Human-Robot Interaction. Analyzing the risks in collaborative environment

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October 9, 2018

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Turin, October 9, 2018

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Chapter 1

Introduction

1.1 History

Today we live in the world with the high technology, we cannot live with them, due to the internet connects each one around the world, they not only support us in daily life, but also help us to deal with the tasks when we at work. We can see changes obviously in the condition of work, from the traditional office work to telework in virtual offices or telecommuting. The development not only for the life or work of the person, but also for reduce the workload of the operator.

As for the method to relief the human, the role of the robot is becoming more and more important and not to be ignored. They have a huge potential to help humans in the diverse aspects, from the medical treatment to education, from leisure time to manufacturing. The International Federation of Robotics predicted that until 2020, in the factory, they will have around 1.7 million new robot installations.

International Organization for Standardization (ISO) decide the industrial robot is the “the equipment can be controlled automatically, they are multipurpose manipulator, programmable in three or more axes, they can be fixed in the certain place or mobile depend the function decided in the industrial automation applications.”[1] Industrial robots possess many disadvantages, like high strength, precision and endurance, they are widely used for special operation: welding, assembling, picking, testing, and moving.

The characteristics of robots are mainly divided into four aspects:

Payload: It’s the weight for the robot can carry. For example, the maximum load of the robot always is larger than its defined value. However, in some cases, it may equip with less accurate, the robot may not follow the trajectory set in the program before, or maybe have the excessive deformation due to the force applied. For safety reason, the payload of robots compared to their own weight is usually small.

Reach: it’s the maximum distance of the robot can reach within its work. for the reason of the dexterous, they much can reach the position which we set before in the program or reach with any desired orientation. But we cannot ignore that the error still exist, we called no dexterous point. This is an important aspect must be considered before a robot is selected and installed.

Precision: it's defined the degree of the accurate for a specified point can be reached. This can be evaluated by the actuators and the robot's feedback device(sensors). Due to the research on the internet, most industrial robots have precision in the range of 0.001 inches.

Repeatability: it's defined that the total times on the same position can be reached in the certain time period. It means that, the method that we got the result is taken by the person or the equipment apply the action on the same position in the certain period in the same limit conditions. Since the vibration of the robot or another factors, we cannot make sure that the 100% accuracy of the position, the robot may be not reaching the same position that we set before every time, but they still in the certain area from the desired destination point. This feature is important, unlike the problem of the precision which can be predicted and corrected by the controller. Repeatability is a random error, it only can be specified through running machine a lot of times.

Many years ago, when the robot is initial used, the international robot market has always been the machine which are designed very heavy, expensive and clumsy robots, in order to process the high - duty manufacturing. But exactly, not all industrial processes require large robots in practical applications to extract heavy loads and replace them with lightweight, the robotic arms are increasingly responsible for assembly and lifting. A more flexible robotic arm then becomes a solution to undertake the feasibility of daily work. The simplest and most reasonable solution to automation is use the small, low noisy, low-power robots for industrial enterprises.

Robot have already been used in many industries and for many purposes. They have excelled when they can perform better than humans or at lower costs. For example, a welding robot can weld better than a human welder because the machine can move consistently also the robot don't need the equipment protection, like protective clothing, fans or other facilities the operator needed. As a result, robots will more productive and better suited for the job.

Due to those merits, the robots are extending quickly in the factory, the following is a list of some robotic application:

1: Palletization and De-Palletizing: Between manufacturing and distribution, they have the place to put the parts named palletizing. Many factories still do this task manually, this operation will cause the injuries for the operator due to this work is always repeat many times and, in some cases, the position of the pallet is not ergonomic for picking. The alternative is a palletizing robot. They can be palletized quickly, accurately and repeatably. In this way, they reduce a lot of workload for the operator.

2: Material Handling: Moving material in a factory is the task possess the repeated, easy to get tired and may create the dangerous. Those are the reason why this job is suitable for the robot. As programmable manipulators, if the designer already set the pathway for the robots, they are the ideal equipment perform moving from point A to point B repeatedly without consider the part’s type.

3: Welding: It’s used to weld parts together. Due to their consistent movement, robotic welds are very uniform and accurate.

After the heavy robot improved to the light robot, the role of robot can replace the operator in much situations, however, for some feature of the task, we may not only need just robot to finish, the participate of the operator is also important. So, responding to this demand, "collaborative robots" are born, those type of the robots can work in the defined area, as for the operator, they can perform the operation with the robot at the same times. They can fill the gap between the full manual assembly line and the fully automatic production line.

In the industry, before the born of the robot, the role of the crane in the factory is important, because they also can help operator to finish some important tasks. If you would like to say the function between those two types is similar, we can compare the robot with a crane. It’s can be observed that the feature and also the contexts of work is very similar: Both of them have a number of links attached each by the joints; no matter the joints or the links, they are both moved by some type of actuator; the end-effort(hand) of the manipulator can be moved to any desired location within the workspace; each one can carry a certain load and all the operation is controlled by a central controller . But the initial difference between those two is that the crane and also other facilities in the factory is controlled by an operator who have actuators, so the people have the function of evaluating the process, however the robot’s manipulator is controlled by a computer that runs a program, in other words, the robot is designed by a computer or similar device. The movement of the robot are controlled through a controller under the supervision of the computer, in the computer, the control program is already set before by designer. So, the position also the force applied on the part to realize the process will be more precise and if we change the program, write the new order in the computer, the actions of robot will change corresponding. The robot can perform many different tasks due to this feature. It’s the reason why they are so flexibility. But for the crane, the character of them is relative fix and they are totally dependence with the operator.

So, if we concluded the character of the collaborative robot, they have many advantages:

1: Due to this characteristic, They also can help people to comply the jobs that are dangerous; repetitive jobs that are boring, stressful, or labour intensive for humans: especially in the field of manufacturing , it will help the worker reduce the workload, it’s not only improve the efficiency of the work, but also reduce the risks to the operator caused by high load work, they also can complete menial tasks that human don’t want to do.

2, The programming and maintenance of the device is very convenient. Because the main task of work of the cooperative robot is usually in a small part of the whole production process, it is relatively simple to design the computer language corresponded, and at the same time, they are very precise. It is also easy to check and repair after the succeed of the failure, so it's convenient for any operator with and without technical background, it will let the robot become more like the tool which is easy to handle. If explain more detailed, especially focus on the aspect of safety. after we design the sensitive force feedback characteristics when it reaches the force set, combine with risk assessment the machine will stop immediately, there is no need to install guardrails;

3, If set the program appropriately and also combine the we can let the robot work by itself without additional staff, the robot can judge the situation and distinguish the position by themselves during the executing of the program.

4, Due to the size of the machine is small, the power consumption and the noise when production is rarely low. So, this human-robot collaboration can create a very safe and also comfortable job for operators. The environment permits employees to quickly get along with robots and collaborate with them;

Due to the advantages that we mentioned below, it can save a lot of the expenses of hire employee in factory, save the cost and at the same time increase the economic efficiency.

Until now, the collaborative robots have extensive application market, In the electronics industry, auto parts industry, food industry, the robot can be found almost anywhere.

Due to the character of this type of robot is different respect before, under the trending of developing such rapidly, the method to evaluate the issues between them is not suitable anymore, therefore, the new research topic is born, named Human-Robot Interaction (HRI). "This is a subject to help the human to understand, design, and evaluate of robotic systems in the collaborative environment" (Goodrich and Schultz 2007). This area is mainly to analysis the possible interaction between the robot and human, evaluate the potential risks in the procedure, although this research is already spread widely, but they still have some challenging aspect need to be development. Following are the technical difficulties and also the dilemma when we apply the research need to be addressed.

First of all, HRI is subject contain many disciplines, they combine together with the great compatibility, they use the resource form communications, computer science, engineering, psychology, creating challenges in researching that covers such a lot of the field. At the technical design level, HRI mix the engineering disciplines and computer science mainly, so when designing and analysing, it's better to consider from two aspects: mechanical and electronical parts. As the diversity of the HRI, it's necessary to discuss the resources of the information, however, there are no specialized HRI resources.

Second. From the point of the technical: They need to guarantee the safety during the operation; ensure the robot can apply appropriately force when they touch the human, even the failure is happened, the program set before will control the failure in the danger limit, so that the safety of the operation will still under considered.

The third aspect is also very important, due to the HRI break the norm that the operator is working separated with robot as before. So, the safety standard is inadequacy anymore. For example, if the robot goes wrong, the machine may stop working, due to the operator also in the working area, this may even hurt human's life. Considering this issue, this topic becomes the top priority for the future development of human-machine collaboration. The fact is that increasing the safety of robots often means compromises in performance. This requires designers to seek a balance between the two to ensure a win-win situation between safety and performance. so, it's necessary to consider all the machine failure modes and the corresponding change methods. This introduces the concept of risk assessment. In this article, the risk especially between human and robot will be evaluated by using the software named IDDA (integrated dynamic decision analysis) according to the process used.

IDDA is a computing environment for integrated dynamic decision analysis, this tool it is based on using the logic to define and to describe all the possible alternative incompatible scenarios. When we analyse, not only needed dynamic but also, it's necessary to integrated with the physical behaviour of the situation in the whole procedure.

In IDDA, we can use the command to simulate the human thought in the construction of logical trajectories, defined in accordance with logic laws, But the thought of human is not fix forever, we cannot simulate an imagination freedom, except the aspect's uncertainty, they can represent in fact almost all the alternatives ways in which the event can happen and so the sum of their probabilities gives directly and correctly the probability of the event itself. [2]

Combine the merit and demerit of IDDA, as a powerful analytical tool, it still plays an important role in all fields:

1. It can identify and to describe the whole of the logical alternative occurrence sequences implied by the analysed problem.

2.It can represent logically and solve from the probabilistic point of view all the events.

3.As the result shown in the software, it can supply the user with cumulative distribution function of consequence or with risk distribution function in order to supply all the information for the client to apply the effective decision process.

4.It can show the critical occurrences in the whole process, so if the user decides optimize the procedure, it will help in recognizing this is the best fixing strategies.

About the method to design the program, the source necessary to define that basic parameter of the decision given by risk. It's like the decision parameter following the analysing.

The definition of risk is the potential of gaining or losing something of value[3], in the industrial. If the risk creates from the robot, The consequences slightly it's failure of the robot itself. If have the accident even influence the operator, the risk will inestimable.

In order to avoid this situation. we can adopt the risk assessment to forecast the situation possibility and manage it in advance.

Risk assessment and risk management are defined as a professional topic and respect the practice, they will offer the user a lot of information to help then plan. Since many years ago, this aspect has been proposed, in the period between 1970s and 1980s. the field through the development remarkably, many analysis methods and techniques are created, until now, they are used mainly in most societal sectors.[4]

In this case, the risk assessment considered both possible equipment failures and the potential personnel errors in executing, mainly manual, testing procedure to help us to evaluate the procedure.

Once we know it, we need to start assessing risk according to the definition. First, we need to know the main source of risk: safe and reliability of the machine those two main aspects through all the phases about the design and control.

There are two main types of operator injuries when they working with the industrial robots in factory: the error due to the engineering part or the human fault. Engineering part include mainly the errors about the mechanics (e.g., the break of the actuator system, failure of the electric part), errors made by the controller (e.g., programming bugs, fieldbus breakdown). According to the data collected from automotive industries, the result show that almost all the type of the failures is caused by the positional error. Those faults are mainly caused by the mechanical part or the problem on the control system[5]. Due to the vibration is inevitable, the demand of the position absolute correct in the work place is difficult, therefore, robots might, for example, the robot arm has the risks to stop or the speed is not under control, like the velocity is modified randomly, the trajectory of the motion is unpredicted. [6]

About the aspect of the fault due to the human error such as the bugs in the programming, the incorrect installation, operator is inattention when process, all the causes may result in the robot have the action unpredicted, in more serve situation, the movement of the robot even can hurt the personnel. Human errors always happen because of the incorrect action or the influence of the worker's emotion, and also contain one possibility, it means that the operator may finish the task with the gesture not respect the ergonomic in the robot's work area, it will be creating the fatigue of them, the failure probability is increase[7]

1.2 The structure of the thesis

After the introduction of all aspects in human robot interaction, in order to analyse the failure about the robot. It's necessary to understand the detail information about the structure of the robot, and how they work with the operator, because for the robot system. Not only the robot themselves, but also the other devices and systems used together with robots, because they need to be programmed and controlled. In those reason, we need to comprehend each component in robot: the control system; actuators system; sensor and so on. After analysing those basic components of the robot, it will be more clearly to point out and evaluate those main issues, in this way, the optimize action will become more efficiently.

So, the structure of the paper is as follows:

A: The structure of each components will be introduced, like the actuator system which supply the power and transform the power to the manipulator;

the cooling system that help the robot maintain in the normal working condition and so on.

B: The failure mode of each components will be concluded and also each failure effect, in order to assess the risks may happen in the procedure. According to the risks, the protection measurements also can be considered. Then the real case will be used, in this article, we will adopt the assembly part of the brake disc, through analysing the real case to explain better the process optimizing based on the failure probability

C: In the case study part, the method named “events tree” will be used, this is a diagram can list all the possible sequences. An event tree represents the order of the sequence corresponding the timeline and the end states of each sequence. We set the input to build the events tree and list all the possible consequence. Then according to the events, the program named IDDA will be used to calculated to evaluate the probability of each occurrence.

D Finally, from safety and the result shown in the diagram, some optimize actions can be used to improve the specific operation and reduce the risks.

1.3 Conclusion

This chapter is mainly introducing the history and the development of the robot system. From the huge, expensive robot which operate the high duty manufacturing to the smart, agile robot arm which reduce the operator’s workload and economical. Then for the research on this new aspect, the HRI (human robot interaction) will be introduced. The risk assessment will be analysed based on this area, in order to improve the operator’s safety.

Chapter 2

The basic component of robot

This chapter is mainly present nearly each component of the robot also the basic function of them. From the mechanical parts to the electrical parts, so it will be easier to analyze the failure mode in each aspect.

2.1 The overview of robot system

In this industrial robotic system. Due to the special character of work, we will use the robotic arms to help operator to complete the task. A robotic arm is the type of the machine, they can finish the task like the human arm, the links between each part are joints, in order to satisfy the motion of the robot. As for the final part of the arm is the components that operator the task exactly, the name is end-effector.

So, in this article, we will figure out the failure possibility corresponding to each part. it will be more convenient to optimize the procedure.

For the general robotic, if we analyze the part of robot depend on the mode of operation. The essential component is the mechanical part, with a moving part (wheels, crawlers, mechanical legs) it will help the robot to move easily in the factory and manipulation parts (mechanical arms, end-effectors, artificial legs), the end-effectors is relative important. For they are the last joint of manipulator, they can be connected to other machines, or performs the required tasks. Like a welding torch, a paint spray gun parts handler and so on. In most cases, the end effector's action is decided by the controller directly or the controller receive the relative information and next step is calculating the next motion. Then sent the order to the end effector's controlling device. And another part is electrical system. They include form the power supply, through the modulation of the voltage or the current, in order to send the suitable state of energy to the robot, and also the part of sensor which is responsible for collect information to controller to optimize the action.

Meanwhile, it's also viable to analyze the robot depend on the duties they need to perform, it's aims to understand profoundly the component of robot. Firstly, for the exerting an action, both moving parts and manipulation are provided by an actuation system, like the manipulator's muscle, the controller sends the signals to the actuators to move the robot joints and links. In this system, they achieved by the servomotors, drivers, transmission system.

For the capability of observing is entrusted to a sensor system, because they can obtain data, collect the state information of the mechanical system (proprioceptive sensor) and the information about the environment (exteroceptive sensors). This information is collected in the controller, in order they can know the position of each link of robot to figure the robot's configuration. For example. When you in the dark environment, even you close your eyes, you still can feel the position of your body, this is the contribution of the feedback sensor in the central nervous system in the human mind. Sensor embedded in muscle and send the information to the brain which is the controller for human. So, the brain will decide the length of the muscle we need to use also out of consider from the condition of the muscle. The same function for the robots, the sensors measure and collect the relative information about the robots and send information to the controller.

For the capability of connecting action to observe is provided by a control system which can command the action of the robot in order to the tasks and also set the limit for the robot to avoid to damage the environment. As for the method about achieving the function wrote before, first they receive the relative information from the computer, control the action of the actuator, and correct the motion with the sensory feedback information. For example: we make the robot to pick a part from a bin, it means that the first joints need to be reached at the certain angle. If the joint is not arrived yet, the controller will send a signal to the actuator to make them move to the desired position. The change about the joint angle will be measured through the feedback sensor. When the joint reaches the destination, the signal for moving will stop. So that this operation will continue to the next step.

For the capability of calculating the data to send to the controller is provided by the processor, they can evaluate the movement of the robot's joints, in order to decide the velocity of each joint, in order to achieve the desired location and speeds, and also need to control the state of the controller and sensor. The processor always means the computer system. In this system, programs like the monitor.

For the program that process needed. The company always need the software to achieve it. It means that the program is set in the software and sent to the controller.

For the capability of the operate effectively. The accessories are also needed. For example. The cooling system is the part unignorable. To maintain the normal working temperature of the system.

Therefore, it can be observed that robotics system is an interdisciplinary faculty. Combining the area of mechanics, control and programming. it can be represented by the diverse subsystem.

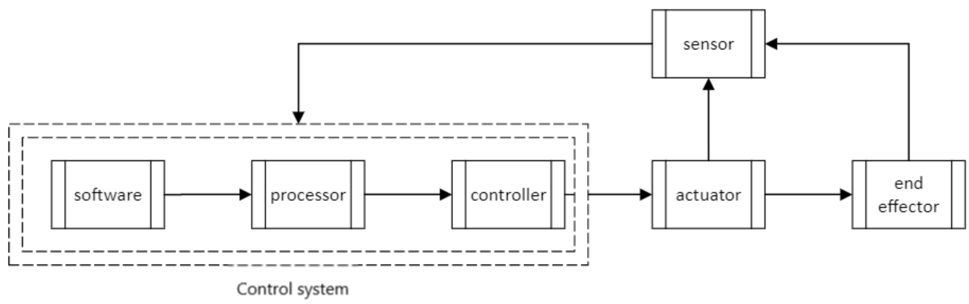

Figure 1 Each component of a robotic system

After showing the basic components of robot, next step is to explain the function detailed of each component.

2.2 The overview of manipulator

For performing the task, it's achieved mainly by the mechanical parts, so robots can be defined as those with a mobile base, called mobile robots and another part with the fixed base named robot manipulator. In the following it will introduce briefly these two types of robot.

The main character of the mobile robots is the robot can be moved freely thanks to the wheel or another moving parts. It's not liked the manipulators. They can move without limit, in other words, the workspace of a mobile robot is potentially unlimited. so, they are needed mainly on the task with is autonomous motion. From the point of the mechanical, a mobile robot is the equipment consists of one or more rigid bodies combine with the moving system, if we talk in more detail way, it can be talked in more detail way. it's can be divided into two types: wheeled mobile robots and legged mobile robot. But for the locomotion system, when modelling the robot, it will also complicate to program and control the robot. So, if we have the specific task and no need to the feature of the mobile robot, robot manipulator will be viable and enough to perform the function.

The mechanical structure of a robot manipulator consists of a rigid bodies(links) interconnected by the articulation (joints); a manipulator is defined by an arm and make sure the mobility. The wrist must be agile and end-effector will perform the task needed.

The mobility of the manipulator is ensured by the joints, they may have different types of joints, like the linear, rotary, sliding, or spherical, as for the spherical joints, this type is used in many aspects. But for the special feature, in order to achieve the agile. they also are little complicated, it will lead to the difficult on the respect of control. So generally, the articulation between two links can be achieved by means of the prismatic or revolute joint. each of them can provides a structure with a single degree of freedom (DOF). A prismatic joint makes the parts have the relative translational motion, as for the revolute joint, they will have the relative rotational motion. In the practical use, the revolute joints are used in more occasion respect to another type. Also, in this thesis, the robotics arm is analyzed, it's all combine by the revolute joints.

About the degree of freedom, this should be discributed on the mechanical structure in order to execute a task. In the most general case, six DOFs are necessary. Three for positioning the object and three for orienting the object with respect to a reference coordinate frame. If the DOFs is larger than six, then the redundant of the robot will be appeared.[8]

For the working area, it means that the area that the manipulator's end-effector can reach. The range depends on the manipulator structure and the limit of the joints.

As for the end-effector is designed according to the function of the robot. For the task of the material handling, the end-effector contain the gripper and its shape is determined by the object. For the task of assembly, the end-effector is a tool with the specialized shape according to the task need, for example: milling, drilling, screwing and so on.

Therefore, when we need to consider which type of robot we should use. First, we need to choose the type of robot depend on the given task, and the it's also decided by the dimension of the working area, the maximum payload needed, the level of accuracy needed. Corresponding in the robot that we analyze in this article. The task of them is screwing, and due to the working area is relative smaller and the task is simple, so the robot arm with the fixed base is enough for finish this task.

2.3 The overview of sensor system

In the robot system. The sensors are used for internal feedback control and the external interactions with the environment, like the function of the neurons to the human.

The sensors have a many type: the proprioceptive sensors which can measure the internal states of manipulator: for the value of joint position, encoders and resolvers are most used, tachometer for measuring the joint velocity, the force sensors are aim to measure the force of end-effector. For the human, we also have the sensor to perceive the ambient, the same as robot, they have exteroceptive sensors that give the information of environment, for example: they have distance sensors for observing the distance between the objects in the workspace and vision sensor for the measurement of the parameters of manipulator.

In order to choose the sensor appropriate to guarantee the precise motion of the joint. Firstly, it's necessary to consider which parameter is needed in the robot: Joint position, joint velocities, joint torques. Then combining the experience. We can point out the following typical sensor:

For the proprioceptive sensors: Position sensors, velocity sensors

For the exteroceptive sensors: Proximity sensor, range sensor, vision sensor

After deciding the main type of the sensor, it will be more convenient to consider different characteristics of each sensor. Those features will help us to decide which model of each sensors is suitable to mount in the robotic system we designed. For example: the cost, basic information about the sensors, sensitivity, accuracy, response time etc. According to the classic type of sensor mentioned above, we will discuss more detailed about the sensor which it's necessary in the system and the outcoming if they failed.

2.3.1 The proprioceptive sensors

Position sensors: the position sensors are used to measure displacement, both the linear and the angular sides, then convert them into the electric signal. They divided into several sorts: potentiometers and linear variable differential transformer (LVDT) mainly used for measure the linear displacement. For the encoder and hall-effector are mainly used to measure the angle displacement.

Potentiometers: they transform the position information into a variable voltage through a resistor, they have many advantages, like the output is continue, less noisy and they can use together with other sensor. It's aims to realize the accuracy as much as possible and reduce the input requirement needed at the same time.

Linear variable differential transformer (LVDT), resolver: Those sensors are similar, they both can convert the rectilinear motion of an object into a corresponding electrical signal to realize the function.

Hall-effect sensors: this sensor is obviously achieved the function based on the hall-effect principle. So, the output voltage of the sensor is changed when the magnet or the coil that generate the flux is close to the sensor.

For the angular position, For the reasons of reliability, precision and so on. The most common sensor are encoder and resolvers.

Encoder: this sensor can output the digital signal for each portion, in order to control the movement of the joint proportionally.

Resolvers: it's similar to encoders, resolvers also convert mechanical motion into an electronic signal. But the type of the signal they use is not the digital, they use the analog signal to transmit.

As above. We can realize that nearly all the position sensor will divert the information about the coordinate position of the parts into the signal electric to send to the control.

Velocity sensors: In this type of the sensors, it also contains the encoder, and when design the robot, if before we already set the encoder for the position sensor, it's no need to add another encoder in the system, because they can send not only one signal. But in order to measure the velocity directly, it's better to use the sensors separated:

The one typical is AC/DC tachogenerators, the main different between AC and DC is that, AC have the merit that they will eliminate the inaccuracy because the DC motor will have the residual ripple when they output the current. They have two types: variable reluctance and AC generator. they convert the mechanical energy into electrical energy, so the output of the sensor is analog voltage proportional to the input angular speed, but the level of accuracy is lower especially at the low speed.

They also have another type of the velocity sensor, it's named Pyroelectric sensors and other. However, almost all velocity sensors are aim to convert the measure value to the electric signal by using diverse method.

2.3.2 The exteroceptive sensors

Piezoelectric: this device will produce the voltage if they are compressed. And the quantity is proportional to the level of force.

Force sensing resistor: they used mainly as parts holding and insertion due to the force is under the control, they can set the parts on the working table through changing the force applied which modified by the resistance in the circuit. Robot can evaluate the forces needed by changing the resistance and apply appropriate force on the surface of the working parts. Strain gauge can also be used to measure force. Like the force sensing resistor, the output of the strain gauge is variable resistance, proportional to the strain.

In order to measure the torque, it also available to apply two force sensor and transform those two forces into the torque to realize the measurement

Touch sensors: Those type of sensor can send the signal when the physical contact is happened. The type simplest is microswitches, this sensor is especially, because they can cut off the current and based on signals the received, so mostly they will used out of the aspect of the safety.

Proximity sensors: This type of the sensor is aim to detect the distance between two objects in order to evaluate the contact will happen or not. In this way, they can optimize the distance to achieve the operation propriety. They have several types: magnetic proximity sensor: this sensor is worked when it close to the magnet. They mostly are used for measuring rotor speeds and switch the circuit on/off. Therefore, in the factory, they not only can measure the distance but also can protect the worker. For example. They will stop the machine when the distance measured is very closely according to the date we set before. Another type is optical proximity sensor: this sensor consists of a light source named emitter and a receiver which is used to distinguish the presence or absence of the light and measures the energy of the light if it is present. So, this sensor through measuring the intensity of the light in order to obtain the distances from the objects. Ultrasonic proximity sensor: this sort of sensor is very similar as the optimal. Only have one different, it means that they use the emitter to emit the high-frequency sound waves replace the light, so the receiver will measure the intensity of the sound wave.

Range sensor: they are different with proximity sensors, they are used to detect the distance maximum or the obstacles and figure the surface of the objects. They generally based on the measurement of the light, laser or the ultrasonic signal.

Last but not the least, in the robotic system, the remote center compliance (RCC) device is also used, this sensor will help the robot to detect the misalignment situation. In order to optimize the trajectory of the robot. They usually mounted between the wrist and the end-effector. They don't like the normal sensor, because they don't have the input and the output.

In the factory, A large number of equipment equip the sensor to optimize the operation. They measure condition of the robot and also the environment around it, then using the electronic signals to send that information to controller. The well function of the sensor is the necessary conditions for the correct operation of the automatic system. It means that the quality of the sensor is directly related to the equipment operational status and critical security issues, in particular for some sensors that provide control signals, and their working status is directly affected to the state of the system.

2.4 The overview of the actuators

Actuator like the muscle of the robots. If the link and the joints like the robot's skeleton, the actuators are more like the muscle to move the links to finish the work. For the actuator, they must have enough power to modify the velocity and carry the load, reliability and also easy to maintain. As for the power of the actuator, it can be provided by electrical, hydraulic and pneumatic. The main components are the power supply; then is the power amplifier; motor and transmission.

The transmission of the power is shown following:

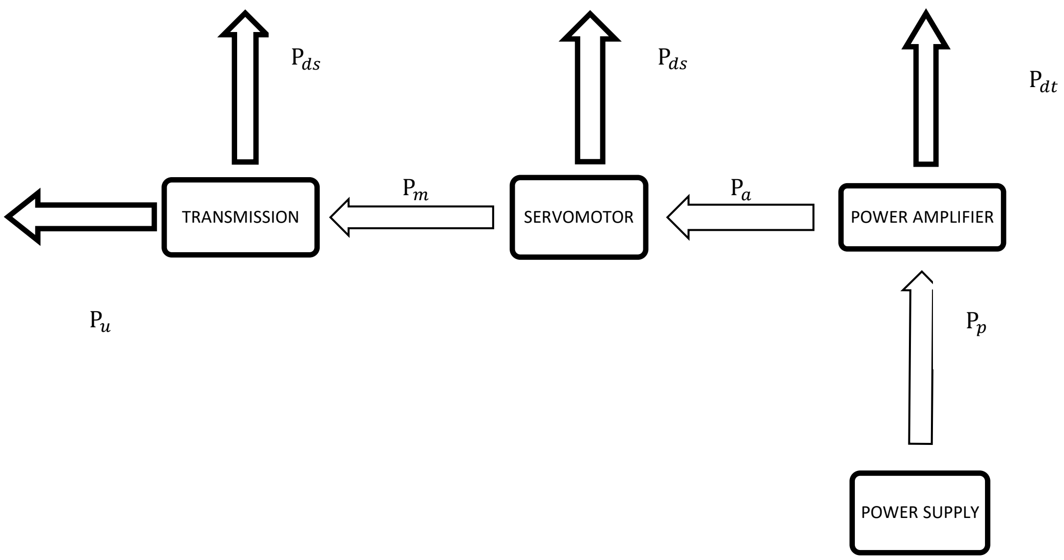

Figure 2 Power transmission

P_u is the mechanical power needed for the joint to perform the operation, P_a is the supply power of motor (this is depending on the type), the primary power supplied P_p and the mechanical power P_m is the primary mechanical power. For the P_{da}, P_{ds},P_{dt}. those are the loss of power in the transmission. Therefore, if we want to choosee the suitable actuate system, it's better beginning from the primary mechanical power P_m. The motor is the necessary part aim to supply the power, so the efficiency of the motor is important, according to the type of the function, we need to choose different model to satisfy the different requirement. [9]

Before we analyze the motor. It's necessary to point out some parameters typical for evaluating the motor:

1：Weight: Because on many robots, the actuators are set directly on the robot, so when we move it, the weight of the actuator will be like the load on the actuator. If we have the heavier actuator at the position close to the end-effector, it means that we need to have more torque at the beginning to hold the load, this will result the larger power requirements. So, consider the weight it's not only for the problem of transport, but also for the consider of the power applied.

2：Power to weight ratio: it's a measurement of actual performance of any engine or power source, when we make the power divide total mass, it means that each kilogram can get how many powers to operate this part, so improve this parameter will also increase the performance of motor.

3： Operating pressure: For the hydraulic actuator, they have high operation pressure, this may range from 50 psi to 5000 psi. For the pneumatic cylinder normally operate around 100 to 120 psi. The higher pressure in hydraulic systems can create higher power concentrations. But it's also needed a higher maintenance, because it will become more danger if the gas leak.

4： Voltage: If we keep the same power output, according to P=UI, the more voltage will decrease the current, so that the size of wire needed will reduce at the same time, the heat dissipated will decrease, then the heat consumed and improve the efficiency.

2.4.1 The Motors

First, according to the type of the source of the motion power, it can be divided into three type: electrical; hydraulic and pneumatic, following is the table to summary the merit and demerit of those three motors.

Table 1 The type of the motor

Type of motor	Hydraulic motor	Electric motor	Pneumatic motor
advantages	Suitable for the large robot and heavy payload	Suitable for all size of robots	Reliable components
	Highest power/weight ratio	Better control	No leaks or sparks
	High accuracy	Need reduction gear to reduce inertia on actuator	Economic and simply
	Without reduction gear	Without leakage, suitable for the clean environment, without pollution	Have low pressure compared to the hydraulics
	Operate in the wide range of speed	Reliable, low maintenance	Good for on-off application and pick and place
disadvantages	Have risk of leakage, not suitable for the clean environment	Need reduction gears, increased backlash, cost, weight …	Difficult to keep linear position
	Expensive and noisy	Low stiffness	Noisy
	Need maintenance frequently	When not have power supply, need the brake device	Lowest power to weight ratio
	The requirement of oil is strict	spark-free, need protection in	Low stiffness, inaccurate respond

		flammable environments	
	High inertia on the actuator		

Hydraulic actuators, This type of the actuators can offer high power to weight ratio, because except the accumulators or other parts which achieve the execution of joints, the main components that provide the energy: hydraulic pump, it can set remotely from the joints to reduce the mass and inertia not like the electric motor, also they can have large forces at low speed, both type of actuation are suitable, have high tolerance of extreme risks environments and they can stop without generate a lot heat at the actuator, increase the torque without need of gearing. However, the problems are also existing, about the gas leakage and the cost. They are not so common in the factory now.

Pneumatic actuators: This motor transforms the pneumatic energy supplied by a compressor into the mechanical energy by using the pistons. It's very similar with the hydraulic system. Because the resource of the force is pressurized air, controlled by the manual or electrically. This resource can also set away from the moving actuators, therefore, they have less mass and inertia. But due the volume of air is compressible. The pressure will influence in many conditions, so this kind of actuator will more adaptable to the operations which don't need the accurate requirement. It means that those robots which have relative lower degree of freedom. Like the insert robot.

Electric motor: Due to the Lorentz force law, the motor can change the electric energy to the torque. This is the main principle of all electric motor. In the factory, we mostly to use the electric motor for the robotics. The also contain many kinds of motors. They have DC brushed motor, stepper motor, DC brushless motor, For the AC motor, because they have the rotor that is permanent magnet, they don't need the commutators and brushes. So, they have three-phase asynchronous or synchronous AC motor.

In conclusion, both type of motors has a good dynamic characteristic, although the electric motor has better behaviors than others. For the other two kinds of motor are easier influenced by the temperature of compressed fluid and gas. And especially for the hydraulic motor, it's more suitable for the operation have high torque at low speed. So, if we consider form the point of the application, hydraulic motor is convenient for carry heavy payloads, and electric motor are suitable for the system relative light and fast. In this article, the AC three phase motor is mainly be discussed.

2.4.2 The Transmission

The performing of joint motion of manipulator need relative low speeds with high torque because the electric motors rotate at very high speed, up to many thousands of revolutions per minute, it's necessary to add the reduction gear to increase the torque meanwhile decrease the speed. The reducer will optimize the power transfer from the motor (P_m) to the joint (P_u) and in this operation, P_{dt} is the dissipation because of the friction.

For the classic type of reducer, they combine the fixed axis and planetary gear with many types of gear.

The following are the types of transmissions used for industrial robot:

Gear: it will change the feature of the rotational motion through changing the rotation axis. For the gear, the disadvantage is backlash, it means that between the gear teeth, they have the clearance. this space is helping the gears to mesh without connect together and to supply the space for the film of the lubricating oil that prevents the temperature is too high and even damage the tooth. But under the high-speed operation. We cannot neglect the vibration between teeth, because of this high frequency vibration, the wear of gear will happen.

On the contrary, the clearance can cause the lost motion between the shafts, it will lead to the difficulties to make the equipment positioning accuracy. For these reasons, we need to ensure the exist the clearance at the same time, use some specific method to reduce or even eliminate the backlash, like using the precision gears, modified gears, or special designs to omit the gear.

Lead screw: it's a screw used as a linkage in a machine, this type of transmission is stiff, for the connection by bearings and shafts. Therefore, the life of devices will be reduced.

Timing belts: It's mainly use belts and chains to transmit the power. they can permit the operator to locate the motor a little far away from the actuator joints. Due the physical character of belt, before we use them, it's better to preloaded to reduce the droop for the weight of themselves and it also may cause strain for applying the load. For the chain, due to their large mass, they can decrease the vibration at high speed.

For the direct drive DC motors, they allow the motor connect directly to the joint without use any transmission part (direct drive). The disadvantage is the friction loss and backlash are eliminated, so the efficient are increase, and simplify the design, improve the reliability also reduce the total weight, cost. But due to the lack of the gears, the nonlinear coupling in the manipulator is not allow, this characteristic limit the range of use, so this direct-drive system is not used too much in the factory.

2.4.3 The power amplifier

The function of the power amplifier is to change the power flow which from the power supply to the actuators.

For the electric motor, the control signal can change the voltage and current directly according the type of the motor.

For the hydraulic or pneumatic motor, it is achieved by changing the flow rate to control the quantity of the compressed fluid or the air.

2.4.4 The power supplies

The function of power supply is to supply the power to the amplifier which is used to operate the actuating system.

For the electric motor, the power supply will have the function to transmit the alternating voltage available to the direct voltage. The main component is transformer and bridge rectifier.

On the other hand, for hydraulic power, it's a little complex. The operation transform will need various system: filter, pressure valves and check valves to ensure the correct performance.

2.5 The overview of the control system

The control system known as the brain of the robotics is used to supervise each activities of the robotic system. In more detail way, this part can manage the position, motion and force also the dynamic effects, in order to let the motion can be operated in the way decided before in the design phase. Because of the errors are always random and unpredictable when the machine working, it's necessary to use some specific device to autocorrect it in the process.

this work can be achieved by software and hardware. The software defines the functionalities of the robotic system and the hardware execute these functionalities. The control system is usually connected the other parts of the system by the fieldbuses. The control system should provide the following functions:

Capable to obtain and manage the information of the ambient and the status of the system

Capable to regulate the mechanical parts of the robotic system

Capable to be programmed to perform various tasks also can calculate the next action.

Due to those function needed, it can be concluded into three phases: the part that receives data (sensory module), calculating the data to renew the trajectory or the tasks following (modeling module) and execute the (decision module). For those function, it can be divided into diverse level, from the task exactly needed in each function to the action level that the motion required to achieve the task, and then is the basic trajectory and control method computed and decided. The most foundation level is the algorithms designed.

So, it can be seen that all the work is achieved by the program wrote before in the robot system. The designer wrote the program in the suitable languages, according to the function of control system, they not only guaranteeing the transmission of the order, but also checking the state of the system frequently and execute the recovery action according to the calculation if the error happened. So, this system is similar with the computer programming but still have some particular character, like the motion control, reading the sensor data, interaction with the physical system, checking the dynamic error, recovering the correct function.

Usually for the robot system, the position of manipulator will update frequently and calculate according to the program set before and output timely.

The hardware architecture is composed of the ECUs and the fieldbus, ECUs like the microcomputer in robotics, the function include communicating with external control interfaces, commanding motor controllers and receive information from sensors. As for the fieldbus, they connect each component embedded or control systems like the network, all the information can transmit on the same bus, so that they can reduce the weight and price, the component can decide which data they need and command the transmit to collect and calculate. The general structure is shown following:

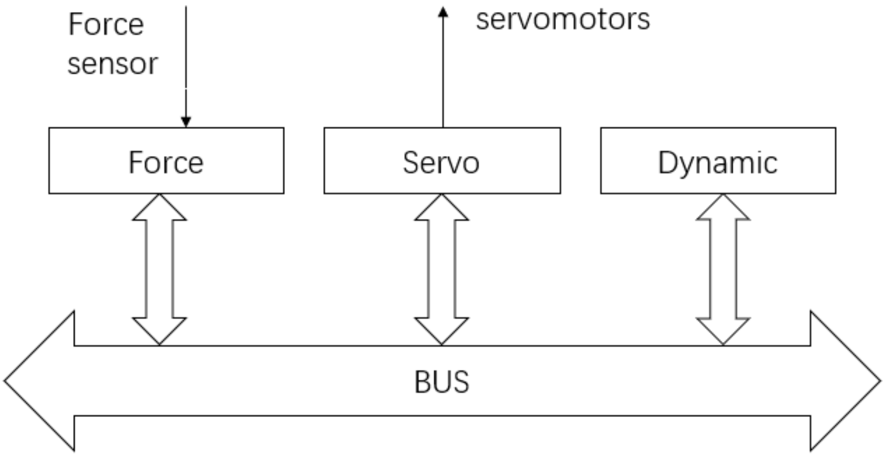

Figure 3 Structure of control system

Each board have their own tasks and they connected to the bus. The function of bus is connecting the information between the board, like the network. The command is carried out in ECU according to the data they collected in the bus, also the command is transmitted by the bus.

After analyzing the components of the control system, it's necessary to point out the methods of control and the characters to be controlled. Therefore, the failure will be analyzed according to the methods and the characters in each level.

The classification of robot control are open-loop feedback control and close-loop feedback control.

The system of open-loop is relative simply to control, because they already designed the autocorrect program for the error predicted, it means that this system didn't have the function of detect and correct the dynamic error during the process. So, this type is suitable for the error can predicted more easier, they error achieved inevitable if the system happened without any discurbance, like the fixed error.

Due to in the robot system, the procedure is relative complex and the dynamic effects are different to consider perfectly before. Because many aspects uncertain will happen, it's better to set the close-loop system, in order to detect error and calculate timely to apply the recovery action to correct them during the process. The typical model is shown following:

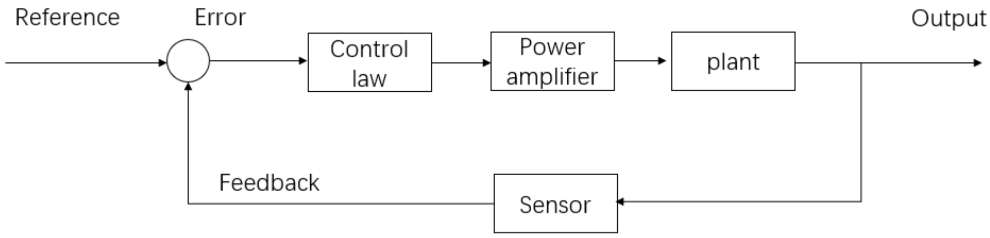

Figure 4 Typical block diagram of a close-loop control

After deciding the structure of the system. It’s inevitable to point out the characters need to be controlled. The position control to supervisor the joint position, the force control and the dynamic effect. The force control classified into damping control: the control on the opposing force which created due to the force added on the end-effect; The stiffness control: the rate of the deflected from the nominal position of the end-effect with the forces increased. The impendence control and torque control. About the dynamic control, because the trajectory of the robot is not linear, so this process means the loads, mass balance may change, vibration, the friction between components and gear backlash will cause the error.

When the Engineering machinery in the process of work, the power system, and transmission the system can produce a lot of heat (heat loss). It will increase the temperatures of the system continually. So, it’s necessary to set the cooling system, in order to ensure the temperature not exceed the limit. Otherwise, the high temperature may result in the motor internal conductor over the ignition point and auto-ignition, this situation will damage the motor and even cause an explosion if the situation deteriorates continually.

Most of the motor in the engineering machinery use the air as the cooling medium, therefore, the main parts in system are ventilation fan and wind hood, and most of them use a mechanical drive fan, it means that they transmit directly the power from the supply through the V belt pulley to the cooling fan. For the parts need to be cooled, in general way, they are installed in front of the fan according to certain order and distance, this cooling system is designed and chosen according to the maximum heat load working condition of the motor or other heat source system. Therefore, once the design of the fan system is completed, its cooling capacity is basically determined. The advantages of this kind of fan are simple structure and reliable. Its disadvantages are long preheating time and cooling capacity cannot vary with changes in heat load of the motor and they also cannot adapt to the change of the environmental conditions. When the motor continued work in a low speed with high load condition, it will reduce the speed of motor and the cooling air flow is reduced. Because the cooling capacity is insufficient, it will make motor overheating. If we cannot observe this failure on time, it will lead to the situation more seriously, even burn the wire and make the machine can't work normally and endanger the operating personnel.

However, it is impossible to realize this complex operation only by hardware, the corresponding software is required to control and coordinate with the hardware, so these hardware and corresponding control software constitute the thermal balance control system. Thanks to the development of technology and the various control systems, the sensors, the cooling process is optimized and the risk is also reduced. Now, for example, in the factory, there are mainly three kinds of main common variable speed fan:

1： Throttling speed control type for hydraulic drive fan: the control process is that each sensor will convert the measured signal of temperature to electrical signals to send to the electronic control unit. When the temperature inside the device below the value what we set the lowest one, the application of electronic control unit will determine the machinery in the low temperature working condition. At this point, the electronic control unit outputs the maximum control current to the proportional throttle valve, this command lead the actuator(valve) keep opening in the maximum position, this position will lead to the minimum motor speed. With the increase of temperature, the electrical signal to the electronic control unit input has corresponding change, the electronic control unit according to the design of program in advance accordingly reduce the output current to the proportional throttle valve, the proportional throttle valve opening was reduced, so that flows through the motor traffic will increase, and the speed of the motor also increases accordingly. When the temperature of the cooling medium is higher than a certain upper limit, the control signal output by the electronic control unit is almost zero. At this point, the speed of the fan reaches the maximum. In this way, the temperature of each cooling medium can be controlled within the optimum working range according to the working condition and environment condition of the motor. It’s also necessary to design out of the aspect safety. When a sensor or ECU (electronic control unit) fails, the ECU (electronic control unit) and the valve will still work at the highest speed, this will help to prevent the system from overheating.

2：Volumetric speed control for the hydraulic drive fan: the principle is similar to first one type, when the sensor or electronic control unit fails, fans also can work at top speed. The difference is that the system adjusts the speed of the motor and the fan mainly by changing the displacement of the variable pump.

3： Electric/magnetorheological clutch fan. The theory is bellowing:

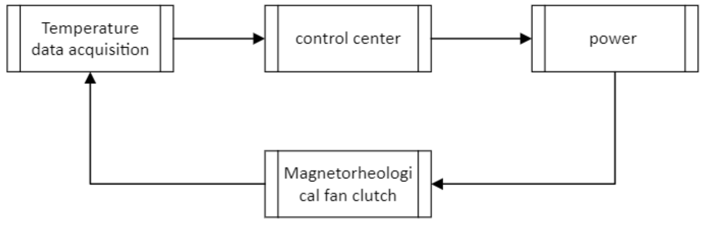

Figure 5 electric/magnetorheological clutch fan control system

Therefore, it can be seen that the inside of the fan is like a self-feedback system， when they require the information about the temperature , they will sent them to the control system, after calculation, the order will give to the power directly to modify the velocity of the cooling fan.

Chapter 3

The failure mode of robots

The aim of this chapter is to distinguish the failure type of the robot, due to the specific character of the robot in this article which is worked with the operator, so the failure caused due to the worker's fault also need to be considered. On other hands, when we worked according to the procedure designed, it may have the certain probability of some specific gesture will make the operator feel uncomfortable, so that the failure may happen. Therefore, we divided those failures into three aspects mainly: the mechanical or electrical failure of the machine themselves, failure due to the ergonomic, failure because of the personal characteristic.

3.1 The failure due to the operator

This problem always aroused due to the unperfect design when planed the procedure, like the operator will bear the physical load excessive and is larger than the normal limit; the improper design for the work cell; ill-suitable the distribution of procedure etc. Those poor design will increase the risk for the procedure also the unnecessary noise when work, it will lead to the physical fatigue for the operator even the uncomfortableness.

As for the influence of the emotion, this part is impacted directly by the worker. When the work condition is terrible; the control panel handled has poor design, those will result in the stress or the anxiety fatigue of the operator, so that the failure may happen although the machine is work well.

3.2 The overall failure frequency of the robot themselves

However, the advantages of the robot are obviously, the failure of the robot still needs to be considered, not only for the efficiency of the production but also consider the aspect of the operator's safety, so the reliability is too important to neglect.

Out of considering the type of the robot in this article is work in the factory, as the indoor robot. When talking about the failure mode of the robot, the effect of the environment is smaller than the field robot.

It will be clearer to consider the failure from the failure frequency of robot and the probability of each component that caused the failure

We analyze two type of indoor robots. Robot A has the fixed base named robot manipulator and the second one: robot B has a mobile base. Those two types as the sample and considering the working hour allowed, we recorded the number of failures in three years, the total number of failures; the overall frequency of failure (failure happened per hour) are shown following[10]:

Table 2 Frequency of robot's failure

Type	Number of failures	Failure/hour
Indoor robot A	16	0.05
Indoor robot B	25	0.01

$$\mathrm{P(t)} = 1 - e^{-\lambda t}$$

λ is the failure rate, t is the total working hour, in this article, the total time of the procedure is 203s

$\mathrm{P(t)} = 1 - e^{-\lambda t}$=$1 - e^{-0.05*(203/3600)}$=$2.82*10^{-3}$

So, the probability of the robot in this procedure is $2.82*10^{-3.}$

As for the probability of failure that caused by the specific component and combines the robot needed to analyze in the article, the following chart is shown the overall failure probabilities of each component of robot A in three years (follow-up analysis):

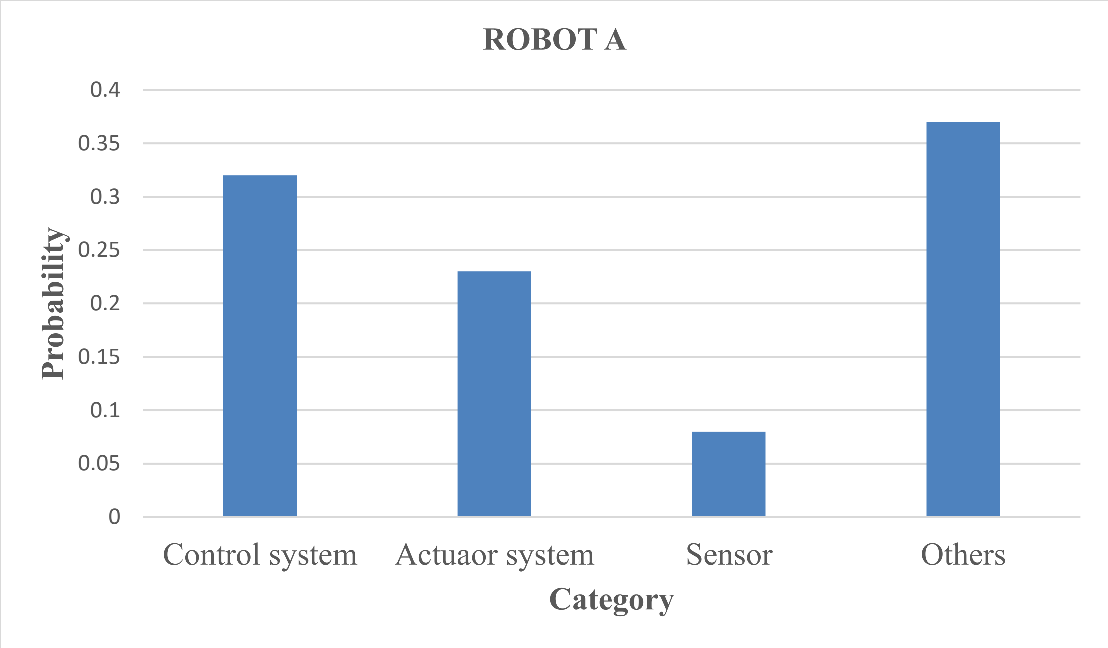

Figure 6 Failure probabilities of each component of robot A

It can be seen that the failure is happened most on the control system, because of their complex structure. Second is the failure of the power, it combines the problem of the supplying and the failure of the power structure. In the others part, they contain the failure of the end-effector, manipulator, cooling system and so on, we concluded those aspects together not means less-important, but the probability is less respect other parts.

3.3 The failure mode of the manipulator

If consider the failure mode, for this part, it's mainly about the mechanical. Generally speaking, it can be divided into the following type:

1: Joint failure: Joint failure is the symptom that reduces the velocity of joints to the zero. it's relatively easy to observe. they can influence the task completion of the manipulators and even damage themselves. Because if the failure happened during the manipulator execution. The operator can close the machine and replace it, even they have the certain value of inertia force on the manipulator and maybe have an effect on the end-effect and joints, increase the vibration of a base. The consequence is not too much serious. But if the failure has happened when they are applying the load by parts like pitching the parts or transmitting the parts, the inertia will be larger than the situation before even have the risk of harm the machine. As for the mode of joint lock, they have two main type: joint-locked and free swing. Free swing is the failure that the joint will still move but motion freely because the error let the joint loss the torque or force decided, as for the joint locked state, the joint will lock directly.

2: Circuit connection: Because inside the robot arm. For the motor may mount close to the executing device. they may arrange the circuit to transmit the signal. So, the problems electric may happen randomly. For example, the short circuit; the electric leakage due to the aging of the wire. If the operator touches those parts, they may have the risk of the people's life.

3: Material failure: According to the function of a robot. Usually, the robot must be made from light but rigid material. if one component of them has wear, although it may affect the accuracy of this phase, the whole mechanism will be influenced. In particular, the material of the gears and slides need to be chosen hard enough even the corrosion will happen non-ignorable. Meanwhile, the material used in linkage should be light. Usually, the materials are steel and aluminum. For they have a better thickness of wall than steel tube of the same weight, increasing its resistance to bending. So, in the manufacturing of robot, the aluminum alloy is used widespread. the character is the light and high force. As for the failure mode of aluminum is mainly:

1: Yielding failure: Due to the plasticity of aluminum alloy is low, the failure of aluminum alloy will occur once the excessive stress is applied.

2: Fracture: Due to some special circumstances, the working environment of aluminum alloy is not ideal especially when it is already deformed. It will deteriorate until fracture.

3: For the seats, because the function is mainly supporting the whole robot, under the condition not affect the performance of the robot. The iron is more suitable, not only the price is economic but also, they have many advantages like they have great wear resistance and shock absorption. In those three types of failure, the first one is easier happened, because of the complexity of the task, in the 100 failure events, it had 65 failure (65%) due to this type of problem. As for the circuit problem, thanks to the insulation system that protect the wire, the probability of this type of failure events is lower than before, about 25%. The probability of the final problem is rarely, because this type of failure is relative the life of the material, if we use normally, under this condition, it's few to happen the failure because of the material, also we can observe through the data, the probability for this fail is 10%[11].

If explain in the more detailed way. Because the joint will connect by the bearing also the coupling. The failure of them also can lead to the damage on the operation. Following is the failure mode detailed about the bearing:

1: Crack defects: Fatigue failure-usually represented as spalling-is the fracture of the running surfaces and subsequent movement of a small and discrete substance of material. The crack is formed when the rolling bearing rotates however it's very small and due to the action, it is not rolling purely but exists much motions of sliding when rolling. So, it will have a sliding frictional resistance between the surface. Under high-speed operation, the interaction between the inertia force of the bearing roller; the holding frame and the sliding friction resistance makes the surface of the bearing roller have a great cyclic contact stress, this stress will become the source of the fatigue. Those spalling can occur on the inner and outer rings, or balls. This type of the failure will initial occur in a very limit area, and then this fracture will spread further. So, if not dealt with timely, more serious cases may lead to bearing fracture directly.

2: Metal stripping on a raceway: There are many causes for the metal stripping on the raceway, such as the defects on the raceway, use the bearing over time, or the defect of the bearing themselves, also the large load forced on the bearing and high operation speed is the important reasons for bearing fatigue.

In addition, the improper bearing installation and shaft bending will also cause the phenomenon of raceway stripping.

3: Overheating: The symptoms of high temperatures (the temperatures in excess of 400F respect the ring and ball materials can bear.) will produce the discoloration of rings, balls, and cages or degrade the lubrication oil, so the efficiency of the lubricate is influenced, the bearing is under the risk of the failure, it will also produce the failure due to the hardness of the metal is reduced. Common culprits are heat paths is inadequate; clearance is too small or over sufficient cooling or lubrication. Because when the bearing grease is too much, the heat generated in the bearing cannot be released, and if the quantity of the grease is too little, the oil film cannot form properly, it will result in the dry grinding. Or the quality of the lubricating oil does not meet the requirements, the bearing assembly is incorrect, etc.

4: The loose and cracking of the cage： The culprits of this failure are excessive torque load, insufficient lubrication, change rotation speed frequently and large vibration in the bearing, the bearing is installed incorrect or the foreign substance enter inside the bearing. As a result, during operation, the collide will happened between the cage and the rolling body.it will wear the bearing. In severe cases, the rivet of the cage becomes loose and fractured, leading to the deterioration of the lubrication conditions, the rolling body maybe break.

5: Loose fit: This mode can cause the relative movement between fitting parts, for this motion is light, but continually, so this looseness will create the unneglectable movement between the inner or outer ring. It will lead to the wear on the surface.

6: Excessive load: It’s a common form of failure. This failure will be appeared between the surfaces of a rolling body, bearing raceway, or shaft neck. The main reasons are the foreign substance enter the bearing; poor lubrication; irregular movement of the rolling body. This will cause premature fatigue.

7: False Brinelling: This type of wear marks in an axial direction at each ball position, because in some cases, the bearing doesn’t rotate, so the small relative movement between balls and raceway will occur, due to the rotate cannot achieve, it means that the oil film cannot be formed correct, so this action will accelerate the wear process.

8: True Brinelling: This phenomenon will occurs when loads forced on the bearing is over the elastic limit of the material. Brinell marks like the indentations in the raceways. For this type, any static overload can cause brinelling. like use hammers to install bearings, treat the equipment violently, like dropping or striking to the machine.

9: Corrosion: This failure mode will damage the surfaces of the ball and roller bearings, we can observe the red or brown areas will appear on balls, raceways or bands of ball

The reasons of this condition appear are exposing bearings to corrosive fluids or corrosive environment, or equip the lubrication oil is not reach the quality needed, if not use the bearing, store them in the improper condition. The part of corrosive always on the raceway wheel, the surface of rolling ball.

10: Contamination: Contaminants mean the dirt or any abrasive substance getting into the bearing. The sources mainly are dirty tools or hands, contaminated work areas, or foreign substance in lubricants. The consequence of this failure is the break on the raceways and balls in the situation of high vibration.

3.4 The failure modes of the sensors

For the definition of the failure of sensors, it's defined as the events or the situation that makes the system behave abnormal phenomenon or failure of some components in the dynamic system in the overall system performance deterioration

Sensor failure classification can be divided into four aspects, it's includes: complete failure fault, fixed deviation fault, drift deviation fault and precision reduction

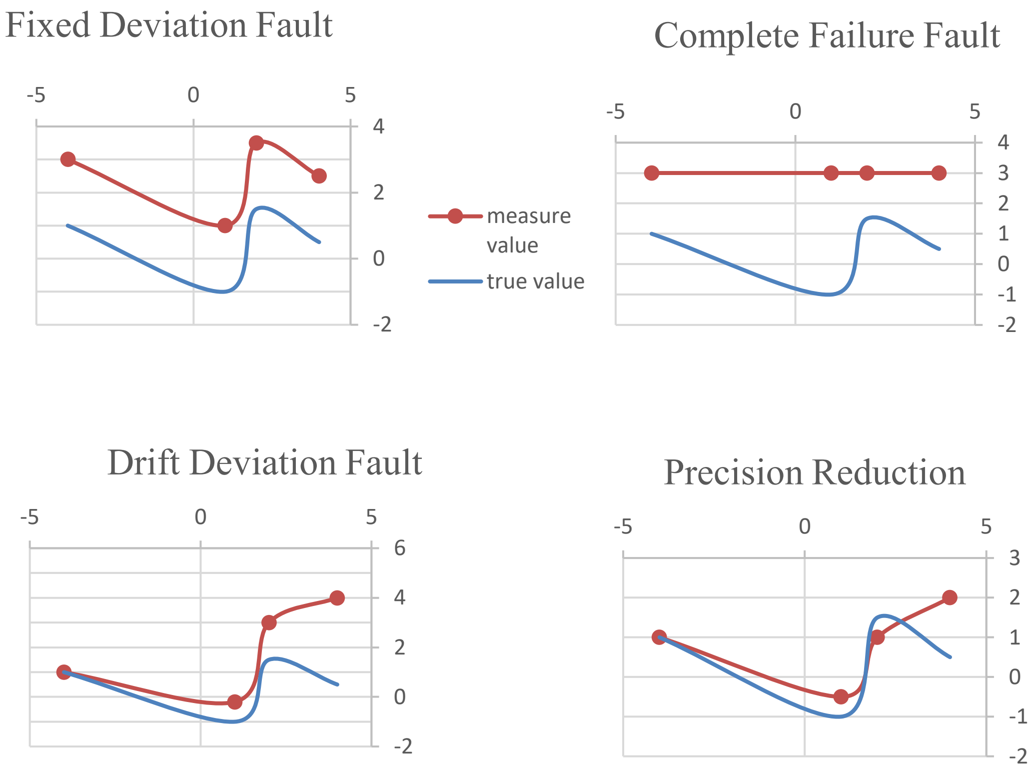

Figure 7 The failure type of the sensor

The complete failure fault refers to the sudden failure of sensor measurement. like the measured value is always a constant;

The fixed deviation fault refers to sensor have a failure whose measured value differs from the true value by a constant number. It can be seen from the figure that the measurement with the fault is parallel to the measurement without fault; drift deviation fault refers to the difference between the measured value and the true value of the sensor and the fault may change with the increase of time;

The precision reduction refers to the sensor's measuring ability becomes worse and the precision becomes lower.

When those faults happened. It can cause a series of unpredictable problems, making the control system cannot function normally. The failure situation of sensors can be noticed in the following method:

1: Classification by the degree of sensor fault: According to the magnitude of sensor fault, it can be divided into hard fault and soft fault: Hard fault means the fault caused by structural damage, general the change happens suddenly. Soft fault means the variation of characteristics, the change is relatively slow and not too obvious to observe. Hard failures are also called complete failures when complete failures occur. The measured value does not change with the actual change, they always keep a certain value. Usually, this constant value is usually zero or the maximum reading. For the soft fault includes data deviation fault, Drift, reduction of accuracy level, etc. Soft faults are relatively small and difficult to be observed, so it’s easier to deteriorate even damage the machine. Therefore, a soft failure is more harmful than hard failure.

2: Classification by the present time of failure.

According to the existence of the fault, performance can be divided into the intermittent fault and permanent fault: intermittent fault happens randomly and the permanent failure can't get back to original status.

3: Classification based on the occurrence of fault and development process: According to this method, it can be divided into the sudden fault and delayed fault: the signal of sudden fault has a high rate of change; for the delayed fault, the rate of change of the signal is small.

4: Classification by the motive of fault: This can be divided into deviation fault, impact fault, open fault, drift fault, short circuit fault, periodic interference, nonlinear dead area fault. The cause of deviation fault is: offset current or offset voltage. The fault cause of impact fault is the random discurbance between the power supply and ground wire, wave surge, discharge of spark, or foreign substance in D/A converter, etc.;

If the signal wire is broken, they will cause the open circuit fault. The pollution caused by the bridge road corrosion, short circuit connection, etc. Those will cause the short-circuit fault.

As for the failure mode, the situation happens more frequently is the sensor wear out, this error caused by the vibration, it can be concluded in the hard failure type that cannot recover. In the 134 failure in two years, the error due to the vibration accounts for 40%. Then the invalidation due to the insulation failure accounts for 20%. Depending on the quality problem of the sensor, the failure due to the components is also needed to be considered, if referring to the average value from the sensor on the market, this type represents 12%. For the rest of 28%, it is mostly because of the external environment, like the corrosions or the contamination[12].

Although each sensor has their own function, so the structure is also diverse, in this way, following we will analyze failure according to their specific task:

3.4.1 The Hall-effect sensor

Due to the characteristic of this sensor, it's vulnerable to temperature, if the environment is humidity, dust or have interference of electromagnetic, the corrosion reaches via interconnects within the IMD (inter-metal dielectric (IMD)layer close-by the die edge. The interconnect metallization was degraded and electrically open. It can be seen that the aluminum metallization within these via interconnects is completely corroded.

3.4.2 The velocity sensor

The type more used is tacho-generators: they combined by the toothed wheel of ferromagnetic material which is attached to the rotating shaft. When the wheel rotates, the discance named air-gap between the coil and the Ferro-magnet modifies. when the wheel rotates until the position in the picture (a). the flux through the magneto resistive element is the maximin. The corresponding resistance is maximum. the output is high value, until picture (b), the flux is reduced until the lowest. So, the output changes to a low level. The signal of voltage is presented like the picture (c). after the modification of the circuit, the final output of the electrical signal is shown as (d).

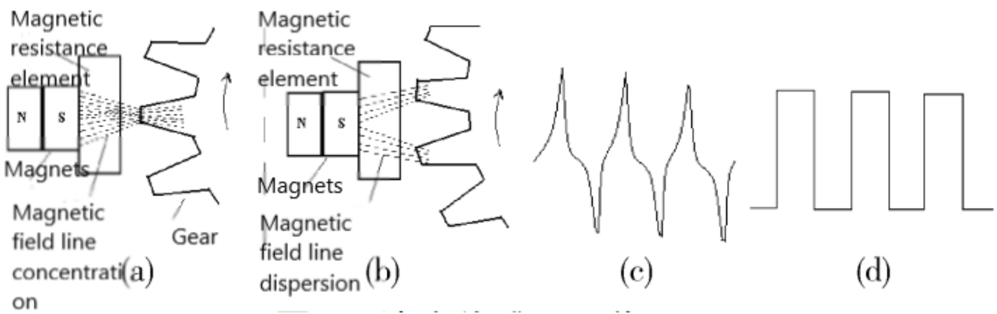

Figure 8 The working principle of the velocity sensor

The failure mode of speed sensor: according to the structure of the sensor and the work theory, aimed at the failure mode of sensors, it's possible to set the fault tree.

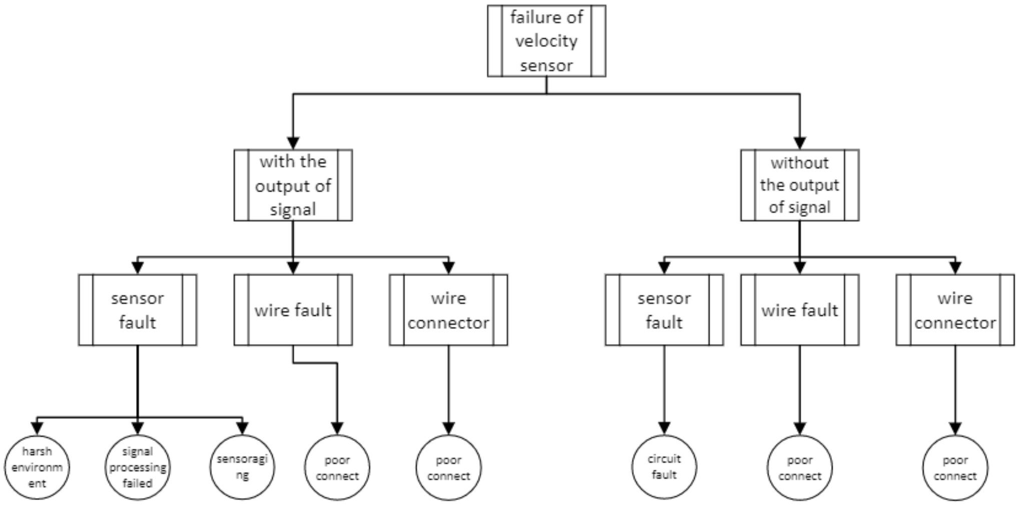

Figure 9 Fault tree analysis of the velocity sensor

Based on the fault tree that we listed, it can be concluded in the following:

1: The break of Magnetoresistive elements: The main reason is the magnetic resistance element fixed angle and support device body fracture. it will cause the relative position between the magnetic resistance element and the center of the probe changes.

The packaging material of magnetic resistance components is crisp, under the influence of the harsh environment in the process of processing, as the fixed foot. it's easier to happen deformation, after a period of using a device to fix will fracture.

2: The connector contacts lose

In the process of processing of the machine, there is a phenomenon of intermittent of the signal, which can be caused by poor contact between the speed sensor and the connector of the motor. Because in a certain climatic environment or vibration conditions, the connector pin of a speed sensor will become loose and has bad contact

3: Mounting position deviation of the speed sensor and speed wheel

The gap between the top of a gear tooth and the probe of speed sensor have required strictly.

The distance will affect reception and also the output of the signal. At the same time, we need to assure that the center position of the top of the gear tooth should be opposite to the center of the speed sensor probe, in this way, the magnetic field can pass through the surface of the magnetoresistive element to the maximum extent, and optimize the precision of trigger. So, when the transport of the sensor or the vibration, after the certain period. Maybe the position will change, generate the deviation, so that the accuracy will be affected.

4: Loosing the impulse

After a period of time, it will occur the loss of pulse. The material problem of speed sensor itself, for some components that in charge of receiving circuit, their sensitivity is reduced, it will lead to loss of pulse during circuit switching. In addition, the speed measuring wheel has missing teeth or exist the residual gear also leads to the phenomenon of loss technical pulse of the output signal of the speed sensor

3.4.3 The Force sensor

A very common method to measure the force is using of electrical resistance strain gauges. So, the strain will be produced when stretched, compressed or bent by the force applied.

The resistance strain gauge pasting on the surface of the components to constitutes the Wheatstone bridge, under the external power supply, they can realize the force deformation, resistance change final lead to electricity change to obtain the result.

As for the failure mode of the sensor, the typical failure of force sensor:

1: Reduction of insulation resistance: This mainly occurs in the sealing cover. In case of the severe humid environment, the waterproof sealing performance of the sealing is not enough good, then the value of resistance of insulation will drop dramatically and cause the output signal to be unstable. Especially resistance strain gauge damp. When the situation is serious, the filament grid will become thinner, making the resistance value significantly larger, even lead to the resistance strain gauge grid break, resulting in the bridge arm broken.

To avoid this kind of failure, we can use a layer of waterproof paint or use a waterproof socket for the lead socket to an improved waterproof effect.

2: Zero drift: Concept of zero drift (zero drift) can be referred to when the input signal amplification circuit equal to zero (i.e., there is no ac input), due to the modify on the temperature, have instable supply voltage, the static working point changes, and was gradually exaggerated and transport, lead to circuit output voltage deviates from the value of the original fixed and floating up and down. They have much reasons to cause this phenomenon. Three of them are listed in this paper:

Sensory overload: When this situation is happened, we can observe that the strain gauge resistance under tensile stress increases obviously and the strain gauge resistance under compressive stress reduce obviously, and the change of resistance value are symmetry. In this situation, the sensor is already damaged and cannot be repaired. So, before we use the sensors, it’s to be noticed that do not allow overrange use.

Low insulation resistance of the strain gauge: If the strain gauge is not properly treated or damaged after used for a long time. The insulation resistance between the film and the elastomer will gradually decrease and the zero output of the sensor will be generated and also change zero output with the decreasing degree of insulation resistance. For this reason, the strain gauge should be a well moisture-proof coating, and prevent external damage to the protective layer.

Solder false: The zero drift can be caused by the empty soldering on the welding spot of strain gauge. In order to avoid empty soldering, proper material for soldering should be used. Weld after the solder joint is cleaned, check the quality of the welding spot and reweld unqualified welding spot.

3: the bridge is broken: for this failure, if discuss in detailed way, they will be divided into four types:

Strain gauge grid corrosion fracture: The humid environment will cause the strain gauge grid corrosion, in the final even result in fracture. The main reasons for the phenomenon are poor water-proof sealing, harsh operating environment, So the strain gauge part past on the sensor is subjected to damp or contact with corrosive materials, resulting in corrosion of the grid of the strain gauge and eventual fracture. To avoid this kind of failure, it’s necessary to have a well moisture-proof seal.

Burn-off the strain gauge grid or the compensation resistance: Most of these failures are caused by lightning or live operation of the sensor or high voltage is introduced outside the bridge. So, this breakdown strength that exceeding the substrate of the strain gauge will break the weakest strain gauge or the grid. When this kind of fault occurs, we can find that there are black spots on the strain gauge or compensation resistance. The situation more serious is the whole strain gauge is black. Therefore, electromagnetic protection should be carried out in the sensor circuit and overvoltage, overload protection. When welding, it must be operated under the power cut operation, do not in the condition of power up.

The leads of sensor falling off: In the process of sensor manufacturing, the wire connection and the soldering empty of the silver wire that connects the strain gauge will fall off for the vibrate in the high frequency. For this purpose, the filling glue should be used after the completion, testing and debugging of the sensor group bridge. In order to fill and fix the connecting wires to avoid the vibration during operation.

Accidental cause: In the process of using, it is usually to happened the lead socket broken or pulled apart the lead wire when installing, when loading beyond the maximum range of the sensor or the use of overrange causes damage to the sensor. So, it’s needed to operate and use carefully.

3.5 The failure mode of actuators

3.5.1 Motors

For the electric motors , they operate on three different principles: magnetism, electrostatics and piezoelectricity.in this article. We will discuss the magnetism type, also it' s the most common type. In this type of the motor, magnetic fields are formed in the rotor and the stator. In order to get the current from the rotation between the rotor and stator. If we classify by the type of the current, it will be divided into DC motors and AC motors, AC electric motors are asynchronous or synchronous. In this robot, AC motor will be used, although they also divided in to the asynchronous motor and synchronous motor, the structure is similar. So, this part will start analyzing from the failure possible according to the component and then we will list the fault analysis tree to accumulate all the possible failure.

The failure will have a serious effect on the motor speed, load capacity, operational stability and the total life. According to statistics, in all situation of motor fault. the fault of rolling bearing accounts for about 40%, 38% of stator fault, 10% of rotor fault and 4% for the air gap failure, the rest of 8% is due to the other faults.[13]

The common faults of the bearing

In motor, the bearing has a support for the rotor, let the rotation function well, therefore, so this part has the highest possibility of failure, also is one of the most vulnerable parts, its running state is not only related to the transfer efficiency but also directly affect the entire state of mechanical equipment. About the detailed information of bearing failure, it's already discussed in the section above.

The common faults of the rotor

They have several aspects can influence the movement accuracy of rotor: thermal; magnetic; dynamic; atmosphere and so on, and each failure mode is nit similar, so it will be listed following:

The thermal stress: Those failures are relatively easier to be observed respect with other types, the sign is the overheating, and the color on the surface is changed. if the situation is worse, they even melt the material, this fail of components in the motor may influence the motor to modify the velocity.

The magnetic failures: this type of failure is a little bit different to observe, so it's only can be detected by checking the associated parts and analyze the failure under the actual operation conditions, if we just observe the phenomenon, the noise is also the evidence of this stress. For the loose rotor bars , they always can cause the noise or sparking during the startup, for the noise, if the force make the rotor pullover and stator connect , the vibration may happen even create the failure, another source of the vibration is the bar pounds outs of the slot and contact with the stator or winding, so the vibration will happen, not only the noise but also the loose or even broken the rotor. For the sparking, they are divided into two type. First is normal sparking, it means that the sparking can be observed during the normal operation, another form is may lead to the fatigue failure.

The dynamic failure: The source of this stress is mainly from the external force. Like cyclical, vibration and torque stress, they may result in the shaft or bearing broken, this factor can create the damage on the entire motor, not just the rotor.

The environment failure: For this factor, the failure will happen mainly because of the ambient temperature or humidity or the wrong maintenance method, they will lead to the overheating or rust the components. If the foreign material enters the rotor, they even may break the rotor [14]

The common faults of stator

the culprits of this failure are the break of the stator winding, they mainly divided into three type: 1) Short circuit between two turns but on the same phase: turn to turn fault .2) Short circuit between two coils on the same phase: coil to coil fault. 3) Short circuit between two turns of same phase: phase to phase fault.4) Short circuit between the winding conductor and the stator 5) Open circuit when winding get break.

if we concluded those failure, it can be divided into several causes, they have three type mainly:

1: Thermal effects, this type of stress is mainly due to the thermal overloading, the culprits of this failure stress are diverse, such as the voltage variations: due to the horsepower of the motor on the given frame structure is larger than before; second is the unbalanced phase voltage; obstructed ventilation; the higher ambient temperature , those above reason both can cause the over current flowing , according to the $Q = I^2RT$, the wire temperature will rise, as a rule of thumb, for the temperature increase every 10°C, the insulation life is decreased half respect before, so the insulation system will become vulnerable and easier fail. This is the failure due to the thermal respect the factor of winding insulation system aging.

2: Electrical reason: this failure mainly because of the supply voltage transient is larger than the normal value, this phenomenon may cause by the different fault (like line-to-line, line-to-ground, or three-phase fault), those fail may reduce the stator life, even cause the premature failures (turn to turn or turn to ground failure)

3: Mechanical stress: this reason means the movement between stator and the rotor, this action will damage the coil insulation, loosen or even break the conductor. Beside this type of action, other damage action named rotor strikes, maybe the bearing failure or rotor-to stator misalignment, the stator will hit against during the startup phase.

4: Environmental stresses: as the name, those stress mainly because of the unsuitable environment, like too hot or too humid, for example, the high temperature may reduce the heat dissipation, it will lead to reduce the insulation life. If the environment is too humid, the condition of the air may also influence the effect of the insulation system.[15]

The Common faults of air gap

This failure means the uneven distribution of air gap between stator and rotor. Insufficient rotor stiffness, bearing wear or installation error, they both can lead to the air gap eccentricity. The air gap eccentricity of the motor can be roughly divided into two types: static eccentricity, it means stator and rotor has different centers, rotor use its own geometric axis as the axis of rotation; The other is dynamic eccentricity, which specifies that the rotor and stator has different centers, but the rotor takes the geometric axis of the stator as its axis of rotation. Other complex eccentricity is a combination of those two basic types, such as mixed eccentricity and axial variation eccentricity. If the air-gap eccentric is happened, it will produce distortion in the gap magnetic field, worsen each performance index of motor, have damage to the motor support system, when motor eccentric fault serious, cause and rotor rub, make motor burn down and may even lead to major accidents machine apart.

The other failures

this type of failure contains many possibility cases, like the foreign substances get into the motor, the external impact on the motor or the mis operation of the worker and so on. Both of them may produce the fail of the motor.

Until now, the failure will happen on the three main components are discussed. The following graph is the FTA (Fault tree analysis) of the motor:

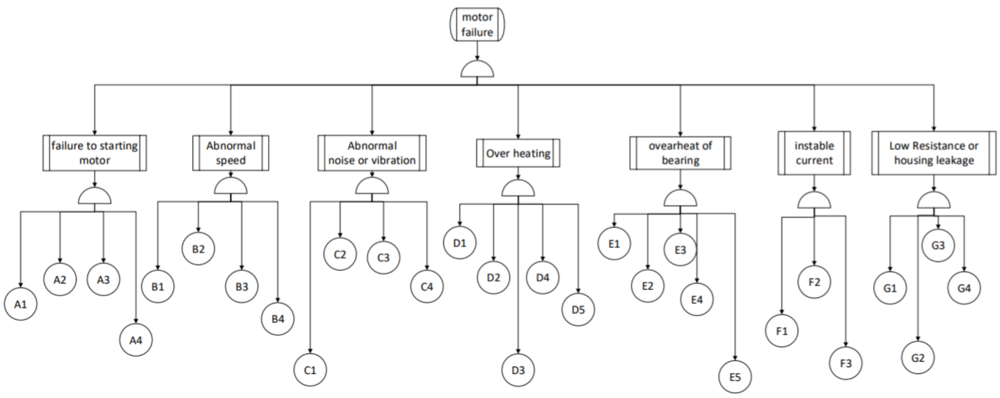

Figure 10 The fault tree of motor

Table 3 Fault tree analysis of motor

Level 0	Motor failure					
Level 1	A	starting mot failed	B	Abnormal speed	C	Abnormal noise or vibration
Level 2	A1	Open circuit	B1	Winding fault	C1	Failure of bearing
	A2	Winding fault	B2	Supply low voltage	C2	motor shaft bent

	A3	Supply low voltage	B3	Payload too high	C3	Mechanical friction		
	A4	Payload too high	B4	Failure of motor rotor	C4	Uneven mounting base		
Level 0	Motor failure							
Level 1	D	Overheating	E	Overheating of bearing	F	Instable current	G	Low resistance and housing leakage
Level 2	D1	Ventilation system blocked	E1	Nearing broken	F1	Assembly defect	G1	Winding dampened
	D2	Operate in one direction	E2	Unsuitable fit between shaft and bearing	F2	Unstable supply voltage	G2	Wire attach the cover of motor
	D3	Incorrect connection of motor	E3	Lubrication problem	F3	Motor winding connection incorrect	G3	Insulation aging
	D4	Overload	E4	Convey is tight	F4		G4	Grounding wire connected incorrect
	D5	rotor and stator friction)	E5	unsuitable assembly of cover				

About the symptom listed below, the abnormal noise is the failure always happened of the motor. So, the following will explain the main source of the noise: they are electromagnetic noise, mechanical noise, and ventilation noise.

electromagnetic noise: in the motor air gap. the radial force changing with time and space which provided by the magnetic field. This force will make the stator core and the frame deformation over time, it will lead to enlarge the vibration amplitude of the stator in the process of operation, so electromagnetic noise is the main source of the vibration of the stator and the surrounding air vibration caused by airborne noise. Generally speaking, it will increase as the power of the motor increases, and if the design or installation is not appropriate, electromagnetic noise will become very obvious and become the main noise source.

Mechanical noise: those noise for mechanical vibration and the noise of bearing are caused by the imbalance of the mechanical, for the noise from the bearing, the cause is mainly due to the surface of bearing which they work is damage, affects the rotating accuracy, causing the vibration noise, often in the frequency range from 1 to 5 KHZ, rush on 2 KHZ or 3 KHZ.

Ventilation noise: when the fan is in operation, the cooling gas will make the surrounding air vibrate periodically, and if it is improperly installed, the design of wind path is unreasonable or the foreign substance getting into the system, the noise will be higher than the usual.

3.6 The failure mode of reducer

In the robot system, the transmission system means the reducer. they will multiply the torque created by the motor. meanwhile, they can reduce the speed of the input value, so that the output will have the suitable speed. the following will analyze the failure mode of the main type of reducer in the factory. In spite of all are combined by gear in the gearbox, they still are a kind of precise mechanical equipment, it can be classified according to transmission type and layout:

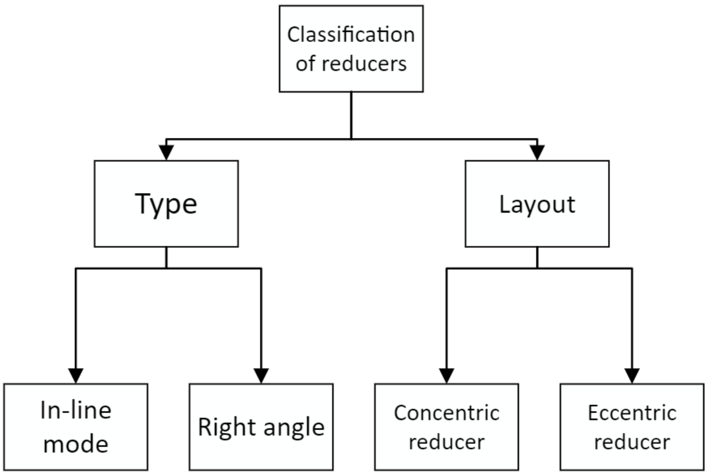

Figure 11 The type of reducer

For the type of reducer, in-line models are combined by the helical or spur gears or planetary gears, Planetary design generally provide the highest torque in small package, the helical and spur reducers are the most economical one and all of them are efficient.

Right angle designs are made with worm gearing or bevel gearing, the effect of reduction is fairly considerable. But an effective will be lower respect the in-line mode. Therefore, it's better to choose the type of device by considering the requirement exactly needed.

When consider the failure, it can be found that no matter the type of the transmission, transmission series, shape or structure of the reducer, its general structure is analog, consisting of gears, bearings, shafts, coupling and other small components. So, the main failures are due to that four main equipment. The statistical results of the failure types are shown in the table.

Table 4 The failure type of reducer

Failure mode	Percentage	Failure mode	Percentage
Gear	52	Bearing	29
Shaft	9	Rotor unbalance	4
Others	6		

As can be seen from the table, several common faults account for 90% of the failure rate of the reducer, mainly caused by the gear and rolling bearing.

3.6.1 The failure of the gear

Because of the gears mesh with each other, the various vibrations between the gears in the process of operation is inevitably. Over time, there will be diverse failure forms of the gears, as shown in the figure below：

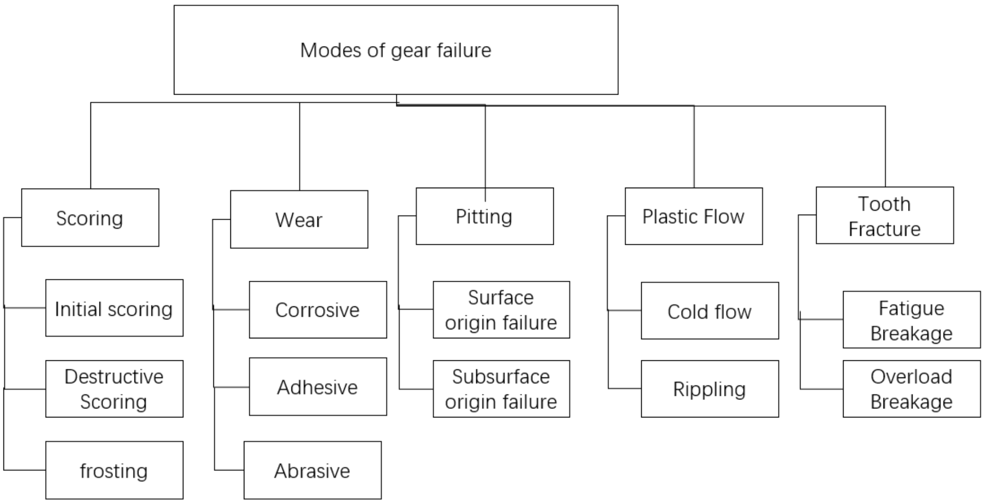

Figure 12 Different mode of failure

For example, the tooth fracture will be happened in the situation of braking suddenly. it will lead to the gearbox bear the shock load also the quantity is extraordinary huge, this peak load will over the limit of the gear, so the fracture is happened.

For the scoring, this situation is occurred due to the failure of lubrication between the contact surface. So, the contact directly between metal will happened. According to the level of severity, it can be classed into three phases: initial, moderate and destructive scoring. those failure happened in sequence with the continually increase of load, speed or oil temperature.

As for the gear wear. The main symptom is tooth thins down and gets weakened. it's mainly because of the lack of lubricate grease, ingress of foreign substance in the oil and have chemical degrade for the lubrication grease.

When the pitting happened. It will be seen that the fatigue failure on the tooth of gear. It happens because of the loading apply on the surface of tooth repeatedly and the value of contact stress exceed the limit of the material can bore.

As for the plastic flow of tooth surface. It will be happened if have the high contact stress under rolling cum sliding action. Surface deformation happens due to yielding of surface. Normally this situation appears in some materials of gear is soft.

Tooth fracture is the most dangerous type in the gear failure, it's leads to lameness of the drive and damage of some components (shafts, bearings, etc.) due to the exist of the broken teeth. this breakage may create the high overloads on the other teeth and this repeated overload causing the fatigue even fracture other teeth.

3.6.2 The failure of the shaft

The pattern of manifestation is mainly the wearing and fracture. For the wearing, it’s caused by the relative motion between the shaft and bearing. As for the fracture, it’s mainly caused by overload.

Another type is list following:

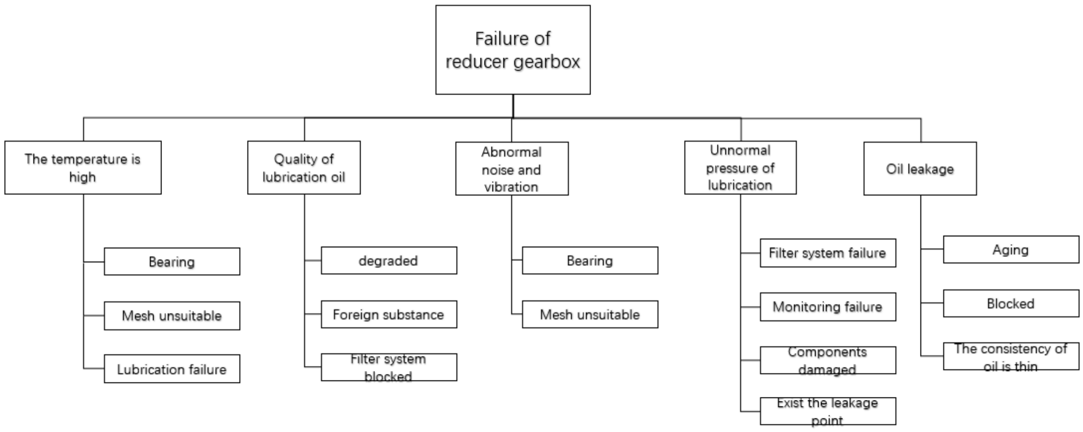

Figure 13 Fault tree analysis of reducer gearbox

Coupling: As the device placed between motors and drive shaft, it is fragile to break. This device is two shafts ends (the driving shaft and the driven shaft) in different mechanisms are connected to rotate them together, in order to transmits torque. They also can reduce the loads on the motor due to the arrangement is misalignment between the shaft. if the power transmission is operated in high speed and heavy load, some couplings also have function of buffering, vibration damping and improvement the function of dynamic performance of shafting.

They have a main type of the transmission joints:

1: Rigid joint: they are used to connect two perfectly coaxial shafts without any divergence. It means they requires strict alignment, cannot contain any relative displacement, like flange coupler or discs.

2: Elastic joint: thanks to the presence of a flexible element, they allow the absorption of torsional vibrations and they allow the divergence exist. Because they can compensate by the elastic element. They can be: pegs, collar or spring. They do not need lubrication periodically but it’s necessary to change it if the function is failure.

3: Toothed joint: they allow a slight misalignment between the two shafts and with respect to the elastic couplings. they can transmit a greater torque. The drawback that they need a periodic lubrication;

4: Universal joint: this coupling can achieve the one or more rotation shaft connect together, so they transmit the rotary motion only, due to this characteristic, the transmission efficiency is high however, for this type of joint, the wear will happen more frequently, so the lubrication is more necessary.

3.6.3 The failure of power amplifier

The failure mode of amplifier mainly divided into two types:

the input waveform cannot be amplified normally, it means that in the circuit, it still exists the output signal, but the voltage or current cannot reach the value needed. The main culprit of this symptom is the resistance in the circuit is increased from some reason, so the other parameters: the current and voltage are changed.

It's not existed the output signal. The main cause is the circuit problem. Because of the aging wire or loop connection in circuit, so the open circuit cannot transmit the signal.

This kind of failure can be found when the power supply work normally but the motor cannot start up even through the motor is function well. If discuss the consequence of those two failures, they both can block the correct voltage and current that amplified by themselves from supplier to the motor. No matter the power is supplied normally. This device like the bridge connect the two parts.

3.6.4 The failure of power supply

Due to the power in the factory is always supplied by the power station which supply the industry voltage. Depending on the voltage required by the robot, if it's same with the industry voltage, it's no need the transformer, but if the voltage required is lower than the 230 V. the transformer is needed. The transformer has many types of failure mode, like short circuit; insulation failure; switch failure, etc. Because the value of the voltage is too high, the consequence is too big to predict, the ignition may happen even explore, bring the damage to the person.

On the other hand, according to the description of this robot. The current is alternate current, so the bridge rectifier is not necessary.

3.7 the failure mode of the cooling system

Although the cooling system have a diverse type, the basic components is nearly same, so the analyzing will be based on the more foundational one, following is the fault tree that mainly describe the mechanical failure, about the electric part, it will be discuss in the chapter control system:

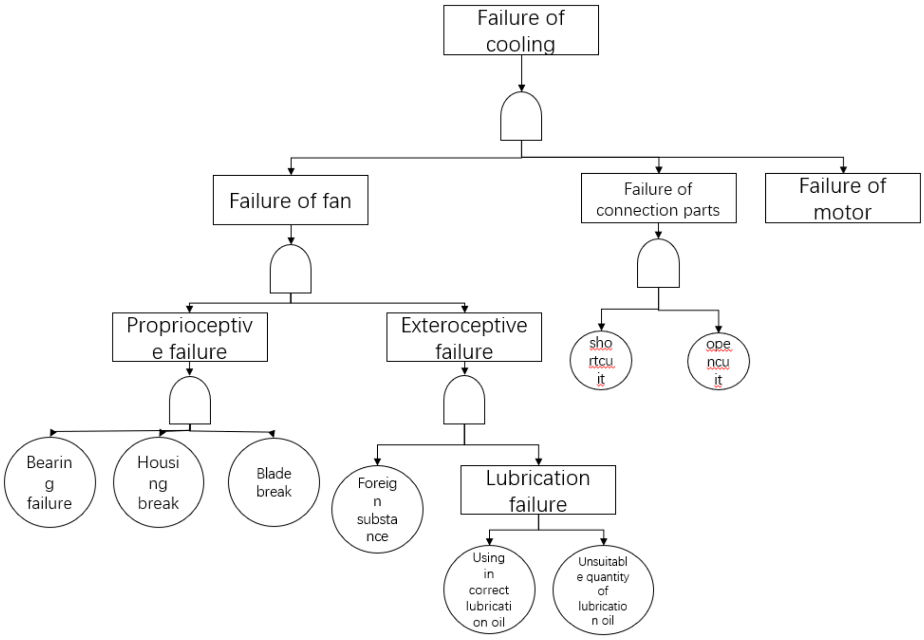

Figure 14 Fault tree analysis of cooling system

The failure of the motor, in this case, it's the failure which happened mostly, the probability around 98.9%, then the probability of following case is just a tiny fraction, like the failure of connection part is just 0.6%, like the insulation problem, as for the failure due to the fan themselves: fan blades or fan housing break, the probability is just 0.5% [16]

3.8 the failure mode of the control system

Due to the control system are combined with two parts: software and hardware, it is more convenient to analyze the failure mode from each part.

In software part: The common failure of program is program crash, like divide by zero or arithmetic overflow, although those failure are happened at the algorithms level, it will lead to the action failure, it will stops functioning properly and exits. even the task cannot be accomplished or the manipulator are out of control directly

In hardware part: About the ECU, out of the consider of their functions, it can be concluded in following three type: failure to transmit data with external control, failure to command controllers and cannot read data from sensors, it means that if the dynamic error happened and lead to the trajectory of manipulate is out of line, it will not recovery even loss control. As for the fieldbus breakdown, considering their function are connect each part's data, the communication with each other will arise the problem. The typical errors on the propagate phase are: receiving data repeatedly; losing the data; being inserted another data irrelevant; the wrong sequence of data; the lower velocity to receive data. Those faults will happen on the part of receive data or the transmit data that already corrected. However, no matter the position exactly happened, the failure mode that the operator will observe is the error cannot be correct during the process.

Because usually the working environment is tough and have many potential risks, the hardware is relative easier to break, the maintenance is necessary. The main failure for the hardware is following: We search the one type of control system in ten years. in the 962 failure. the failure probability due to the external environment is frequently, around 4% (39 times). For the failure of the components themselves is rarely, around 0.2% (2 times). The failure due to the incorrect installation at the beginning is relative higher, they have 324 times (34%) in this period. For the problem of the connection, about the wire which exposed in the working condition, the likelihood of occurrence is higher: the weather issue; short-circuit due to the wire damaging or the vibration of the robot. If collected together, the probability is around 61% (588 incidents). However, the failure owe to the connection problem in the fieldbus is just 4 times (0.4%). As for the remaining of 5 incidents, it's the software's error, due to the mainly component is the program designed, the invalidation mostly caused by the programmer's error (2 times 0.18%) or the bug for the system (3 times 0.22%). (fieldbus and availability). And due to this article is calculate the fault in two years, it's necessary to divided in five to consider the probability in two years.[17]

Chapter 4

The case study

In this chapter, the real operation which need the worker and robot to work together will be introduced, and we will use the software to analyze the sequence. After the result showing up, the user also can decide to take some measures to decrease the risks through reducing the failure probability of each sequence, so that the safe of operator will be ensured.

4.1 the case study

In this article, the procedure that need to be analyzed is the assembly of the break disc, this is the type of brake that uses calipers to compress the pads to create friction, in order to stop the action of the wheel efficiently.

In this article, the procedure that assemble the break disc is divided into following phase:

1: The manipulator takes the dust protection from the plate and put it on the assembly station

2: Then, the operator takes the M6 screws from the box and then put it inside the dust protection

3. The operator exits the assembly station and the manipulator begin the screwing operation. When the task finish, go back to the home position.

4: The operator enters the assembly station again and changing the manipulator's tool, then take the hub from the plate and put it on the dust protection. Finally, leave the working area, the robot starts to work.

5: The last step is the manipulator taking the break disc on the assembly station, the operator enters again and takes M8 screws, puts them on the parts, exits the assembly station. Then the manipulator begins to screw.

Because in this procedure, not only the robot, but also the operator is joined. Due to the exist of the interaction between human and robot. Before analyzing the sequence, we can list all the events in more detailed way. Firstly, we divided those tasks into three main tasks:

Assemble the dust protection on the assembly station

Insert the hub and change the robot tips

Assemble the brake disc on the assembly station

Then, we divided those three tasks into the single task and point out the procedure which finished by the operator (M means manipulator H means human)

1.1M: carrying the dust protection from the pallet (13s)

1.2M: position the dust protection on the assembly station (14-30s)

1.3H: the human gets into the working area (31-35s)

1.4H: operator takes the three M6 screw from the screw kit and position them on the dust protector (36-47s)

1.5H: operator exits the working station (48-50s)

1.6M: the robot moves to the right position to begin screwing(tighten) (51-86s)

1.7M: After the screwing, go back to the home position (87-91s)

From this phase, the first task is finish, then it's the assemble of the hub

2.1H: operator enter the working station again (92-95s)

2.2H: changing the robot tool from tip 1 to tip 2(put tip1 from gripper to the tip kit and position the tip 2 to the gripper) (96-108s)

2.3H: take the hub and position it on the dust protection (109-119s)

2.4 H: the operator exist the working station and the robot continue to work (120-122s)

Until now, the second phase is finish, as for the last task:

3.1M: taking the brake disc and then position it on the hub in the assembly station (123-150s)

3.2H: the operator enter the working area (151-153s)

3.3H: the operator takes two M8 screw form the kit and put it on the brake disc (154-171s)

3.4H: The operator leaves the working station (172-174s)

3.5M: The robot continues to finish the screwing task and when finish the task, go back to the home station (175-203s)

According to the procedure described above and the equipment's failure mode analyzed at the second chapter, the graph to list all the failure mode and effect will list below:

Table 5 The failure mode and effect of the manipulator

Manipulator					
Failure type / Procedure	The performance under the failure of joint (65%)		The performance under the failure of circuit connection(25%)		The performance under the failure of material(10%)
	Joint-locked(35%)	Free swing(30%)	Open circuit(10%)	Short circuit(15%)	
Carrying the protection	robot arm cannot move	robot arm move freely but have wrong destination	robot arm cannot move	robot cannot move and burn out the electric components	working normally but observe the crake on robot. Even fracture.
Set the protection on station					
Return the home position					
Back to assembly for screwing					
Tightening the screw					
Carrying the brake disc					
Setting the disc on station					
Tightening the screw					

Table 6 The failure mode of the end effect

End Effect			
Failure type / Procedure	The performance under the failure of circuit connection		The performance under the failure of material failure(20%)
	open circuit(40%)	short circuit(40%)	
Carrying the protection	robot arm cannot move	robot cannot move and even burn out the electric components	picking unstable, cannot open the fixture, the part fall down when operate
Set the protection on station			during the operation. Part fall down;put on the wrong position
Return the home position			no end effect to be needed
Back to assembly for screwing			
Tightening the screw			apply force incorrect
Carrying the brake disc			cannot picking by suitable force;cannot open the fixture;the part fall down during the operate
Setting the disc on station			load down on the half way; unload at the wrong position
Tightening the screw			apply force incorrect

Table 8 The failure mode of the sensor

Sensor				
Failure type / Procedure	Vibration(40%)	Insulation (20%)	Components (12%)	External Environment (28%)
Carrying the protection	precision reduction	complete failure fault; drift deviation fault	fixed deviation; fault drift deviation fault; precision reduction	complete failure fault
Set the protection on station				
Return the home position				
Back to assembly for screwing				
Tightening the screw				
Carrying the brake disc				
Setting the disc on station				
Tightening the screw				

Table 7 The failure mode of reducer

Reducer				
Failure type / Procedure	shaft&gear failure(52%+9%)	bearing(29%)	rotor unbalance(4%)	other(lubrication, seal)(6%)
Carrying the protection	components failure(fracture)	abnormal noise & high temperature	bolt fracture	incorrect pressure of lubrication;oil leakage
Set the protection on station				
Return the home position				
Back to assembly for screwing				
Tightening the screw				
Carrying the brake disc				
Setting the disc on station				
Tightening the screw				

Table 9 The failure mode of cooling system

Cooling System					
Failure type	failure of fan 0.5%		failure of connection parts 0.6%		motor 98.9%
Procedure	propriocetive failure	exteroceptive failure	shortcuit	opensuit	
Carrying the protection	crack on the fan components	fan abrasion	cannot work or even burn the components	fan cannot work	velocity is not correct
Set the protection on station					
Return the home position					
Back to assembly for screwing					
Tightening the screw					
Carrying the brake disc					
Setting the disc on station					
Tightening the screw					

Before we use the program to analyzing the failure probability and reduce the value to decrease the risks, the relationship between the risks and failure probability.

In the factory, if you want to apply some measures to reduce the risks for the machine itself or human, the analysis and evaluation of risk is necessary. As for the assessment method, when the risk occurs, most of them are caused by the failure happened, So the analysis of the failure mode and effect of the failure, it’s also means that we are analyzing the corresponding risks that may occur due to those failure, the action applied to reduce the failure probability also means the risks can be also reduced. In this article, we not only focus on the robot failure itself, due to the specificity of human-robot interaction, the source of the failure is also from the human error and the failure when interacting. In this way, we will analyze the possible failures of each component combine the probability and then take the measures according to those sources.

4.2 the program analyzes

In this article, the software: IDDA will be used. For writing the program, the graph needs to be used, named events tree, we will introduce later. In the result windows, they can analyze all the failure probability of events also the diagram of the cumulative probability, it will be more clearly to assess the risks of all the sequence and optimize the consequence in the procedure through the result, increase the operator's safety when they work with the robot.

As for the event tree, this is the graph that can list all the sequence in the operation, they start from the initial event, named Top-tree. A "consequence tree" describes the possible chains of consequences initiated from the Top-event. A consequence may further cause other consequences, they are leading to the different results finally, as for the events, they are exclusively or independently. This combination of cause trees and consequence trees will be called as "functional failure modes cause-consequence tree" also named "events tree". They also have one characteristic: The sum of the probabilities of each event that forms a branch is equal to 1. Thanks to the events tree method, all the events in the process can be distinguished, according to the request of the software, we describe all the events(sequence) by using the question. Each time we have the question, we called each level in this procedure, so according to the description of the procedure before, all the possible sequence of events will be shown. Then the probability of each level will be calculated in software, at the same time, the diagram of the cumulative probability will be drawn. So, each level will be represented by the probability of the alternative outcome, in this article, only two outcomes: success and fail will be considered.

According to the description of the procedure, the event tree can be listed below:

Table 10 The events tree

Level	The name of each level
1	carrying the dust protection
50	position the dust protection on the assembly station
100	the human gets into the working area
150	operator takes the three M6 screw and position them on the dust protector
200	operator exits the working station
250	screwing
300	go back to the home position
350	operator enter the working station
400	changing the robot tool

450	take the hub and position it on the dust protection
500	operator exist the working station
550	taking the brake disc and position it on the hub in the assembly station
600	operator enter the working area
650	operator takes two M8 screw and put it on the brake disc
700	operator leave the working station
750	screwing
800	go back to the home station

As for the method to calculate the failure probability in each level. First of all, we need to know this is the calculation in the aspect of reliability problem. In order to get the probability of the machine can perform its required function in the certain period of time, the MTBF (mean time between failure) can quantified this into parameter.

According to the data that we search before, we already knew the failure rate λ (0.05 failure happened per hour), due to the MTBF is the inverse of the failure rate in the constant failure rate phase and this formula combine the exponential modeling of the bathtub curve:

$$\mathrm{P(t)} = e^{-t/MTBF} = e^{-\lambda t}$$

To get the probability, however this value is the probability of success, Using the P(f)=1-P(t) to get the probability of the failure which equal to $2.82*10^{-3}$. Due to this probability is the failure in the 203s which the total operation time, in each sequence, the operation time is diverse, so the probability is not same, it means that more operation time corresponding the larger failure probability. On the other hand, because in those process, they also contain the events finished by the operator, the failure probability of them will be referenced directly on the graph [18]. combining the robot failure probability in this process and the occupational failure the graph can be listed below:

Table 11 The evens tree and the corresponding data

Level	The name of each level	The operation time	The probability
1	carrying the dust protection	13	0.000180591
50	position the dust protection on the assembly station	16	0.000222
100	the human gets into the working area	4	0.0004(G)
150	operator takes the three M6 screw and position them on the dust protector	11	0.02(E)
200	operator exits the working station	2	0.0004(G)

250	screwing	35	0.000486
300	go back to the home position	4	0.0000556
350	operator enter the working station	3	0.0004(G)
400	changing the robot tool	12	0.02(E)
450	take the hub and position it on the dust protection	10	0.0004(G)
500	operator exist the working station	2	0.0004(G)
550	taking the brake disc and position it on the hub in the assembly station	27	0.000375
600	operator enter the working area	2	0.0004(G)
650	operator takes two M8 screw and put it on the brake disc	17	0.02(E)
700	operator leave the working station	2	0.0004(G)
750	screwing	24	0.000333
800	go back to the home station	4	0.0000556

Until now, all the information is collected, we will input in the IDDA, the program is listing below:

1 1, 0.000222266 1., 50 2000, 'carrying dust protection?' 'Yes' 'No'

This sentence means that, for the question of the first task (first events in the sequence), if the answer is yes, it means the dust protection is been taken, they will get to the next level (50), if the answer is no, it means the failure is happened, so we will make the command the robot to jumped to the final level (2000): stop the machine. We translate this question and the option occurrence into the input. As for the 0.000222266, this means the probability of this failure happened.

The following is input language to express the second question:

Question 2: does the dust protection position perfect?

50 1, 0.000222266 1., 100 2000, 'position the dust protection?' 'Yes' 'No'

the logical constraint will be used, in order to recognize the output must be forced:

L 50 1, 2000 1

Question 3: does the dust protection position perfect?

100 1, 0.0004 1., 150 2000, 'the operator enter in the working area?' 'Yes' 'No'

L 100 1, 2000 1

Question 4: does the operator takes the screw?

150 1, 0.02 1., 200 2000, 'the operator takes the screw?' 'Yes' 'No'

L 150 1, 2000 1

Until now, in the first task, all the events finished by the robot are translated into the order, the following command is relative different, because the human will participate, so beside the failure of the robot, we also need to consider the failure about human and the incident may occur. For example, if the operator cannot exit from the working station, the incidents will happen when the next level is running.

Question 5: Does the operator exits from the working station?

200 1, 0004 1., 250 250, 'the operator exits from the working station?' 'Yes' 'No'

This order named address level, when the situation that the operator cannot leave the working area, we need to evaluate the probability of the incident, because if the robot cannot screw at next level, the part is failed but the incident will not happen. Aim at this possibility, the address level constraint is necessary.

A 200 1, 250, 2001 2000
L 200 1, 2001 1

Question 6: does the robot begin the screw?

250 1, 0.000486207 1., 300 2000, 'start screw?' 'Yes' 'No'

If the robot start screw, we can make sure the incident is happened, so the stop order will be applied, that is the meaning of the next order.

L 250 1, 2001 0
L 250 1, 2000 1

Question 7: does the robot go back to the home position?

300 1, 0.0000556 1., 350 2000, ' go back at home position?' 'Yes' 'No'
L 300 1, 2000 1

Question 8: does the operator get in the working station?

350 1, 0.0004 1., 400 2000, 'operator in the working station?' 'Yes' 'No'
L 350 1, 2000 1

Question 9: does the operator replace the robot tool?

400 1, 0.02 1., 450 2000, 'replace the robot tool?' 'Yes' 'No'
L 400 1, 2000 1

Question 10: does the operator takes the hub on the dust protection?

450 1, 0.0004 1., 500 2000, 'take the hub on dust protection?' 'Yes' 'No'
L 450 1, 2000 1

Question 11: does the operator exits from the working station?

500 1, 0.0004 1., 550 550, 'The operator exits from the working station?' 'Yes' 'No'

The function of those two sentences are same like before:

A 500 1, 550, 2001 2000
L 500 1, 2001 1

Question 12: does the robot take the brake disc in the hub?

550 1, 0.000375 1., 600 2000, 'The robot take the brake disc in the hub?' 'Yes' 'No'
L 550 1, 2001 0
L 550 1, 2000 1

Question 13: does the operator enter the working station?

600 1, 0.0004 1., 650 2000, 'operator in the working station?' 'Yes' 'No'
L 600 1, 2000 1

Question 14: does the operator takes the screw?

650 1, 0.02 1., 700 2000, 'the operator takes the screw?' 'Yes' 'No'
L 650 1, 2000 1

Question 15: does the operator exits from the working station?

700 1, 0.0004 1., 750 750, 'The operator exits from the working station?' 'Yes' 'No'
A 700 1, 750, 2001 2000
L 700 1, 2001 1

Question 16: does the robot start to screwing?

750 1, 0.000333 1., 800 2000, 'start screw?' 'Yes' 'No'
L 750 1, 2001 0
L 750 1, 2000 1

Question 17: does the robot get back to the home position?

```
800 1, 0.0000556 1., 2000 2000, ' go back at home position?' 'Yes' 'No'
L 800 1, 2000 1

2000 1, 0. 1., 2001 2001, 'Procedure is finish in correct way?' 'Yes' 'No'
2001 1, 0. 1., 0 0, 'The operator incidents?' 'No' 'Yes'
```

After checking all the question in the procedure are wrote in the program, we will get the result directly (All the results are listed at the appendix, following is the result need to be analyzed mainly):

```
Current event sequence number 1, Event tree sequence number 1
Sequence probability: 0.936958
No consequences file defined
Level Out Probability Cumulative T. Factor Mission T. Description
1     0  1-1.81e-04    9.9982e-01       carrying dust protection?  Yes
50    0  1-2.22e-04    9.9960e-01       position the dust protection?  Yes
100   0  1-4.00e-04    9.9920e-01       the operator enter in the working area?  Yes
150   0  1-2.00e-02    9.7921e-01       the operator takes the screw?  Yes
200   0  1-4.00e-04    9.7882e-01       the operator exits from the working station?  Yes
250   0  1-4.86e-04    9.7835e-01       start screw?  Yes
300   0  1-5.56e-05    9.7829e-01       go back at home position?  Yes
350   0  1-4.00e-04    9.7790e-01       operator in the working station?  Yes
400   0  1-2.00e-02    9.5834e-01       replace the robot tool?  Yes
450   0  1-4.00e-04    9.5796e-01       take the hub on dust protection?  Yes
500   0  1-4.00e-04    9.5758e-01       The operator exits from the working station?  Yes
550   0  1-3.75e-04    9.5722e-01       The robot take the brake disc in the hub?  Yes
600   0  1-4.00e-04    9.5683e-01       operator in the working station?  Yes
650   0  1-2.00e-02    9.3770e-01       the operator takess the screw?  Yes
700   0  1-4.00e-04    9.3732e-01       The operator exits from the working station?  Yes
750   0  1-3.33e-04    9.3701e-01       start screw?  Yes
800   0  1-5.56e-05    9.3696e-01       go back at home position?  Yes
2000  #0               0.937            Procedure is finish in correct way?  Yes
2001  #0               0.937            The operator incidents?  No

Current event sequence number  21  , Event tree sequence number  21
Sequence probability : 0.000180591
No consequences file defined

Level Out Probability Cumulative  T. Factor  Mission T. Description

1     1    1.81e-04    1.8059e-04       carrying dust protection?  No
2000  #0               0.0001806        Procedure is finish in correct way?  Yes
2001  #0               0.0001806        The operator incidents?  No
```

If analyzing from those data, it’s can be found that:

- Due to the third column. it’s the probability of the event happened success, we can calculate the level 150,400,650 are three events which have highest probability of the failure, those three levels are also the procedure that finished by the worker
- The probability of this sequence (success one) is 0.936958
- The sequence number is equal to 21

● We translate the cumulative probability into the graph to represent the cumulative probability of the failure, the result is following:

From the graph, we also observe the influence of those three levels. In this way,

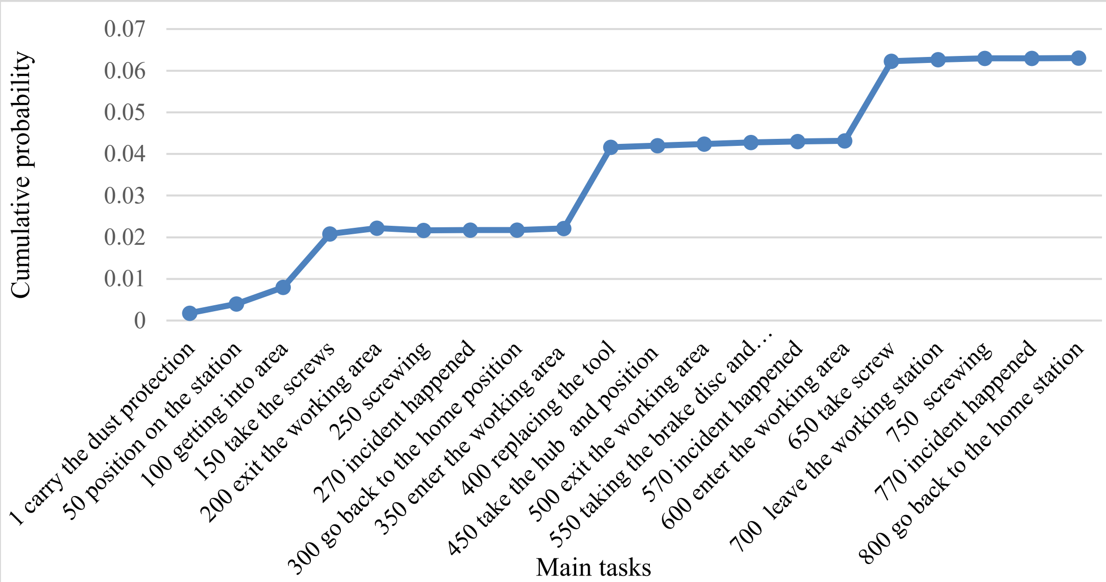

Figure 15 The cumulative probability of failure

we can highlight which tasks within the procedure are mainly contributes to the failure of the robot in activity.

If we bring to the production delay, if the one of the procedures is fail, the delay time need to be considered, according to the operation time and the complex level of each task, each number is different, for example, for the level 250, the robot will start the screwing. This procedure needs the participate of nearly all equipment. so the if the failure happened, the recovery time is 22 minutes, however for the level 300, if the robot cannot go back to the home position, the delay time may just 2 minute, so the risk didn't account a lot in this procedure.

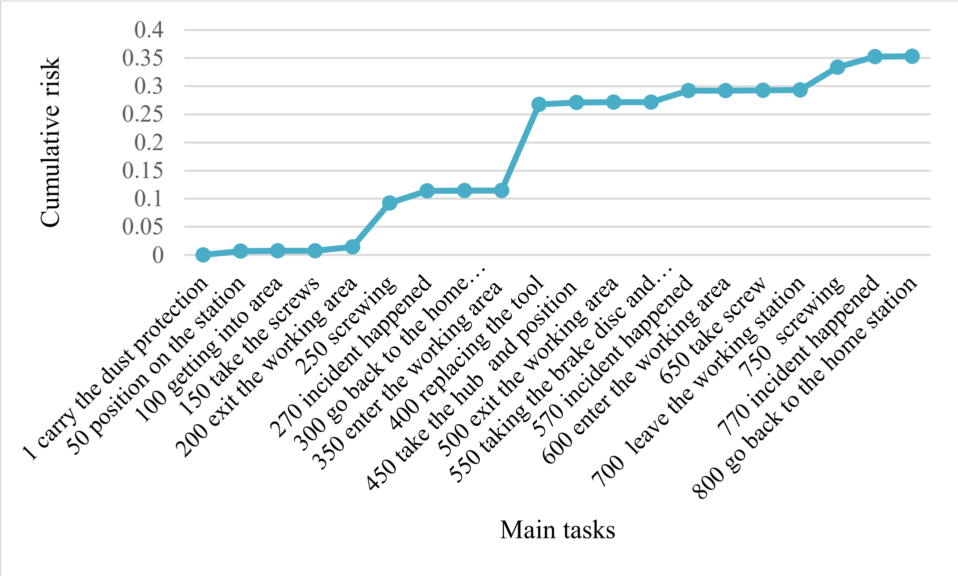

Figure 16 The cumulative of risk in delay time

If we compare those two figures, it can be observed that one phenomenon, although the probability of the failure is relative larger at the level 150,650: taking the screw and level 400: replace the tool, when we consider the production delay problem. The high risk may influence the operator's safer will be the level 250: screwing 400: replace the tool and the 750 screwing again. Beside this, we can observe that the incident happened also have a relative higher risk. It means that the levels needed to be optimized are not only depend on the probability. But also the consequence of the risk. In this way, the result can help user to decide the optimize action.

So, according to those results, due to the risk happened at the event which worker are participate and also the robot system working. the one of the optimize action that I propose is set the guide to the operator when they take the screws, because the failure probability will decrease a lot when the task is completely familiar for the operator that have high practiced. And the probability even can decrease more if the task will be finished by the assist of the supervisory system, like set the guide to help operator, another method also can improve the success probability is ensuring the ergonomic position for the operator in the task, in this way, they won't become fatigue more easily and improve the productivity Those are the optimize action for the operator. As for the measurements based on the robot system, the mainly methods are use the machine following the instructions, check the state of the robot regularly to avoid the potential risks. For the aspect of structure system like modifying the structure of the control system, set the independent safe system on the fieldbus rather than set the safety protect on each board. In this way, this design will be more convenient to observe and fix the error parts, not only reduce the time, but also save the maintenance cost.

Chapter 5

Conclusion

In this paper, it concludes the introduction about the robot system, especially the mainly components of the robot arm, like the manipulator, actuator system, sensor and so on, because this type of robot is necessary to collaborate with the worker to finish some complex tasks, so evaluating the potential risks when they work in the same working area is initial. In this way, at the second and third chapters, we described the failure mode, cause and the effect of each components, according to those failure, we evaluate the risks may happened during the working period, and in order to describe them in more detailed way, we used the IDDA software to evaluate the probability of the risks, list the occurrence sequence, also list the probability of the risks due to the production delay. Then we can point out the number of levels which is needed to be optimized. Through the result, the user can understand all the events may happened also the corresponding failure probability, and also the risks due to the production risks, so that the clients are easier to observe and make the optimize action.

The program of this sequence is attached at the end of the thesis. About the first one, we analyze based on the general evaluation about the events, it means that all the outcomes of the events in each level are only have two result, success or failure so, as the inputs of the program, the data we need to use is the probability of the failure for each sequence. This analyze is under the general evaluation, when the failure happened, the task will be end directly. However, in the real case, this operation will be carried out in more efficiency way. So, the future work is detailing the type of the failure mode in each level no matter the type of component and adding the corresponding possibility, in this article, the information that the probabilities of each failure mode in each component are already supplied. In this way, we can add the them in the program to evaluate the probability of each failure mode, due to the failure mode will show up in the same result although the broken part is different, therefore the probability is different with the information that I supplied in the above.

About the second part of the program, all the production delay time of each level if they failed are listed. Through the result, the level which need to be optimized is shown up. However, the delay not only the process delay, but also th another type of delay, like occupational delay, So we need to also consider the risk brought by this type of the delay, in order to get more precision results.

Appendix A

Result of program (failure probability)

October 4, 2018 11:35:02 am - View: c:\documents and settings\ieuser\desktop\robot\rev1\1.out

Current event sequence number 1 , Event tree sequence number 1
Sequence probability : 0.936958
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takess the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exitss from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exitss from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot takes the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 0 1-2.00e-02 9.3770e-01 the operator takes the screw? Yes
700 0 1-4.00e-04 9.3732e-01 The operator exitss from the working station? Yes
750 0 1-3.33e-04 9.3701e-01 start screw? Yes
800 0 1-5.56e-05 9.3696e-01 go back at home position? Yes
2000 #0 0.937 Procedure is finish in correct way? Yes
2001 #0 0.937 The operator incidents? No

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Current event sequence number 2 , Event tree sequence number 2
Sequence probability : 5.20977e-05
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enters in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takess the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exitss from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes

400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exitss from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot takes the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 0 1-2.00e-02 9.3770e-01 the operator takess the screw? Yes
700 0 1-4.00e-04 9.3732e-01 The operator exitss from the working station? Yes
750 0 1-3.33e-04 9.3701e-01 start screw? Yes
800 1 5.56e-05 5.2098e-05 go back at home position? No
2000 #1 5.21e-05 Procedure is finish in correct way? No
2001 #0 5.21e-05 The operator incidents? No

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Current event sequence number 3 , Event tree sequence number 3
Sequence probability : 0.000312128
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot take the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 0 1-2.00e-02 9.3770e-01 the operator takes the screw? Yes
700 0 1-4.00e-04 9.3732e-01 The operator exits from the working station? Yes
750 1 3.33e-04 3.1213e-04 start screw? No
2000 #1 0.0003121 Procedure is finish in correct way? No
2001 #0 0.0003121 The operator incidents? No

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Current event sequence number 4 , Event tree sequence number 4
Sequence probability : 0.000374954
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes

350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot take the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 0 1-2.00e-02 9.3770e-01 the operator takes the screw? Yes
700 1 4.00e-04 3.7508e-04 The operator exits from the working station? No
750 0 1-3.33e-04 3.7495e-04 start screw? Yes
2001 #1 0.000375 The operator incidents? Yes

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Current event sequence number 5 , Event tree sequence number 5
Sequence probability : 1.24901e-07
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot take the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 0 1-2.00e-02 9.3770e-01 the operator takes the screw? Yes
700 1 4.00e-04 3.7508e-04 The operator exits from the working station? No
750 1 3.33e-04 1.2490e-07 start screw? No
2000 #1 1.249e-07 Procedure is finish in correct way? No
2001 #0 1.249e-07 The operator incidents? No

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Current event sequence number 6 , Event tree sequence number 6
Sequence probability : 0.0191367
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes

400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot take the brake disc in the hub? Yes
600 0 1-4.00e-04 9.5683e-01 operator in the working station? Yes
650 1 2.00e-02 1.9137e-02 the operator takes the screw? No
2000 #1 0.01914 Procedure is finish in correct way? No
2001 #0 0.01914 The operator incidents? No

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Current event sequence number 7 , Event tree sequence number 7
Sequence probability : 0.000382887
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 0 1-3.75e-04 9.5722e-01 The robot take the brake disc in the hub? Yes
600 1 4.00e-04 3.8289e-04 operator in the working station? No
2000 #1 0.0003829 Procedure is finish in correct way? No
2001 #0 0.0003829 The operator incidents? No

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Current event sequence number 8 , Event tree sequence number 8
Sequence probability : 0.000359091
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 0 1-4.00e-04 9.5758e-01 The operator exits from the working station? Yes
550 1 3.75e-04 3.5909e-04 The robot take the brake disc in the hub? No
2000 #1 0.0003591 Procedure is finish in correct way? No

2001 #0 0.0003591 The operator incidents? No

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Current event sequence number 9 , Event tree sequence number 9
Sequence probability : 0.00038304
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 1 4.00e-04 3.8318e-04 The operator exits from the working station? No
550 0 1-3.75e-04 3.8304e-04 The robot take the brake disc in the hub? Yes
2001 #1 0.000383 The operator incidents? Yes

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Current event sequence number 10 , Event tree sequence number 10
Sequence probability : 1.43694e-07
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 0 1-4.00e-04 9.5796e-01 take the hub on dust protection? Yes
500 1 4.00e-04 3.8318e-04 The operator exits from the working station? No
550 1 3.75e-04 1.4369e-07 The robot take the brake disc in the hub? No
2000 #1 1.437e-07 Procedure is finish in correct way? No
2001 #0 1.437e-07 The operator incidents? No

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Current event sequence number 11 , Event tree sequence number 11
Sequence probability : 0.000383337

No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 0 1-2.00e-02 9.5834e-01 replace the robot tool? Yes
450 1 4.00e-04 3.8334e-04 take the hub on dust protection? No
2000 #1 0.0003833 Procedure is finish in correct way? No
2001 #0 0.0003833 The operator incidents? No

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Current event sequence number 12 , Event tree sequence number 12
Sequence probability : 0.019558
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 0 1-4.00e-04 9.7790e-01 operator in the working station? Yes
400 1 2.00e-02 1.9558e-02 replace the robot tool? No
2000 #1 0.01956 Procedure is finish in correct way? No
2001 #0 0.01956 The operator incidents? No

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Current event sequence number 13 , Event tree sequence number 13
Sequence probability : 0.000391317
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 0 1-5.56e-05 9.7829e-01 go back at home position? Yes
350 1 4.00e-04 3.9132e-04 operator in the working station? No
2000 #1 0.0003913 Procedure is finish in correct way? No

2001 #0 0.0003913 The operator incidents? No

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Current event sequence number 14 , Event tree sequence number 14
Sequence probability : 5.4396e-05
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 0 1-4.86e-04 9.7835e-01 start screw? Yes
300 1 5.56e-05 5.4396e-05 go back at home position? No
2000 #1 5.44e-05 Procedure is finish in correct way? No
2001 #0 5.44e-05 The operator incidents? No

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Current event sequence number 15 , Event tree sequence number 15
Sequence probability : 0.00047591
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 0 1-4.00e-04 9.7882e-01 the operator exits from the working station? Yes
250 1 4.86e-04 4.7591e-04 start screw? No
2000 #1 0.0004759 Procedure is finish in correct way? No
2001 #0 0.0004759 The operator incidents? No

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Current event sequence number 16 , Event tree sequence number 16
Sequence probability : 0.000391495
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 1 4.00e-04 3.9169e-04 the operator exits from the working station? No
250 0 1-4.86e-04 3.9149e-04 start screw? Yes

2001 #1 0.0003915 The operator incidents? Yes

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Current event sequence number 17 , Event tree sequence number 17
Sequence probability : 1.9044e-07
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 0 1-2.00e-02 9.7921e-01 the operator takes the screw? Yes
200 1 4.00e-04 3.9169e-04 the operator exits from the working station? No
250 1 4.86e-04 1.9044e-07 start screw? No
2000 #1 1.904e-07 Procedure is finish in correct way? No
2001 #0 1.904e-07 The operator incidents? No

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Current event sequence number 18 , Event tree sequence number 18
Sequence probability : 0.0199839
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 0 1-4.00e-04 9.9920e-01 the operator enter in the working area? Yes
150 1 2.00e-02 1.9984e-02 the operator takes the screw? No
2000 #1 0.01998 Procedure is finish in correct way? No
2001 #0 0.01998 The operator incidents? No

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Current event sequence number 19 , Event tree sequence number 19
Sequence probability : 0.000399839
No consequences file defined

Level Out Probability Cumulative T. Factor Mission T. Description

1 0 1-1.81e-04 9.9982e-01 carrying dust protection? Yes
50 0 1-2.22e-04 9.9960e-01 position the dust protection? Yes
100 1 4.00e-04 3.9984e-04 the operator enter in the working area? No
2000 #1 0.0003998 Procedure is finish in correct way? No
2001 #0 0.0003998 The operator incidents? No

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Current event sequence number 20 , Event tree sequence number 20
Sequence probability : 0.000222226
No consequences file defined

Level	Out	Probability	Cumulative	T. Factor	Mission T.	Description
1	0	1-1.81e-04	9.9982e-01			carrying dust protection? Yes
50	1	2.22e-04	2.2223e-04			position the dust protection? No
2000	#1		0.0002222			Procedure is finish in correct way? No
2001	#0		0.0002222			The operator incidents? No

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Current event sequence number 21 , Event tree sequence number 21
Sequence probability : 0.000180591
No consequences file defined

Level	Out	Probability	Cumulative	T. Factor	Mission T.	Description
1	1	1.81e-04	1.8059e-04			carrying dust protection? No
2000	#0		0.0001806			Procedure is finish in correct way? Yes
2001	#0		0.0001806			The operator incidents? No

Result of program (Cumulative distribution risk)

Seq.N.	Event Tree N.	Probability	Consequence	Risk
1	1	9.369576e-01	0.000000e+00	0.000000e+00
2	2	5.209774e-05	3.000000e+00	1.562932e-04
3	3	3.121282e-04	2.200000e+01	6.866820e-03
4	4	3.749539e-04	1.000000e+00	3.749539e-04
5	5	1.249012e-07	2.300000e+01	2.872728e-06
6	6	1.913667e-02	4.000000e+00	7.654669e-02
7	7	3.828866e-04	1.000000e+00	3.828866e-04
8	8	3.590908e-04	2.000000e+01	7.181817e-03
9	9	3.830398e-04	1.000000e+00	3.830398e-04
10	10	1.436938e-07	2.100000e+01	3.017570e-06
11	11	3.833368e-04	8.000000e+00	3.066695e-03
12	12	1.955800e-02	8.000000e+00	1.564640e-01

13	13	3.913166e-04	1.000000e+00	3.913166e-04
14	14	5.439603e-05	3.000000e+00	1.631881e-04
15	15	4.759100e-04	2.200000e+01	1.047002e-02
16	16	3.914949e-04	1.000000e+00	3.914949e-04
17	17	1.904402e-07	2.300000e+01	4.380124e-06
18	18	1.998395e-02	4.000000e+00	7.993579e-02
19	19	3.998389e-04	1.000000e+00	3.998389e-04
20	20	2.222259e-04	4.000000e+00	8.889034e-04
21	21	1.805910e-04	5.000000e+00	9.029550e-04

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