

Research Article

Innovative Design of Replacement Device for Vulnerable Parts in the Nuclear Radiation Environment

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Received 23 August 2018; Revised 26 October 2018; Accepted 31 October 2018; Published 14 November 2018

Academic Editor: Eugenijus Ušpuras

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Vigorously developing nuclear power is the main development direction of current renewable energy. In the nuclear environment, in order to avoid nuclear radiation damage to maintenance personnel and improve the efficiency of nuclear reaction, it is necessary and urgent to realize automatic replacement of vulnerable parts in the electron gun. As the key equipment for the generation and control of nuclear reactions in nuclear reactors, electron guns have been widely used in nuclear power plants of traveling wave reactors. However, the “high-voltage conductive ring” in electron guns is a vulnerable part. It is likely to cause nuclear reactor accidents when the vulnerable part is damaged. Automatic replacement of vulnerable parts is an important part of the entire maintenance equipment. Considering the entire maintenance equipment and the working environment, an innovative design process for vulnerable parts replacement is established. Under the guidance of the process, in order to ensure the continuity of a series of maintenance actions, the technical contradiction resolution theory is first used to conduct the overall analysis of the general direction to obtain the design layout. Then, the contradiction resolution theory and the object-field model analysis are utilized to get and improve the detailed design of the device mechanism. The theory of TRIZ can help us to get the overall mechanical structure design that meets the engineering requirements. The device is designed with a replacement part adjustment scheme to ensure the completion of the maintenance actions. Furthermore, the design provides a solution to the possible jamming phenomenon in the automatic maintenance process and achieves the maximum use efficiency of the storage and replacement of vulnerable parts.

1. Introduction

With the widespread use of nuclear power, nuclear safety has always been the focus of attention [1, 2]. In the nuclear industry, electron guns are the important part of the high-energy electron beam. The electron gun operates in a high-radiation environment in the heat island, and the regular maintenance is required, because the parts of the electron gun are prone to be damaged or aged. At present, the automation of the replacement device for vulnerable parts has not been realized. Therefore, in the process of repairing the electronic gun system and replacing the vulnerable parts, it needs to be completed by professional maintenance personnel. Moreover, there is no suitable storage device for the vulnerable parts. Thus, the small storage amount often causes the replacement work to be stopped, which seriously affects the work efficiency. On the other hand, various high-energy rays generated by nuclear radiation not only cause

nuclear pollution, but also seriously endanger the health of maintenance personnel [3, 4].

The replacement device is mainly used in the fields of drones, CNC machine tools, various industrial robots, etc. At present, there are few reports on the research and application of automatic replacement devices for electron gun vulnerable parts in the nuclear environment. Scientists of foreign countries have already begun to study the robot maintenance in the nuclear environment. In the late 1940s, the scientists in United States developed the first manipulator and later developed the TFTR device maintenance manipulator [5] for specific observation and maintenance operations. The JET team in the UK developed the JET (Joint European Torus) teleoperation robot for maintaining internal components [6]; France CEA LIST team developed AIA (Articulated Inspection Arm) series joint detection robot [7], etc. They are mainly used to deal with radioactive material leakage accidents and replacement of malfunctioning system components [8, 9].

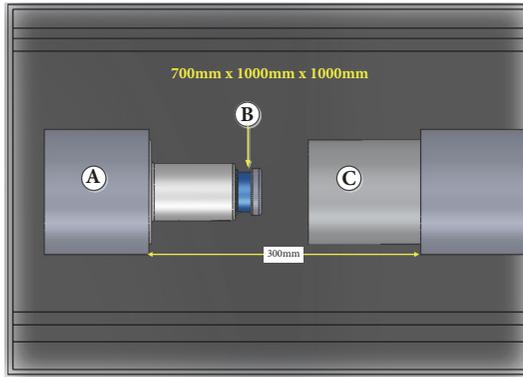


FIGURE 1: The schematic diagram of part replacement.

The main research contents of nuclear robots include robot body structure, sensing detection system, control system, and nuclear protection. The research cycle is long and the cost is enormous. In the nuclear environment, if the device mechanism is complex and placed in a nuclear radiation environment for a long time, the hardware is easily aging, and the difficulty of debugging and maintenance can lead to a sharp increase in costs [10].

In view of the current research status, to improve work efficiency and realize the automation of electron gun maintenance, this paper proposes an innovative design scheme for the automatic replacement device of the electron gun vulnerable parts in the nuclear industry. In order to design the device, the design uses the innovative theory method from the whole to the part, mainly being contradiction resolution theory combined with object-field model.

2. Statement of Problem

2.1. Maintenance Sequence. Before the appearance of the overhaul device design, when the vulnerable parts of the electron gun are damaged, the electron gun cannot be safely withdrawn. After the nuclear reactor stops, the workers enter the hot cell to take out the electron gun, replace the vulnerable parts, and then send it to the hot cell.

After manually transporting the electron gun out of the hot cell, the following maintenance operations (shown in Figure 1) are required in a space of 700 mm in length, 1000 mm in width, and 1000 mm in height. To expose the vulnerable part B, the right end joint C is fixed and the left end joint A is moved 300mm to the left. Then remove and replace the vulnerable part B in the horizontal direction, and restore the connection relationship. This paper will design an automatic replacement device for vulnerable parts to change the present situation of traditional manual work.

2.2. Component Description. There is a part mating between the vulnerable part B and the left end joint A. There are two holes with a diameter of 9mm on the vulnerable part B. The wheelbase of the two holes is 16mm and the error interval is in the range of 0.1mm. When the B is connected to A, the coaxiality between the hole and the shaft is required to

be less than 0.05mm. Inserting or unplugging B requires the axial force about 50 N. In the case of incorrect position, it is prohibited to insert B into A. Part B is in an unpowered state, and only the blue portion can be used for contact installation (see Figure 2).

2.3. Configuration Description. To achieve the whole process, it is necessary for all mechanisms to work together in the replacement device. The part mating has a high requirement in coaxiality. The completion of the maintenance work requires the removal of vulnerable parts, the installation of new parts, etc. In addition, when the small-diameter cylinder is inserted into the cylindrical hole, A may be caught in C due to incorrect entry angle. Thus, the part mating cannot be completed. At the same time, due to the position of the two holes of B, it is necessary to adjust B to the right position before entering. Therefore, during installation process, there must be a mechanism for position adjustment in the device.

At present, replacement devices in other industries are mainly divided into two categories: one type is specially designed to face different working environments, component specifications, and installation requirements, so the structure of these devices is also different and cannot be generalized [11, 12]; the other is a robot-based automatic replacement in a field-specific work environment to achieve work efficiency and reduce harm to the working personnel [13, 14]. In this paper, considering the cost and development cycle of the device, a kind of special replacement device is designed, which is compact, stable, reliable, easy to realize, and easy to maintain. The whole device needs to meet the requirements of automation and large storage of parts, but it also ensures small volume, high reliability, and easy maintenance. There are many contradictions between these requirements. In order to design accurately and quickly, an innovative design method is adopted.

3. Design Flow of Replacement Device Based on TRIZ

The automatic replacement device is a completely new design. It needs to complete a series of maintenance and replacement movements. There are a series of design contradictions that are difficult to break through and solve in the design process. In order to better automate the parts replacement device, it is not enough to refer to the design experience of replacement devices in other industries.

TRIZ (Theory of Inventive Problem Solving) is particularly useful for stimulating the development of new products [15]. It is an effective theory of contradiction resolution and states that the core of the invention problem is to find and resolve contradiction. The device design is a process of contradiction resolution. Contradictions exist in the overall conceptual design of the device design, as well as in the structural design of the detailed scheme. In practical engineering problems, the TRIZ theory can use 39 general technical parameters to describe the majority of the technical contradictions or physical contradictions in the engineering field. In this way, a specific problem is transformed and expressed as a standard TRIZ problem, and the corresponding intermediate

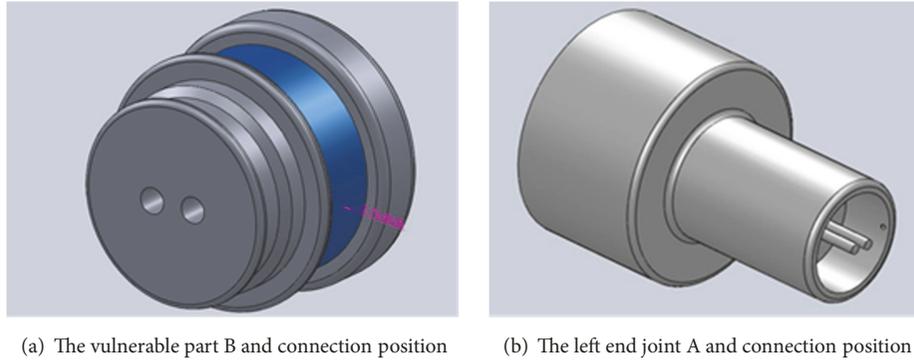


FIGURE 2: Important parts drawing.

tools are used to inquire the classic contradiction matrix. Then the corresponding principle is adopted to solve the problem. The object-field model analysis is an important tool used in problem description and analysis [16, 17]. In order to get the solution of the detailed scheme, the design uses the contradiction resolution theory combined with the object-field model, which can improve the solving speed and the accuracy of the scheme. By relying on the TRIZ theory, the overall layout of the device is first obtained, so that a series of maintenance actions are coordinated and coherent. Then combined with the object-field model, the device is designed and implemented in detail. Based on the theoretical research of the research group, the flow of the innovative design is established for the vulnerable parts replacement device, and shown in Figure 3 [18, 19].

Analyze the problems faced by the design of the automatic replacement device for vulnerable parts, define the design requirements, and get the innovation problem; use the technology contradiction resolution theory to analyze the device as a whole and get the conceptual scheme; use the contradiction resolution theory and the object-field model to solve the structural design plan for each mechanism, and get the detailed scheme; obtain the institutional design scheme and combine the designer's experience to judge the feasibility; if not feasible, improve the scheme; obtain the overall design layout of the organization and evaluate it.

4. Problem Solving

4.1. Innovation Issues. Analyze design issues and define design requirements. For the overall device, the following should be achieved:

(1) The automation of the device is mainly achieved by mechanical design. We must also consider reducing the complexity of the design and maximizing the reliability of the device.

(2) Improve time loss in operating time. Time loss is mainly caused by factors such as structural design, which can be improved by ensuring the consistency of maintenance actions.

(3) Increase the amount of storage for spare parts and vulnerable parts. The increase in storage volume can easily lead to a larger space occupied by the device.

Design a set of automatic replacement device to complete the replacement of vulnerable parts. According to the above requirements, the device requires a compact structure, a small space occupied by the device, and low complexity.

4.2. Conceptual Scheme: Overall Analysis of the Device. Generate a conceptual scheme. The technical contradiction resolution theory is used to analyze actual engineering problems and get the solution of conceptual scheme.

The first step is to define technical contradictions. Analyzing the device as a whole, aiming at problems (1), (2), and (3), the contradictions are as follows.

In problem (1), the automation of the entire replacement process requires a certain number of power components, control components, actuator components, etc. Such components are extremely vulnerable to damage under nuclear radiation. Therefore, if automation requires too many components to achieve, it will become more difficult to maintain and monitor the control system, which will increase the complexity of the entire device. The more automated the device, the more complex it is. Obviously, it constitutes a contradiction between 38-the degree of automation and 36-the complexity of system.

In problem (2), in the various steps of transporting the electron gun, such as repairing the electron gun, taking out the vulnerable part, and replacing it, the improper cooperation will lead to excessive time loss of these processes. Therefore, in order to shorten the connection time between each step and improve the consistency of maintenance actions, the entire device design needs to be compact. However, if the steps of the entire device are designed to be excessively compact, then the running time and the connecting time of each step are too short; it will affect the accuracy of the action and reduce the reliability of the device. It constitutes a contradiction between 25-time loss and 27-reliability.

In problem (3), in the process of automating, the spare parts need to have a certain amount of foundation; otherwise they need to be manually supplemented at any time, and the vulnerable parts also need to be stored after being replaced. However, the entire maintenance room is small in size, so there is no excess area to accommodate the storage of these parts. At the same time, to facilitate access, the storage of parts needs to be orderly arranged in a row. The more storage,

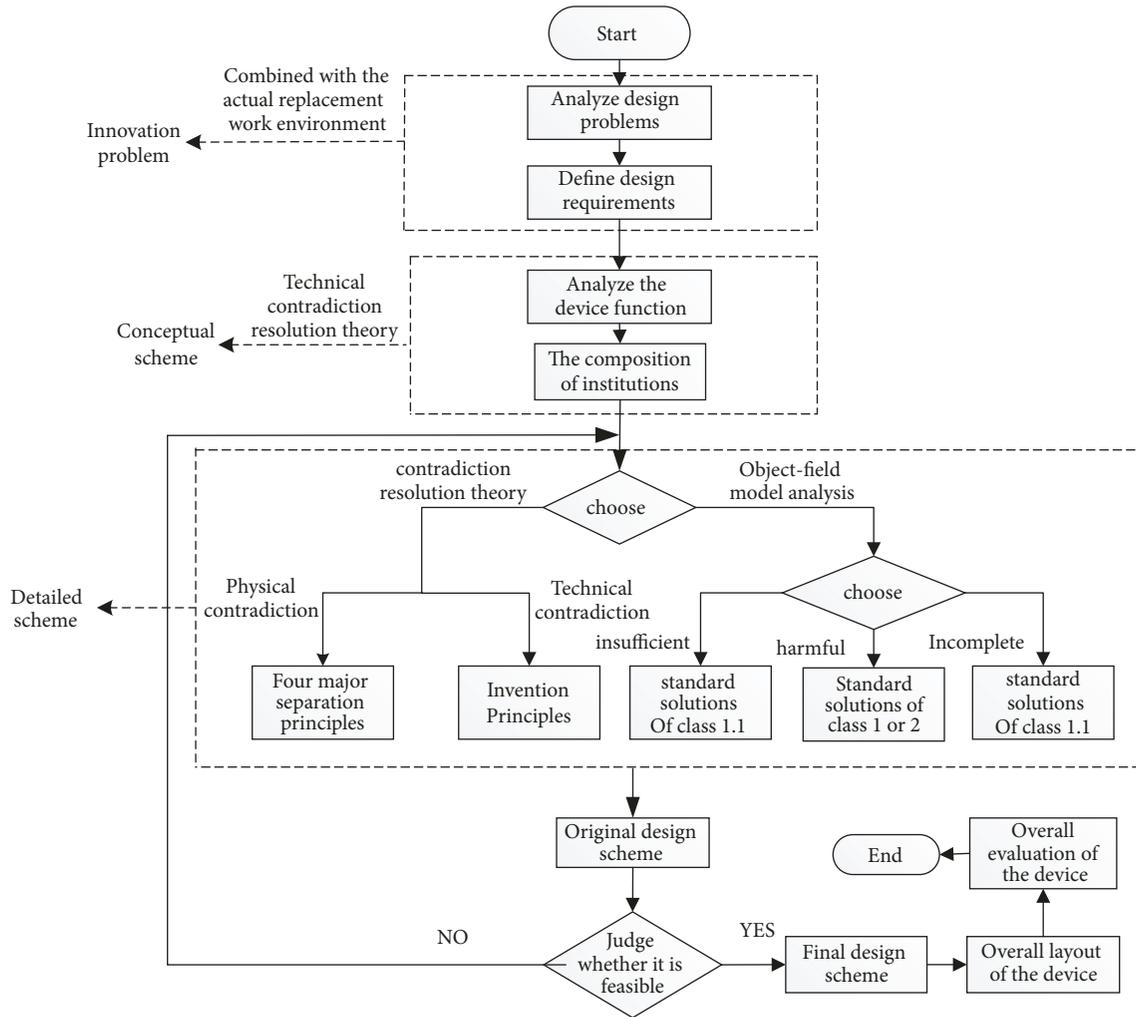


FIGURE 3: Design flow chart.

TABLE I: The resolution of technical contradiction.

Improvement parameters	Deterioration parameter	Contradiction type	Principle of invention
38-degree of automation	36- complexity of system	Technical contradiction	15 24 10
25-Time loss	27-reliability	Technical contradiction	10 30 4
4-Length of stationary object	6-Area of stationary object	Technical contradiction	17 7 10 40

the longer the length of the arrangement, the larger the area required. It constitutes a contradiction between the 4-length of stationary object and 6-the area of stationary object.

The second step is to query the contradiction matrix. The invention principles for solving the contradiction in problem (1) are 15 dynamic characteristic, 24 with mediation, and 10 pre-action; the invention principles for solving the contradiction in problem (2) are 10 pre-action, 30 flexibility shell, and thin film, etc.; the invention principles for solving the contradiction in problem (3) are 17 spatial dimension change, 10 pre-action, etc. Refer to Table 1.

The third step is to apply the principle of invention. Combining the actual problems with the working environment of the device, the interaction is considered between the three

contradictions, and the invention principles 17, 15, and 10 are applied after comprehensive thinking. The specific solutions for the three contradictions are as follows.

①According to the invention principle 17 spatial dimension change, that the reverse surface of a given surface can be utilized, the solution is obtained. In order to reduce the footprint of the device, the surface of the given device can be used. The new and old parts can be suspended from the inner box top of the accommodating box by the mechanism, thereby reducing the volume of the device. And increase the capacity of the parts.

②According to the invention principle 10 pre-action, that the object is repositioned so that it can function at the most convenient position without wasting the transportation time,

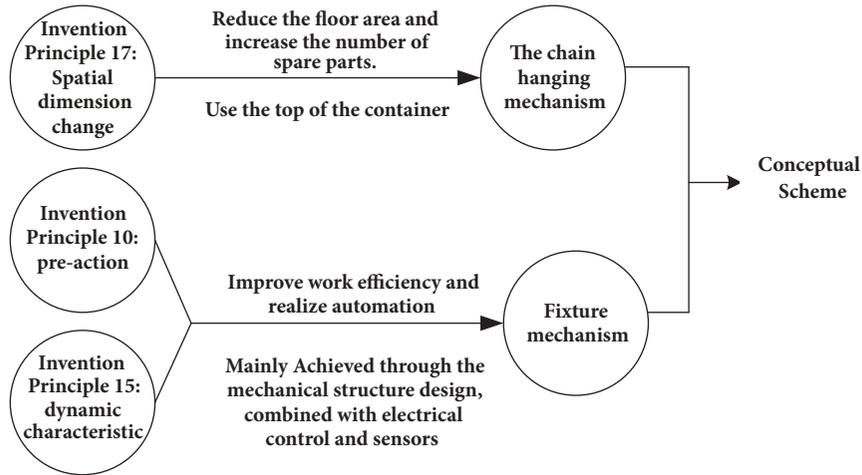


FIGURE 4: Concept scheme generation diagram.

the solution is obtained. The transport trolley carrying the electron gun will run through the track to a specified position, and in this fixed position, the repair of the electron gun and the replacement of the vulnerable parts are completed.

③According to the invention principle 15 dynamic characteristic, that an object as a whole is stationary and partly moving or movable, the solution is obtained. When the transport trolley stops at the designated position, the mechanism adjusts the designated vacancy for storing the vulnerable parts to the correct position, and simultaneously the fixture designed in a fixed position disassembles the vulnerable parts on the trolley parked at the designated position. Then the mechanism transports the spare parts to the designated position and the fixture assembly mechanism installs the new parts. The entire process is fixed and repeated, which can reduce the complexity of the entire device.

The overall conceptual scheme is as follows: the mechanism for transporting the vulnerable and spare parts adopts the chain transport device, that is, the chain hanging mechanism; the mechanism for completing the replacement of the vulnerable parts is the fixture mechanism (see Figure 4).

4.3. Detailed Scheme: Specific Design of Each Mechanism

4.3.1. The Design of Chain Hanging Mechanism. The generation of the detailed scheme: the function of the chain hanging mechanism is the storage of the new workpiece and the replaced workpiece. The mechanism mainly includes the plane chain and the workpiece clamping mechanism. The chain is used to complete the transportation of the parts, and according to the working environment, the chain is designed on the top of the inner box of the accommodating box. The movement mode adopts the chain transmission mechanism in the plane layout. The power output end is connected to the workpiece clamping assembly and drives them to perform a circular motion on the designed track for the replacement; then the storage of new and spare parts can be realized. By determining the specific movement of the chain nodes in each replacement, the initial position for

replacement is exactly determined. In the initial state, there is only one vacant position in the chain mechanism, and the rest are the locations where new parts are stored. The vacant position is reserved for the first replaced vulnerable part. The workpiece clamping mechanism is pressed by the spring element. The pressing method is to adopt axial pressing of the end surface, which can provide an accurate initial position for the entire mechanism and reduce the burden for the subsequent adjustment (see Figure 5).

Judge whether the analysis plan is feasible. The mechanism is simple and reliable in design, easy to implement, and highly feasible. In the initial state, the storage area of the mechanism has only one empty position, and the rest are all spare parts that wait for replacement. It can ensure the storage capacity, and the maximum utilization principle of the entire storage area is guaranteed.

4.3.2. The Design of Fixture Mechanism. The design of the fixture mechanism is obtained based on the object-field model analysis and the physical contradiction resolution theory. The main steps are as follows: (1) identify the component and construct the object-field model; (2) judge the type of the model and find its general solution; (3) aiming at the problems in practical application, contradiction resolution theory is applied to find the solution quickly.

To analyze the functions to be realized by the fixture, an existing function must be composed of three elements; that is, any complete system function can be represented by a complete object field model. At present, the objects are the vulnerable part and a fixture to be designed, which is an incomplete object field model. So the next thing we have to do is to determine the field and determine the design of the fixture mechanism based on the choice of field.

The preliminary object-field model for establishing the fixture mechanism is shown in Figure 6.

According to the function to be realized, the electric field and the magnetic field are excluded, so the mechanical field is selected. According to the preliminary problem analysis, the clamping part has insufficient and harmful effects on

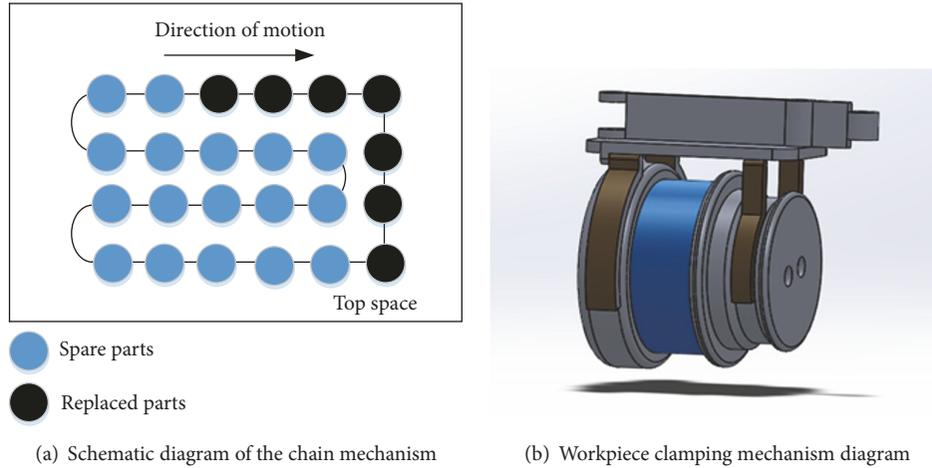


FIGURE 5: Schematic diagram of the chain hanging mechanism.

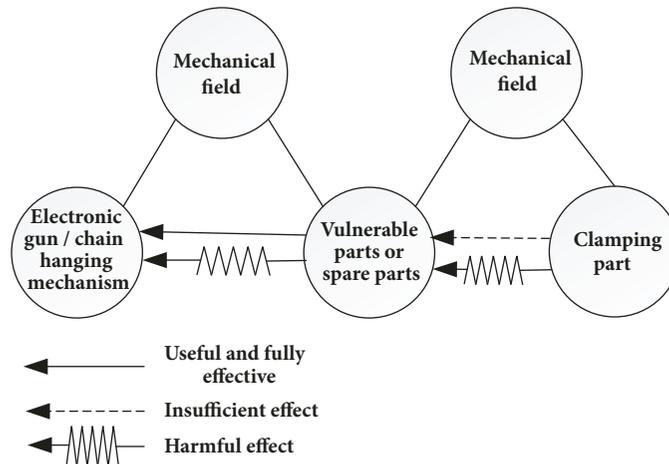


FIGURE 6: Preliminary analysis of the object-field model.

the vulnerable parts at the same time. Among them, the insufficient effect means that the clamping part does not guarantee the fixing of the part; the harmful effect means that if the angular position of the spare vulnerable part is deviated, it may lead to erroneous installation. At the same time, since a certain force is required for the installation, the harmful effect is that the workpiece is damaged due to inaccurate positioning and forced installation. At the same time, the spare vulnerable parts will also have a harmful effect on the electron gun or chain hanging mechanism.

The harmful effect, produced when the spare vulnerable part is installed in the electronic gun or the chain hanging mechanism, can be eliminated by adding a new substance. The new substance is to introduce a detection feedback element to interrupt the work in time and make an emergency response in the event of harmful effect.

Analyze the insufficient effect and harmful effect that the clamping part has on the vulnerable parts. When ensuring the fixing of the parts, the parts should be adjusted to the correct angle range before they are installed. What is more, it needs

TABLE 2: Correspondence between separation principle and invention principle.

Principle of separation	Principle of invention
Spatial separation	1,2,3,4,7,13,17,24,26,30
Time separation	9,10,11,15,16,18,19,20,21,29,34,37
Overall and partial separation	12,28,31,32,35,36,38,39,40
Conditional separation	1,5,6,7,8,13,14,22,23,25,27,33,35

to ensure that the installation can be completed successfully. Therefore, the fixture mechanism to be designed requires both the fixing of the parts and the angular adjustment of the parts, which is a physical contradiction. And when there is a stuck phenomenon, it is required to have countermeasures. Refer to Table 2.

Get the specific steps as shown in Figure 7.

In the process of disassembling and installing, it is necessary to keep the parts fixed. However, when the clamping angle of the parts is not correct, it needs to be adjusted,

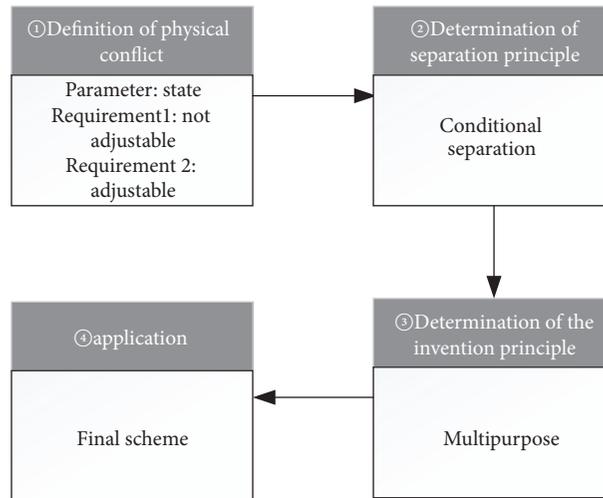


FIGURE 7: Separation principle solution process.

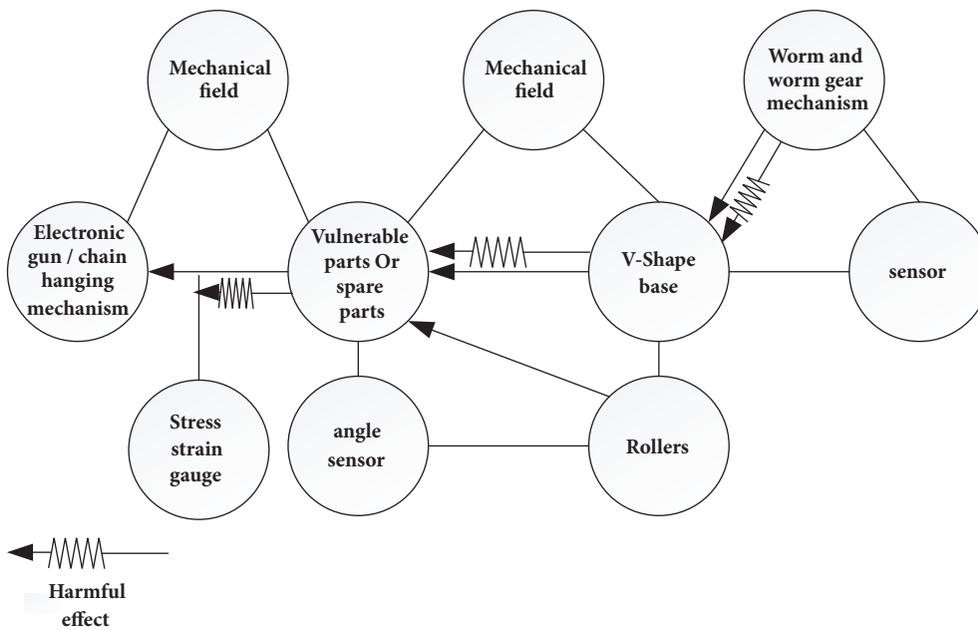


FIGURE 8: The original project object-field model diagram.

so the principle of conditional separation is adopted. The principle of conditional separation is to separate the two parties under different conditions to reduce the difficulty of solving the problem. Through the principle of conditional separation, inquire the corresponding invention principle and get the solution. Then, the design concept is that a device can be added to the initial clamping part for improvement, so that parts can be fixed and adjusted in different situations.

The object-field model corresponding to the original scheme is shown in Figure 8.

Analyze feasibility and improve. The fixing of the components mainly depends on the clamping force. The angle adjustment before installation depends on the friction of

the rollers on the parts. The friction force can change the direction of the friction by changing the relative motion state; when the parts are stuck during the installation process, the rollers produce vibration on the parts, so as to change the angle of the part entry and realize the complete entry and the connection. In order to prevent the damage of the workpiece due to inaccurate positioning, the stress strain gauge is placed on the horizontal linear track below the rear and the front pillars, to detect the horizontal pushing force for real-time overload protection. At the same time, the triangular non-contact laser displacement sensor is used to detect the angle of the part. To ensure that the position of the vulnerable parts is optimal, the small range adjustment of angle is controlled by controlling the steering of the two rollers. The design shown

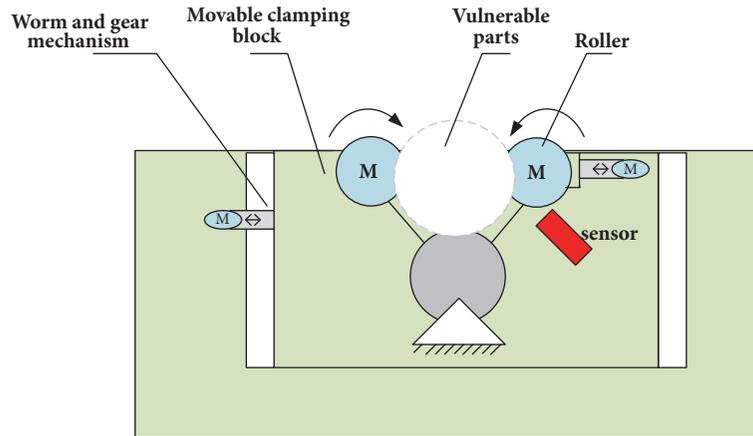


FIGURE 9: Initial plan schematic.

in Figure 9 was obtained: a rolling clamping wheel was added to the clamping portion as shown.

The main function of the fixture is to enable clamping and adjustment of the workpiece. The clamping of the workpiece is carried out by the worm and gear mechanism on the right side, and the worm and gear mechanism on the left side is used to adjust the horizontal position of the workpiece. The different rotation modes of the two tensioning small wheels can realize the rotation adjustment of the position and ensure the installation precision.

The original solution basically achieved the functions required for the fixture. However, the entire device requires multiple feedback mechanisms to drive the four motors in the diagram, so the efficiency is low. The worm and gear clamping method inevitably uses components such as sensors, which are easily damaged in the nuclear environment, and the control part is difficult to design. Therefore, the overall device should be designed with mechanical structure and reduce the use of sensors as much as possible. Considering the safety and economy of the device, the stainless steel material and protective cover with strong radiation resistance are adopted in the structural design. The other components are made of composite materials with more hydrogen content; the mechanical structure design and the strong electric control technology are adopted. All of this is done to achieve the function of the device and resist radiation.

In view of the above problems, the contradiction between system complexity and detection accuracy is formed. The contradiction resolution theory and the contradiction matrix [20] are used to query the invention principle 35 (changing the flexibility of the system), and the S1.2.2 is introduced, to introduce the improved S1 or (and) S2 to eliminate harmful effects. The worm and gear mechanism is changed to a spring clamping mechanism with a certain elastic coefficient, and the V-shaped base is divided into two parts for clamping. The object-field model is improved (only the improvement is shown) (see Figure 10).

The working schematic of the final innovation is as in Figure 11.

Compared with the original scheme, the spring clamping mechanism replaces the worm and gear clamping

mechanism. When the vulnerable part enters the holding part, the clamping block clamps the component by movement. The spring has a certain elastic coefficient, so the variable displacement is within the controllable range and its accuracy is guaranteed. Initially, the fixture uses four motors in clamping and adjustment, which requires more sensors and feedback mechanism support. After the worm and gear clamping mechanism is replaced by a spring clamping mechanism, the complexity of the device is reduced under the premise of ensuring accuracy.

4.4. Operation Description. Describe how the various agencies work together to complete the entire workflow and evaluate it. The entire vulnerable replacement device mainly includes a transfer trolley, the track of trolley, an electron gun maintenance device, a fixture mechanism, a chain hanging mechanism, a vulnerable part replacement base, etc. The schematic diagram and model diagram of the arrangement of the whole organization are, respectively, shown in Figures 12 and 13.

The implementation process is as follows.

(1) The electron gun repairing device equipped with vulnerable parts moves to the inside of the equipment through a horizontal linear track, and the fixture moves along a vertical linear track; then the vulnerable part is clamped and pulled out horizontally along the horizontal direction.

(2) After the fixture pulls out the vulnerable part, it moves back to the upper block through the vertical linear track. At this time, the chain hanging mechanism has adjusted the vacant position to the top of the fixture; when the fixture reaches the upper block, the vulnerable part removed from the electronic gun can be loaded into the workpiece in the vacant position of the chain hanging mechanism.

(3) After the vulnerable part is installed, the fixtures are loosened, the outer chain hanging motor of the chain hanging mechanism is started, and the chain hanging mechanism is driven to perform the surrounding motion. At this time, the chain hanging mechanism transports a new spare workpiece. The fixture then takes the spare part out and the vertical straight track begins to move slowly downwards, controlling the steering of the two rolling clamping wheels in real time,

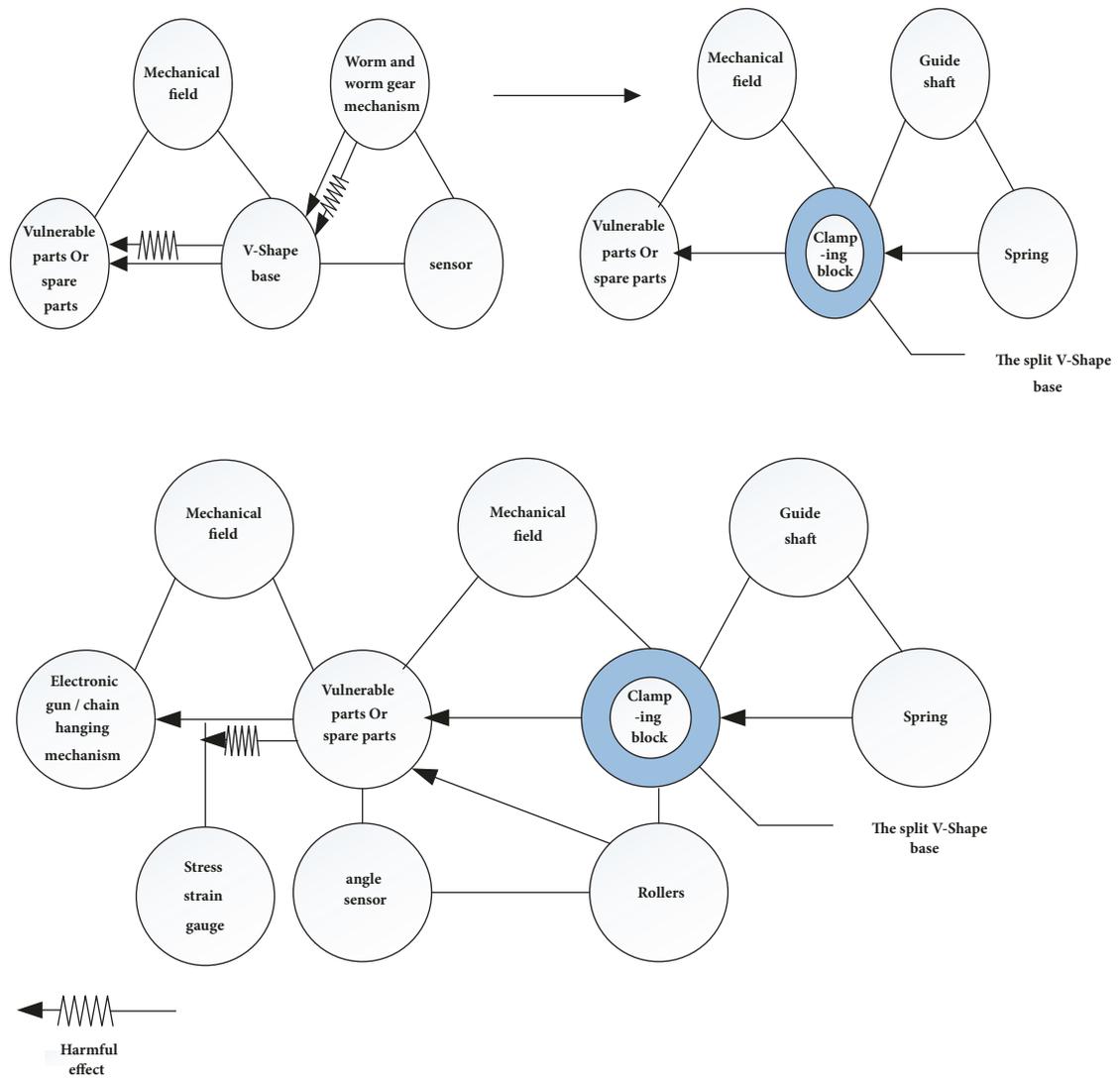


FIGURE 10: Improvement of the final object field model.

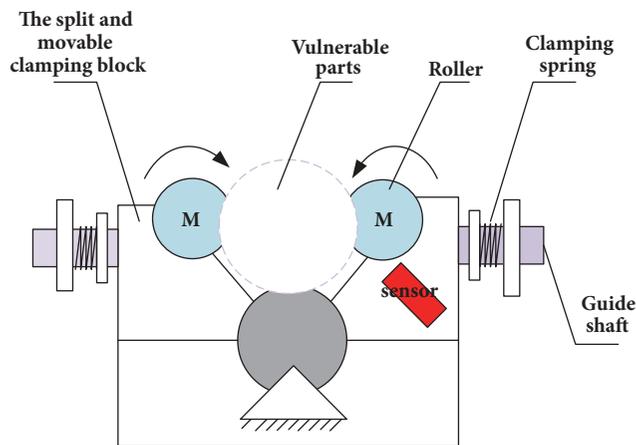


FIGURE 11: The final schematic diagram of the final scheme.

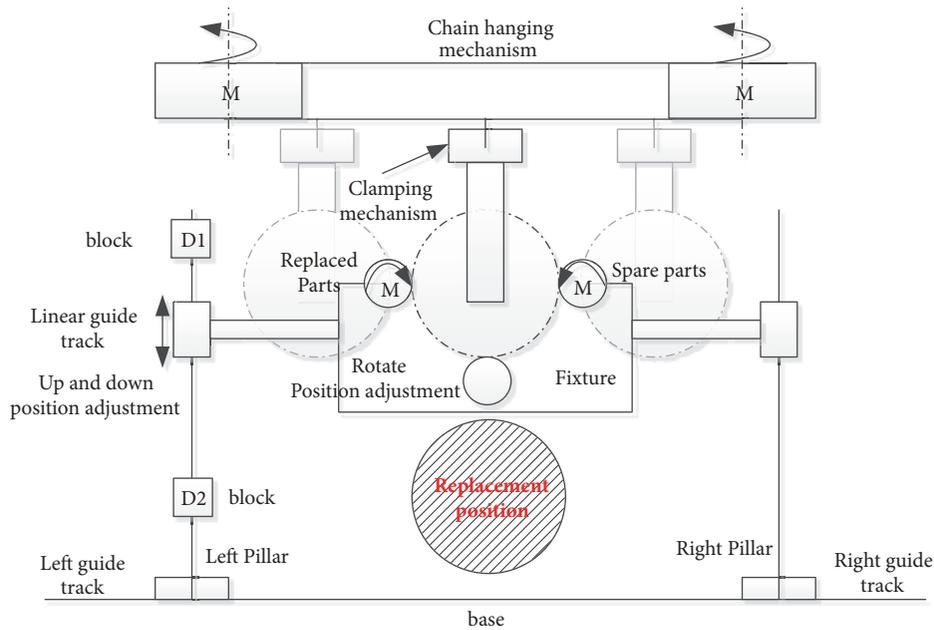


FIGURE 12: A schematic diagram of replacement device for vulnerable parts.

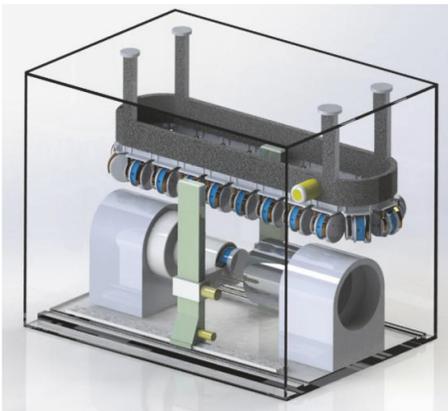


FIGURE 13: 3D model diagram.

thereby adjusting the spare part's angle to a suitable position for installation. After the fixture is moved to the position of the lower block, the spare part can be reinserted into the electron gun in the direction of the horizontal straight track. If a stuck phenomenon occurs, the part will be shaken by the rollers to change the angle of its entry so that it can enter successfully. It enters, and then the fixture continues to move up a certain distance vertically, waiting for the next command to replace the vulnerable parts. The electron gun repairing device is reclosed and exits the replacement device in the horizontal direction.

Combined with engineering design experience and existing resources, the above scheme is further supplemented and optimized, and the final innovative design scheme is obtained. The structure design satisfies the working efficiency, has the advantages of simple structure, small volume, high

precision, stability, and reliability, and can effectively replace the work of professional maintenance personnel.

5. Conclusion

In order to replace the manual replacement work and improve the efficiency of nuclear reactors, this paper proposes a design of automatic replacement device for vulnerable parts in the nuclear environment. Combining the design of the entire overhaul equipment with the working environment of vulnerable replacement, an innovative design flow method for the device is obtained. The contradiction resolution theory and the object-field model are combined and implemented overall to detail design of the device. And the innovative method can assist designers to integrate design resource information and provide design ideas. The design idea of the device is innovation problem-conceptual scheme-detailed scheme. Then, the structural design schemes of the various mechanisms of the replacement device are obtained. In addition, the targeted improvement of the fixture mechanism is described. Finally, the collaborative work process of each mechanism is elaborated. The feasibility of the vulnerable replacement device effectively improves the operating efficiency of the overall maintenance device and the safety of the nuclear reactor.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation, China (Grant Nos. 51435011) and Sichuan Province Science Technology Support Program (Grant Nos. 2018GZ0064, 2018GZ0019).

References

- [1] D. Butler, "Nuclear safety: reactors, residents and risk," *Nature*, vol. 472, no. 7344, pp. 400-401, 2011.
- [2] J Ferreri, A. Clausse, J. P. Ordóñez et al., "Nuclear Activities in Argentina," *Science & Technology of Nuclear Installations*, vol. 2011, no. 1, pp. 1-2, 2011.
- [3] X. Dong, "The design of basement rebuilding into radial shielded room," *Journal of Shandong Institute of Architecture & Engineering*, 2001.
- [4] D. He, F. Dong, Y. Deng et al., "Study on Composite Wall Surface Putty with Anti-Radon and Anti-Radioactivity Properties," *Chemical Industry & Engineering Progress*, vol. 24, no. 8, pp. 930-934, 2005.
- [5] D. Kungl, D. Loesser, P. Heitzenroeder, M. Selig, G. Boehme, and G. Cerdan, "The TFTR maintenance manipulator," *Fusion Engineering and Design*, vol. 10, no. 89, pp. 273-279, 1989.
- [6] O. David, A. B. Loving, J. D. Palmer et al., "Operational experience feedback in JET Remote Handling," *Fusion Engineering & Design*, vol. 75-79, no. 11, pp. 519-523, 2005.
- [7] R. E. Shuff, "Development of remote handling pipe jointing tools for ITER," *Tampereen teknillinen yliopisto - Tampere University of Technology*, 2012.
- [8] R. O. Buckingham and A. C. Graham, "Dexterous manipulators for nuclear inspection and maintenance—case study," in *Proceedings of the 1st International Conference on Applied Robotics for the Power Industry (CARPI '10)*, pp. 1-6, IEEE, 2010.
- [9] A. Kitamura, T. Namekawa, K. Hiramatsu, and Y. Sankai, "Operating manipulator arm by robot suit hal for remote in-cell equipment maintenance," *Nuclear Technology*, vol. 184, no. 3, pp. 310-319, 2013.
- [10] E. Popova, W. Yu, E. Kee, A. Sun, D. Richards, and R. Grantom, "Basic factors to forecast maintenance cost and failure processes for nuclear power plants," *Nuclear Engineering and Design*, vol. 236, no. 14-16, pp. 1641-1647, 2006.
- [11] H. Kubo, Y. Kamanaka, G. Sato et al., "Automatic tool-replacement apparatus," EP, US5079828, 1992.
- [12] K. A. Suzuki, P. K. Filho, and J. R. Morrison, *Automatic Battery Replacement System for UAVs: Analysis and Design*, Kluwer Academic Publishers, 2012.
- [13] S. Shi, Y. Song, Y. Cheng et al., "Conceptual design main progress of EAST Articulated Maintenance Arm (EAMA) system," *Fusion Engineering & Design*, vol. 104, pp. 40-45, 2016.
- [14] G. S. Vasilash, "Automation replacement: robots," *Automotive Design & Production*, vol. 4, pp. 52-53, 2008.
- [15] Y.-J. Wan, Y. Li, W.-Q. Li, Y. Xiong, and X.-Q. Yan, "Strategy and realization for integrated product innovation design based on cognitive multi-method," *Computer Integrated Manufacturing Systems*, vol. 20, no. 6, pp. 1267-1275, 2014.
- [16] I. L. Yan and L. I. Wen-Qiang, *Method to Creative Design*, Science Press, Beijing, China, 2012.
- [17] I. M. Ilevbare, D. Probert, and R. Phaal, "A review of TRIZ, and its benefits and challenges in practice," *Technovation*, vol. 33, no. 2-3, pp. 30-37, 2013.
- [18] K. Zhang, W. Zhao, J. Wang, L. Chen, C. Wang, and X. Guo, "Research on knowledge support technology for product innovation design based on quality function knowledge deployment," *Advances in Mechanical Engineering*, vol. 8, no. 6, 2016.
- [19] X. Guo, J. Wang, W. Zhao, K. Zhang, and C. Wang, "Study of medical device innovation design strategy based on demand analysis and process case base," *Multimedia Tools and Applications*, vol. 75, no. 22, pp. 14351-14365, 2016.
- [20] W. Xia, K. Wang, Y. Li, and Y. Xiong, "Innovative Design for Adaptive Detection Module of In-pipe Robot Based on TRIZ," *Journal of Mechanical Engineering*, vol. 52, no. 5, pp. 58-67, 2016.

