Mechanical Safety Risk Analysis of Smart Factory

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Abstract: In view of the mechanical safety risks of industrial robots, AGVs and other mobile devices that are widely used in smart factories, a mechanical safety risk analysis of smart factories method is carried out. First, it analyzes the mechanical safety risks of CNC machine tools, industrial robots, AGVs, and warehouses in smart factories. Then, a specific seal production workshop is taken as an example. It conducts a mechanical safety risk analysis and gives a safety plan to reduce the risk. The mechanical safety of the personalized seal workshop has achieved sufficient risk reduction. This article can provide a certain reference for conducting mechanical safety risk analysis during the construction of smart factories.

1. Introduction

With the integration and innovation of a new generation of information technology and advanced manufacturing technology, a new round of industrial revolution represented by intelligent manufacturing has emerged in the world, and intelligent manufacturing is causing tremendous changes in the manufacturing industry. Smart factory is the carrier to realize smart manufacturing. Compared with existing factories, smart factory pays more attention to the automation and flexibility of product manufacturing. It uses a large number of mobile devices such as industrial robots and AGVs. The use of these mobile devices brings new mechanical safety risk. For example, in June 2015, when workers in the Volkswagen factory in Germany were installing and debugging the robot, the robot suddenly "shot" and hit the worker's chest and crushed it on the metal plate, causing the worker to die on the spot; in August, an industrial robot accidentally started on an assembly line of an American auto parts manufacturer and assembled the parts on the head of a maintenance technician, causing his skull to be crushed and killed on the spot [¹]. These events all warn us that smart factories need more stringent safety requirements to match them to ensure their healthy development.

2. Mechanical Safety of Smart Factory

Equipment is the basis for realizing smart factories. Smart factory equipment can be roughly divided into three types: production equipment, production facilities, and auxiliary equipment. Production equipment refers to equipment directly involved in the production process. Common production equipment mainly includes CNC machine tools, 3D printing equipment, special equipment and so on. Production facilities refer to machines or devices used to serve or support the work of production equipment, including warehouses, industrial robots, and AGVs. Auxiliary equipment refers to the general name of equipment or devices in the workshop except production equipment and production facilities. This kind of equipment does not participate in the processing process directly, but serves the production process. Such as three coordinate measuring machine, spectrometer. Whether it is an industrial robot, an AGV, or a complete set of logistics and warehousing facilities, they are all typical digital equipment with specific functions. Most of them are a combination of information technology,
computer technology, intelligent sensor technology, intelligent analysis technology and other innovations. The complexity goes without saying, the uncertainty also increases, and the security issues become more prominent.

The safety of smart factories includes functional safety, physical safety, and information safety. Physical safety is to reduce the damage caused by mechanical safety, fire, chemical hazards and other factors [2]. Among them, mechanical safety is the most likely risk in all dangerous states. Mechanical safety refers to the ability of a machine to perform its intended functions without causing damage to the human body or endangering health when the risk is sufficiently reduced during its life cycle. Mechanical safety risks in smart factories are mainly caused by direct contact with the human body when production equipment (such as CNC machine tools) and production facilities (such as industrial robots, AGVs) are running. It may cause extrusion, collision, impact, shearing, entanglement, twisting, Throwing, cutting, cutting, puncturing and other consequences.

Safety tasks often start with risk analysis. How to identify and analyze mechanical safety hazards in smart factories has become the first problem to be solved. The purpose of risk analysis is to identify hazards and estimate hazards. Risk analysis provides the information needed for risk evaluation, and ultimately determines whether risks need to be reduced.

3. Mechanical Safety Risk Analysis of Smart Factory

Conduct risk analysis on CNC machine tools, industrial robots, AGVs, and warehouses that are prone to mechanical safety risks in smart factories. Risk analysis mainly includes the determination of various limits of the machine, hazard identification and risk estimation process, the core of which is risk estimation.

3.1 Machine Limit Determination

The determination of machine restrictions includes use restrictions, space restrictions, time restrictions and other restrictions [3]. Among them, use restriction refers to the purpose and scope of use of the machine; space restriction refers to the space required for installation, disassembly, repair, and maintenance of the machine; time restriction refers to the service life of the machine. For example, when identifying the danger of industrial robots, use restrictions include the operation of industrial robots in different operating modes, and the operation of equipment by operators of different levels; space restrictions mainly consider the operating range of industrial robots, human-computer interaction methods and space requirements; The time limit mainly considers the life limit of certain components or parts in the use of industrial robots; other restrictions are factors that may have a greater impact on safety in addition to the above restrictions, such as the use environment of industrial robots.

3.2 Hazard Identification

After determining the machine limits, it is necessary to systematically identify foreseeable hazards, dangerous situations, etc. Document [3] Appendix B gives detailed hazard sources and possible results. For different types of machinery, it is necessary to refer to the relevant standards of the machinery at the same time.

3.2.1 CNC Machine Tools

CNC machine tools are important production equipment in smart factories and have certain advantages in the processing of complex, precise, small batch, and multi-variety parts. The mechanical safety hazards of CNC machine tools mainly include extrusion, cutting and winding [4]. The main mechanical safety risk analysis of CNC machine tools is shown in Table 1.

| Hazard Type     | Hazard Description | Risk Level | Measures to be Taken                      |
|-----------------|--------------------|------------|------------------------------------------|
| Danger of       | The distance       | High Risk  | 1. Set up a protective door with interlocking |
3.2.2 Industrial Robot

An industrial robot is a multi-joint manipulator or a multi-degree-of-freedom machine device oriented to the industrial field. It can realize various functions based on its own power and control capabilities according to pre-designed instructions. The mechanical safety hazards of industrial robots mainly include extrusion, collision \(^5\). The main mechanical safety risk analysis of industrial robots is shown in Table 2.

### Table 2   Mechanical safety risk analysis of industrial robots and measures to be taken

| Hazard Type | Hazard Description | Risk Level | Measures to be Taken |
|-------------|--------------------|------------|----------------------|
| Danger of crushing or collision | When a worker stands near the robot arm during teaching, the robot arm hits the operator. | High Risk | 1. In the process of manual teaching, the operating speed is limited, so that personnel may avoid injury, and the low speed causes limited injury to worker |
| Cutting hazard | Injuries caused by people coming into contact with stationary, moving sharp tools or burrs of machined parts. | High Risk | 1. Set up a protective door with interlocking device; 2. After the protective door is opened, each axis of the machine tool can only be kept in motion by manual continuous operation; 3. When the workpiece is rotating or the tool is rotating, it is forbidden to operate with gloves; 4. Machine tool Do not change the handle and perform measurement, adjustment and cleaning work during work; 5. Put down the protective baffle during processing, and do not directly use hands when removing chips. |
| Entanglement danger | Rotating tools, spindles, leadscrews, processed parts, etc. may cause hazards such as twisting hands and getting hair in | High Risk | 1. Set up a protective door with interlocking device; 2. After the protective door is opened, each axis of the machine tool can only be kept in motion by manual continuous operation; 3. The lead screw must be covered by a retractable protective door; 4. Pay attention to the correct use of protective equipment. |
| Danger of injury from flying objects | Unclamped tools and workpieces fly out and hurt people; chips fly out and hurt people | High Risk | 1. Set up a protective door with interlocking device; 2. Monitor the overspeed, steering and stop status of the rotating spindle; 3. Pay attention to the correct use of protective equipment. |
### Danger of crushing or collision

Restart after the interruption of operation. When restarting, it is in automatic mode. The robot arm selects a shorter return path, which may be uncontrolled and cause a collision.

| High Risk | 1. After interrupting the automatic operation of the robot, choose to return to the established path  
2. Reduce the speed of the process of returning to the established path |

### Danger of electric shock

When the maintainer touched the robot, the wires were damaged, which caused the metal parts of the robot to become live, which caused the contact personnel to get an electric shock.

| High Risk | 1. The metal parts of the robot are grounded to avoid electric shock |

### Danger of crushing or collision

When the trapped person was rescued, the rescuer pressed the wrong brake release button, and the falling of the robotic arm caused the trapped person to be more squeezed.

| High Risk | 1. An indication mark is added near the brake release button to let the operator know the function of the button |

### 3.2.3 AGV

AGV refers to a transport vehicle that can travel along a prescribed guidance path through electromagnetic or optical automatic guidance devices, with safety protection and various transfer functions. The mechanical safety hazards of AGV mainly include extrusion, collision [7-8]. The main mechanical safety risk analysis of AGV is shown in Table 3.

| Table 3 AGV machinery safety main risk analysis and measures to be taken |
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| Hazard Type | Hazard Description | Risk Level | Measures to be Taken |
| Danger of crushing or collision | AGV starts abnormally when receiving unplanned signals | High Risk | 1. Safety inspection before operation;  
2. Periodic inspection and maintenance of the robot;  
3. Alarm for abnormal robot behavior;  
4. Emergency stop function of the robot |
| Danger of crushing or collision | Workers strayed into the AGV moving area | High Risk | 1. Photoelectric far avoidance obstacle;  
2. Photoelectric near obstacle avoidance;  
3. Mechanical obstacle avoidance;  
4. Obstacle avoidance indicator;  
5. Emergency stop. |
| Danger of crushing or collision | The operating environment changes beyond the scope of normal work requirements, causing | High Risk | 1. The space layout is far away from or reduces the source of environmental impact; |
operating failures or wrong behaviors

| Hazard of crushing or collision | The safe stopping time is too long and the avoidance is not timely | Medium Risk |
|-------------------------------|---------------------------------------------------------------|-------------|
| Danger of crushing or collision | The safe stopping time is too long and the avoidance is not timely | Medium Risk |
| 2. The operating environment monitoring and early warning | 1. Intrinsically safe design; set enough safety distance; or short enough chain response time |
| | 2. Robot emergency stop |

3.2.4 Warehouse

The warehouse uses high shelves, pallets, elevators, shuttles and other equipment to achieve high-level storage, which improves the space utilization rate. It can realize automatic and efficient access through RFID and other technologies. The mechanical safety hazards of the warehouse mainly include extrusion, collision, and involvement\cite{9-10}. The main mechanical safety risk analysis of the warehouse is shown in Table 4.

Table 4 Analysis of main risks of mechanical safety of warehouses and measures to be taken

| Hazard Type | Hazard Description | Risk Level | Measures to be Taken |
|-------------|--------------------|------------|----------------------|
| Danger of crushing or collision | When the lifting working, If workers accidentally enter in. It may cause extrusion. | High Risk | 1. Install a safety fence; 2. Install a safety gate, cut off the power supply of the regional movement mechanism when personnel enter. |
| Danger of crushing or collision | During the movement of the shuttle, if workers accidentally enter in, it may cause crush injuries | High Risk | 1. Install the safety door system, install the safety door system at the entrance and exit of each storey, when the personnel open the door, cut off the power supply of the shuttle |
| Danger of crushing or collision | In the process of conveying materials on the conveyor belt, if workers accidentally enter in, it may cause collision | High Risk | 1. Install safety grating and shield photoelectric to isolate safe area and non-safe area to prevent people from entering dangerous area. |
| Danger of fall from height | Maintainers are at risk of falling during the maintenance of the warehouse | High Risk | 1. Set fence around the platform; 2. Use non-slip floor on the platform and stairs |

4. Mechanical Safety Risk Analysis Case of Smart Factory

4.1 Introduction to The Production Workshop of Personalized Seal

The layout of a specific seal production workshop is shown in Figure 1. The seal production workshop is mainly composed of PLC, automated warehouse, AGV, CNC lathe, carving machine, loading and unloading robot, assembly robot. The automated warehouse is mainly used for the storage of stamp blanks and finished products; AGV is mainly used for the circulation of materials between stations; loading and unloading robots, CNC lathes, and carving machine are mainly used for loading and unloading and machining; assembly robots are mainly used for the assembly of seals.
4.2 Risk Estimation Method

There are many risk estimation methods, and the risk map method is chosen as the mechanical safety risk estimation method of the personalized seal production line. The risk graph is based on a decision tree, and its schematic diagram is shown in Figure 2. Each node in the graph represents a risk parameter (severity, exposure, probability of occurrence of dangerous events, possibility of avoidance), and each branch of the node represents a level of parameter (for example, mild or severe) [3]. The equipment risk index score (PLR) is multiplied by the scores of the severity (S), exposure (F), probability of occurrence of hazardous events (O), and likelihood of avoidance (A). Which is:

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PLR = S \times F \times O \times A
\]  

(1)

The higher the PLR score, the higher the risk. In this case \( S_{\text{max}} = 4 \), \( F_{\text{max}} = 5 \), \( O_{\text{max}} = 3 \), \( A_{\text{max}} = 3 \), \( PLR_{\text{max}} = 180 \).

Fig. 1 Layout of the seal production workshop

Fig. 2 Risk diagram used for risk estimation

Taking severity (S) as an example, the description of each score is as follows:
Severity (S) is the consequence of the identified danger, S is the severity of possible injury, and the
scores are as follows:
S=1: scratches, which can be cured by ambulance Abrasions or similar injuries;
S=2: Serious scratches, abrasions, stab wounds that require medical care by a professional doctor;
S=3: Injuries that cannot be recovered normally, it is difficult to continue working after healing;
S=4: Unrecoverable, even if it is possible to heal, it is very difficult to continue working after healing.

4.3 Risk Estimation Process
The equipment with mechanical safety risks in the personalized seal production line mainly includes warehouses, mobile AGVs, CNC lathes, engraving machines, loading and unloading robots, and assembly robots. Here take a warehouse as an example to illustrate the risk assessment process, as shown in Table 5.

| Danger point                                   | Picture                  | Danger Zone                     | Type of Danger | Danger description                                                                 | The Initial Risk | Risk level |
|-----------------------------------------------|--------------------------|---------------------------------|----------------|-------------------------------------------------------------------------------------|------------------|------------|
| Work spaces and around machines               |                          | Collision                       |                | During the movement of the shuttle, if workers accidentally enter in, it may cause crush injuries | 96               | Middle     |

| Security Solutions | Risk estimation (initial risk) | Risk reduction recommendations | Risk estimation (after risk reduction) | Whether to continue to reduce the risk |
|--------------------|--------------------------------|---------------------------------|---------------------------------------|--------------------------------------|
| S F G A PLR        | 4 4 2 3 96                    | Install safety light curtains on the periphery of the warehouse, if workers enter in, the warehouse stops working; at the same time, it is equipped with an interlocking device safety door, when the door is opened, the warehouse stops working. | S F G A PLR 2 2 1 1 4 | Not needed |

The risk index scores of other equipment are there: PLR of Moving AGV =54, PLR of numerical control lathe =72, PLR of carving machine =72, PLR of loading and unloading robot =108, PLR of assembly robot =72.

4.4 Security Protection Plan
Safety protection is a method of isolating the dangerous source of the machinery from the operator through fixed, enclosed protection and/or interlocking devices. According to the results of the analysis and estimation, the schematic diagram of the safety protection plan of the personalized seal production line is shown in Figure 3. The specific measures are as follows:

1) Install safety light curtains on the periphery of the warehouse. When workers enter, the warehouse stops working; at the same time, it is equipped with a safety door with interlocking device. When the door is opened, the warehouse stops working.

2) Install a non-contact magnetic induction switch on the door of the CNC lathe to detect the status of the safety door. When the safety door is not closed in place, the CNC lathe cannot start running.
(3) Install a non-contact magnetic induction switch on the safety door of the carving machine to detect the switch status of the safety door. When the safety door is not closed in place, the carving machine cannot start operation.

(4) Install laser scanners at the front and rear of the loading and unloading robot to cover the working area of the robot as a presence detection, and the robot stops working when an object is detected.

(5) Install laser scanners at the front and rear of the assembly robot to cover the working area of the robot as a presence detection, and the robot decelerates when an object is detected.

![Schematic diagram of security protection scheme](Fig.3)

5. Conclusion
The smart factory is the carrier to realize smart manufacturing. The industrial robots, AGV and other mobile devices used in a large number of smart factories have brought new mechanical safety risks. The mechanical safety risks of CNC machine tools, industrial robots, AGVs, and warehouses in smart factories are analyzed. Taking the personalized seal production workshop as an example, the risk map method is used as a risk estimation tool to analyze the existing mechanical safety risks and give a safety plan to reduce the risk. After taking certain safety measures, the mechanical safety of the personalized seal workshop has been achieved by reducing the risk.

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