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FAULT TOLERANCE ANALYSIS AND OPTIMIZATION OF CENTRALIZED CONTROL PLATFORM BASED ON ARTIFICIAL INTELLIGENCE AND OPTIMIZATION ALGORITHM

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Abstract. To enhance the reliability and self-healing of the system, the research on fault tolerance of the reconfigurable modular centralized control center is its development trend. Most of the previous research has focused on hardware redundancy. Improving fault tolerance performance is an essential topic in the research of centralized control platforms. Firstly, the problem of centralized fault tolerance in the working configuration of a reconfigurable manipulator is studied. The effect of each hinge on fault tolerance in the existing configuration is studied with the criterion of manoeuvrability and tolerable space. The fault module was first modelled to represent the system architecture information. A modular motion rule based on autonomous recombination technology is proposed. A self-organizing deformation algorithm with fault tolerance is studied. The fault tolerance of the motion pairs is compensated by adding a small number of motion pairs to ensure the configuration characteristics. With the addition of a failure compensation device, the joint's range of motion was reduced, and the fault tolerance rate was enhanced. After the failure of the robot arm, the fault tolerant control method can still ensure that the robot arm can perform work in its tolerable working space. The test results show that the fault tolerance analysis method is practical and feasible. It lays a theoretical foundation for the application in aerospace, industry and other fields.

Key words: Reconfigurable robot; Fault tolerance; Configuration design; Fault-Tolerant Control

1. Introduction. Self-reassembling robot is a new kind of robot technology developed in recent decades. The self-assembling robot, also called a self-transforming robot, is formed by organically connecting several modular robots with certain intelligent and essential functions. Self-reassembling robots can realize self-adaptability through their form. It can adjust its configuration in a complex environment and work to achieve self-adaptability to the environment and task. This method can effectively reduce the construction and fabrication cost of the robot arm and improve the function and construction of the robot arm. Its diversified structure has the advantages of high reliability, good flexibility, strong self-assembly and self-repair [1]. The system highlights high adaptability in terms of fault tolerance. The first autonomously reassembled robotic prototype system is from the perspective of the space station. Some scholars have researched self-reassembling robot technology [2]. This will provide technological support for variable space vehicles such as satellite dishes, solar panels, adaptive operators, and new ways to explore the planet. The self-reconfigurable robot has a flexible global topological configuration. Through the independent docking and disconnection between the components, the whole or part of the configuration change is completed [3]. According to the function of each component in the whole robot construction process and the construction of the object system, it can be divided into link type and lattice type.

The chain-linked robot arm includes a flexible arm, snake, foot and other open-loop and closed-loop walking machinery. Such as flexible arm, snake, and foot walking robots, PolyBot, and Conro robots are chain-connected systems. The components in the lattice system can be combined in any shape in two or three dimensions, thus giving it a hexagonal modular structure: molecular robots and crystal robots produced by Kotay KD, RusDL and other companies. Yoshida et al. 's three-dimensional crystal structure robot also adopts a lattice crystal structure. In this project, the fault tolerance performance of a self-assembling robot platform is studied based on the configuration determined by the task [4]. Moreover, fault tolerance and compensation are added to

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ensure the configuration can perform the work correctly and reliably.

2. Fault-tolerant obstacle climbing rules. The first case is first to identify the system's objects and then transform the existing objects. The second case is given the object's shape but does not understand its specific shape information needed to extract the shape information of the object from the external environmental conditions to form the target shape [5]. The third case studies the movement from the initial to the predetermined point in an unstructured environment. It involves problems such as obstacle avoidance and path optimization. Among them, the first two types of deformation problems can be summarized as the deformation problem of static mechanism, and the third type of deformation problem is how to obtain better action through deformation [6]. No matter what kind of variant work is performed, it must be able to learn rationality and fault tolerance by itself. This means that a particular link's failure will not impact the entire system [7]. This method is to replace the component with other non-critical parts if the component fails due to the failure of the component. Or the component can be separated from the system to achieve the purpose of self-healing [8]. At the same time, the system can also carry the fault module and make it move or deform to achieve fault tolerance management [9]. This project will study the fault-tolerant deformation method of two-dimensional square lattice robot crossing obstacles.

3. Research on the wrong description of the structure of the reconfigurable robotic arm. The corresponding parameters evaluate the fault tolerance of the mechanism configuration. Selecting a tolerable performance index is an essential aspect of tolerable configuration design. Assume that the total motion rate of the manipulator in the workspace is $\dot{v}_1$. The connection rate is $\dot{v}_2.K$ is the Jacobian matrix of the manipulator. The corresponding relationship between $\dot{v}_1$ and $\dot{v}_2$ is:

$$\dot{v}_1 = K\dot{v}_2$$

There is $K = \begin{bmatrix} k_1 & k_2 & \cdots & k_n \end{bmatrix}$ in the formula. In this project, the minimal singularity of the failure configuration is used to measure the fault tolerance in the failure process. As the amount of singular point computation required is too large, it is challenging to meet the real-time requirements [10]. This project will take the degree of operation as the evaluation standard of destruction resistance. The following is a definition of the operability of the current robotic arm configuration:

$$\lambda = \sqrt{\det\left(KK^T\right)}$$

The physical meaning of this method is to characterize the volume of the operation ellipsoid, which can reflect the dexterity of the fault-tolerant mechanism configuration.

3.1. Relative operability. At present, simply using the operating degree of the failure configuration to measure the fault tolerance of the robot arm can not reflect the loss caused by the failed robot arm [11]. Therefore, comparing the dexterity of the failed robot arm before and after failure is necessary. Relative operability is used to characterize the system's fault tolerance before and after configuration. In the case of failure, if d node fails, the performance of the manipulator is reduced as follows:

$$\lambda_{i_1,i_2,\cdots,i_d} = \sqrt{\det\left(K_{i_1,i_2,\cdots,i_d} K^T_{i_1,i_2,\cdots,i_d}\right)}$$

$$K_{i_1,i_2,\cdots,i_d}$$

$$= \begin{bmatrix} k_1 & \cdots & k_{i_1-1}k_{i_1+1} & \cdots & k_{i_d-1}k_{i_d+1} & \cdots & k_n \end{bmatrix}$$

$K_{i_1,i_2,\cdots,i_d}$ is the degraded Jacobian matrix obtained by removing the corresponding column vector of the failed joint by Jacobi K of the robotic arm. Then the relevant operation is:

$$L_{i_1,i_2,\cdots,i_d} = \frac{\lambda_{i_1,i_2,\cdots,i_d}}{\lambda}\lambda \neq 0$$

Since $K_{i_1,i_2,\text{ L},i_d}$ is a subclass of $K_{i_2,\text{ L},i_d}$, there is the following relationship:

$$0 \leq L_{i_1,i_2,\cdots,i_d} \leq L_{i_2,\cdots,i_d} \cdots \leq L_{i_d} \leq 1$$

3.2. Fault tolerance space. Relative maneuverability can only reflect the degree of flexibility of the mechanism configuration after the failure and locking of the robot arm but cannot reflect its effect on the working environment. At the same time, the working environment is also a critical factor in measuring work quality. Therefore, the expandability design method is proposed in this paper [12]. When one or more nodes in the robot arm fail, the redundant robot arm can still perform the desired task. The fault-tolerant space measures the fault-tolerant capacity of each node in the mechanism configuration. The node with the smallest error tolerance space is found. The inclusion degree of fault-tolerant space is calculated by joint compensation. The robot has the following workspace:

$$W=\{\varphi_1,\varphi_2\cdots\varphi_n \mid \varphi_{1\min}<\varphi_1<\varphi_{1\max},\varphi_{2\min}<\varphi_2<\varphi_{2\max},\cdots,\varphi_{n\min}<\varphi_n<\varphi_{n\max}\}$$

The fault-tolerant space for the d joint is represented as follows

$$\begin{aligned}&W_{\varphi_d}=\{\varphi_1,\cdots\varphi_{d-1}\varphi_{d+1}\cdots,\varphi_n \mid \varphi_{1\min}<\varphi_1<\varphi_{1\max},\cdots\\&\varphi_{d-1\min}<\varphi_{d-1}<\varphi_{d-1\max},\varphi_{d+1\min}<\varphi_{d+1}<\varphi_{d+1\max},\cdots\\&\varphi_{n\min}<\varphi_n<\varphi_{n\max}\}\end{aligned}$$

The standard space volume describes the relationship between the fault-tolerant space and the task space of the d joint. Then, determine the d fault-tolerant space evaluation function as:

$$\psi_d=\frac{M\left(W_{\varphi_d}\mathrm{I}W_\lambda\right)}{M\left(W_\lambda\right)}$$

$M\left(W_{\varphi_1\cdots\varphi_{d-1}\varphi_{d+1}\cdots\varphi_n}\cap W_\lambda\right)$ is the volume of joint space of fault-tolerant space and task space in the section $d.M\left(W_\lambda\right)$ represents the volume of the work area [13]. Because $W_{\varphi_1,\varphi_2\ \mathrm{L}\varphi_d}\subset W_{\varphi_2,\varphi_3\ \mathrm{L}\varphi_d}\ \mathrm{L}\subset W_{\varphi_d}$, the following relationships exist:

$$0\leq\psi_{1,2\cdots d}\leq\psi_{2\cdots d}\cdots\leq\psi_d\leq 1$$

3.3. Comprehensive fault tolerance performance. In this project, the fault tolerance characteristics related to the configuration of reconfigurable robots and the fault tolerance ability of moving pairs are studied [14]. Through the integrated research of the two, the fault-tolerant ability of the multi-degreeof-freedom motion mechanism is compared and analyzed. Then, the evaluation function of the integrated fault tolerance performance of the d joint is:

$$C_d=L_d+\psi_d$$

From formula (3.6) and formula (3.10), it can be obtained:

$$0\leq C_{1,2,\cdots,d}\leq\cdots C_d\leq 2$$

Currently, the simplest fault tolerance compensation method is to connect the compensated hinges in series, but this will affect their original topology and reduce their working characteristics. The optimal configuration generated by a specific task can simultaneously meet the higher performance requirements, so the existing configuration cannot be modified while ensuring system reliability [15]. An adaptive control method based on a robotic arm is proposed in this paper. The compensation hinge does not affect the topological structure of each hinge under the closed condition. The designed motion pair accords with the dynamic characteristics of the system. The worst one or two nodes are compensated according to the order of the effect of each node on the fault tolerance of the system, which can significantly improve the fault tolerance of the system.

4. Case analysis. The endpoint of the robotic arm reaches a point in the basic coordinate system (Figure. 4.1a). In this project, the 4-DOF manipulator is first constructed, and then the system's fault tolerance is studied. Its fault tolerance ability is found weak in the whole operation process, the maneuvering degree is only the order of A, and the fault tolerance working area is narrow [16]. It cannot accommodate mission points.

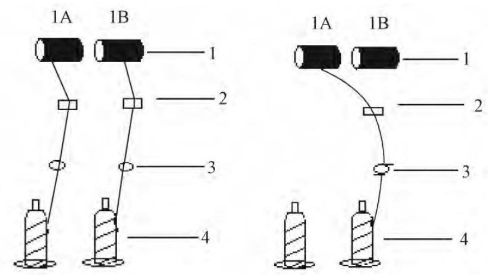

Fig. 4.1: Configuration of the robotic arm.

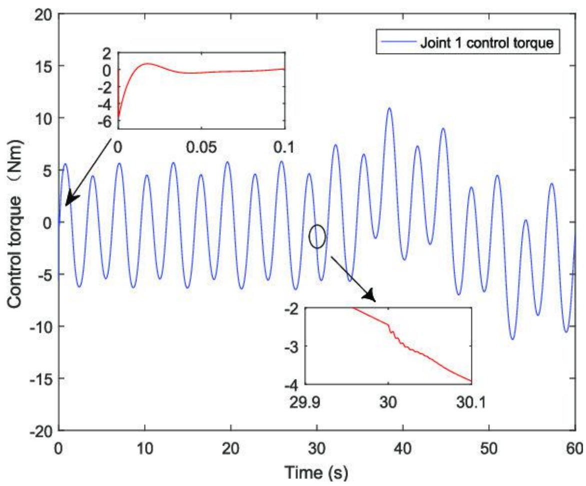

Fig. 4.2: Maneuverability of the fault-tolerant robot configuration.

The robotic arm will lose its function if something goes wrong. According to the effect of the operation on each joint, find out the joints that are easy to fail. Although joint 1 is the lowest joint, its load-bearing capacity and torque in the direction of movement are much smaller than joint 2. Joint 2 has ample working space for the whole robot configuration. So, joint 2 is a failure-prone node. Fault tolerance compensation was applied to the model to construct the robot structure (Figure 4.1b).

The fault-tolerant design of the constructed mechanism is carried out. The fault-tolerant capability and fault-tolerant gap in mechanism configuration were studied. Figure 4.2 shows the configuration maneuverability of the arm during the operation during the 10-second movement. The effectiveness of this method is proved by simulation experiments [17]. The shaded part in Figure 4.3 is the fault-tolerant workspace of mechanism 2 of the fault-tolerant operation. It's not much different from its working space. And its working point is in the fault-tolerant working space.

In this paper, a 5-DOF manipulator configuration is established, in which the configuration of 4 a is the addition of the fault-tolerant compensation joint, and the swing joint 2 is the fault-tolerant compensation joint [18]. In fault-tolerant control, it can reach a certain point in the fault-tolerant space regardless of the state of the end-swing node (figure 4.4). The motion equation of the robot at the target point is established. The compensation node is added. The motion Angle of oscillating node 1 is 154.24° when oscillating node two does not participate in the action. At this time, the moving Angle of oscillating node 3 is 95.12°. At this time, the movement Angle of oscillating joint 1 is substantial, which has exceeded its moving distance, so the robot can not reach the destination [19]. When joint two is moved, the target point is in the flexible working space, which can achieve a particular pose requirement. When the manipulator's end center faces the target vertically,

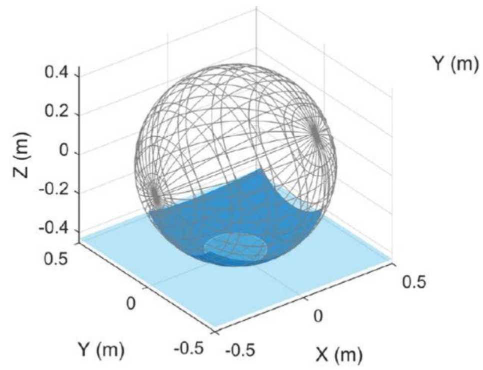

Fig. 4.3: Fault-tolerant workspace of joint 2.

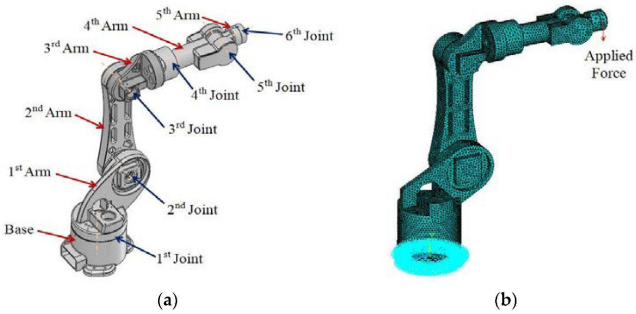

Fig. 4.4: Robot configuration.

the moving angles of the shaking joints 1, 2 and 3 are 51.245°, 64.211° and 67.145°, respectively. At this time, the range of motion of the joints prone to failure is significantly reduced, thus reducing the chance of their failure. The robot arm, which is easy to fail, is simulated, and the fault tolerant control test is carried out. The mechanical arm prone to failure fails when moving to 28, as shown in Figure 4.5. The robot's end can still reach the target point while the other joints continue to move. During this period, the moving Angle of moving node 2 is 51.24°, and the moving Angle of swinging node 3 is 64.35°. The failure occurred when swing node 1 moved to 47.21°. You can see this in Figure 4.6. The robot's end reaches the target point when the moving Angle of swinging node 2 is 44.56 ° and the moving Angle of swinging node 3 is 80.15°.

The test results show that the displacement amplitude of the failed joint and the failure rate of the joint can be reduced effectively by adding the failure compensation joint. A fault-tolerant controller is adapted to enable the robot arm to perform work in the fault-tolerant working space after the failure of the easily failed robot arm.

5. Conclusion. This project studies the reliability of reconfigurable manipulator configuration under operational conditions. The evaluation theory of configurational integration fault-tolerant performance of relative operability and fault-tolerant space is established. The fault tolerance compensation method is given for the joints which are easy to fail. Then, a method to reduce the flexible manipulator's failure times and application range is proposed to improve the fault tolerance of the manipulator configuration. The machine's path is re-planned because of various joint failure phenomena during operation to ensure it can perform the job smoothly. The research results of this project will lay a foundation for the application of aerospace, industrial robots and other fields.

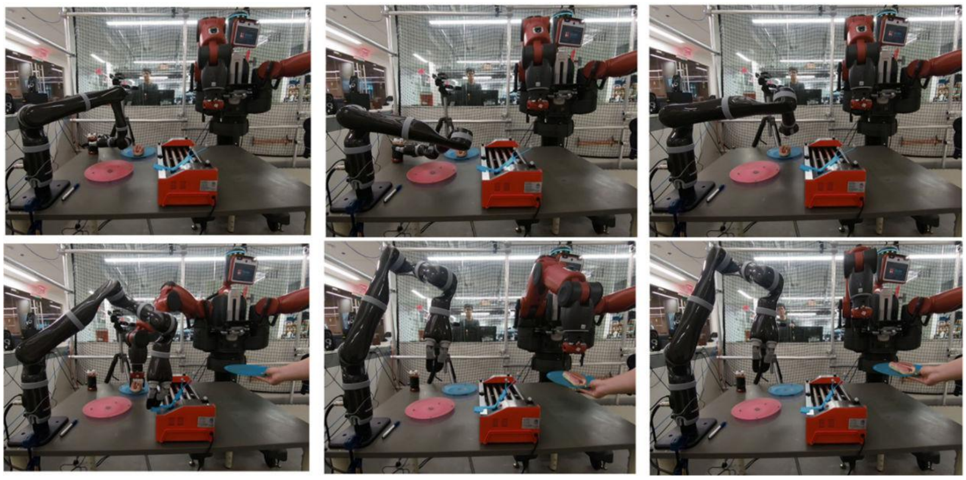

Fig. 4.5: Fault tolerance experiment of mechanical arm 1.

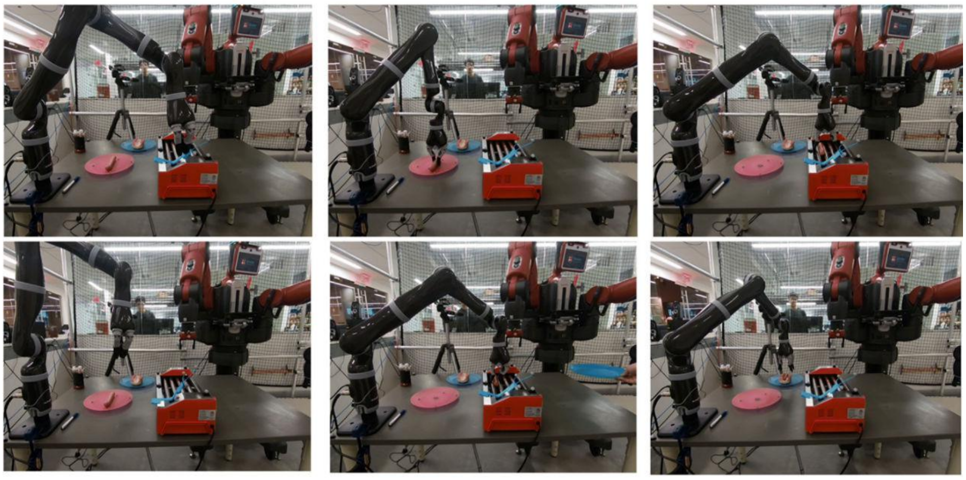

Fig. 4.6: Fault Tolerance Experiment 2.

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