedom; d represents order of mechanism; n represents number of components including rack; g represents number of all kinematic pairs; f_i represents number of degrees of freedom of the i-th kinematic pair; ν represents number of redundant constraint; ζ represents number of local degree of freedom.

From the formula (1), it can be seen that metamorphic source mechanism has three degrees of freedom, and the complex welding tasks can be carried out by the three servo motors based on the stander (component 1). It is suitable for many kinds of free welding, such as spot welding, curve welding and so on.

3.2 Local Welding Configuration (Configuration 1)

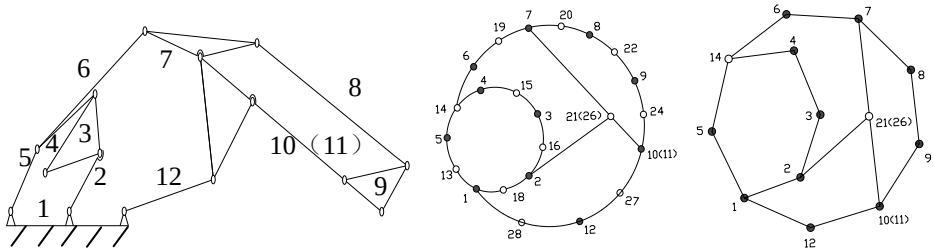


Fig.4. Mechanism diagram and bichromatic topological graph of configuration 1

We can see from the topological diagram that the motion pairs 21 and 26 coincide in the same axial direction, and the link IJ and KJ coincide, and the motion pair 21 forms a new compound hinge through some electromagnetic relay control. So the components 10 and 11 are consolidated into one. The number of components and kinematic pairs of the mechanism changed to 11 and 14 respectively. It's adjacency matrix is

$$A_1 = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10(11) \\ 12 \end{array} \begin{array}{c} \begin{array}{ccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10(11) & 12 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

The degree of freedom of configuration 1 can be obtained as follow

$$\begin{aligned} M &= d\left(n-g-1\right)+\sum_{i=1}^{g} f_i+\nu-\zeta \\ &= 3(11-14-1)+14+0-0=2 \end{aligned} \tag{2}$$

Thus configuration 1 has 2 degrees of freedom. Large range of position can be adjusted by motor drive at A and small range angle can be adjusted by motor drive at G. It can carry out relatively simple local welding operation, especially suitable for small range precision welding operation.

3.3 Downward and Vertical Welding Configuration (Configuration 2)

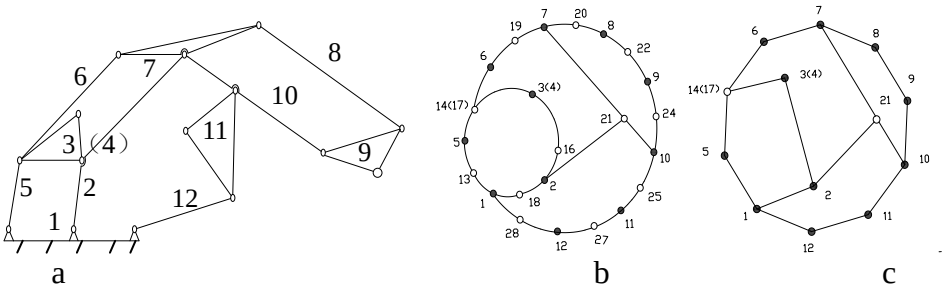


Fig.5. Mechanism diagram and bichromatic topological graph of configuration 2

We can see from the topological diagram that the motion pairs 14 and 17 coincide in the same axial direction, and the link BD and CD coincide, and the motion pair 14 forms a new compound hinge through some electromagnetic relay control. So the components 3 and 4 are consolidated as a whole. The number of components and kinematic pairs of the mechanism changed to 11 and 14 respectively. Quadrilateral ABEF and BEKO are parallelogram, which ensures that the end member 9 posture is unchanged during movement. Where, the adjacency matrix is

$$A_2 = \begin{array}{c} \\ 1 \\ 2 \\ 3(4) \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \end{array} \begin{array}{c} \begin{array}{cccccccccccc} 1 & 2 & 3(4) & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

The number of degrees of freedom is

$$\begin{aligned} M &= d\left(n-g-1\right)+\sum_{i=1}^{g} f_i+\nu-\zeta \\ &= 3(11-14-1)+14+0-0=2 \end{aligned} \tag{3}$$

It also has 2 degrees of freedom and the special configuration ensures that the attitude of the end member 9 remains unchanged. After adjusting the attitude of the welding torch, the welding operation can be completed by driving the two motors of the frame F and G. The control of the driving motor is reduced and the error accumulation of the serial welding torch device is eliminated. This configuration is suitable for special welding methods such as flat welding and vertical welding.

3.4 Invalid Configuration (Configuration 3)

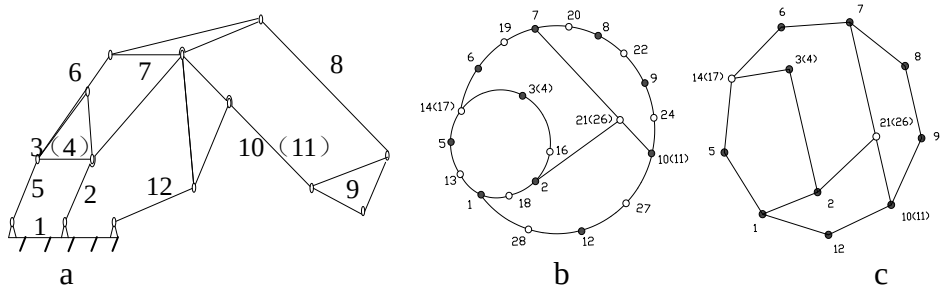


Fig.6. Mechanism diagram and bichromatic topological graph of configuration 3

According to the topological diagram, the motion pairs 21 and 26, 14 and 17 coincide with the axial direction respectively. By controlling, the motion pairs 21 and 14 form new composite hinges. Components 10 and 11, components 3 and 4 are consolidated into one body respectively. Of which, the number of mechanism components and kinematic pairs changed to 10 and 13 respectively. The adjacency matrix is

$$A_3 = \begin{array}{c} \\ 1 \\ 2 \\ 3(4) \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10(11) \\ 12 \end{array} \begin{array}{c} \begin{array}{cccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

The number of degrees of freedom is

$$\begin{aligned} M &= d(n-g-1)+\sum_{i=1}^{g} f_i + \nu - \zeta \\ &= 3(10-13-1)+13+0-0=1 \end{aligned} \tag{4}$$

Because this configuration has only 1 degrees of freedom, it is not suitable for welding work.

From the above topological graph and adjacency matrix, we can see that the metamorphic mode of the mechanism is changing the number of elements. The principle is the degeneration and derivation of the link group. The five-bar mechanism is degenerated into four-bar mechanism, and then loosening it into a five-bar mechanism. There are four different configurations in this combination. According to the analysis of DOF, the whole mechanism has three effective configurations, which can be reconstructed topologically to accomplish different welding tasks.

4. Conclusions

In this paper, a controllable metamorphic ship welding manipulator is designed for shipbuilding welding field. The topological analysis is carried out by using bichromatic topology diagram and adjacency matrix. We can obtain The Metamorphic Principle of the closed chain mechanism, and reveal its evolution process. Based on the theory of screw, the modified Grübler-Kutzbach formula is used to calculate the degrees of freedom under different configurations. It is found that three effective configurations with three degrees of freedom and two degrees of freedom are suitable for free welding, local welding, horizontal welding and vertical welding respectively.

Acknowledgment

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