Master Degree Thesis

Human-Robot Collaboration
Analyzing the safety for human-robot collaboration in automotive industry

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Chapter 1 Introduction

1.1 Background

Human-Robot collaboration (HRC) is a new trend in the field of industrial and as an important part of the strategy Industry 4.0. The main goal of this new solution is to improve the safety, ergonomic, productivity and quality. This solution aims to fill the gap between manual manufacture and fully automated production, which means human shares the workspace with the robot where it helps operator with non-ergonomic, repetitive, uncomfortable and dangerous operation.

This solution integrates the advantage of both human and robot. The robot aims to increase the efficiency and productivity. The role of the operator is to improve the system flexibility and intelligence. Robots are fast, tough and very accurate machines that can complete their tasks faster, have better quality and lower cost than humans. Why do we still want to preserve the human which may have error in dealing with collaborative robots? Some operations must be adapted to actual conditions. Robots can't think, they just execute commands and perform pre-designed actions. In other words, robots are limited by programming. Manipulators are typically designed to have 6 or 7 degrees of freedom (axes of motion), compared with about thirty degrees of freedom for human limbs. This leads to another limitation of these robot, precise operation with large range of motion. So, there are two limits to operating between human workers and robots. Human-robot collaboration breaks through these barriers and benefits from the advantages of robot to succeed in challenging applications where operators are needed. Generally, we can divide the manufacturing process into two different categories. In the first category, there are many assembly steps where robots are used to perform effective tasks, lift objects, and respect rules and standards. Thanks to the development of industrial robots in recent decades, they can assemble simple products autonomously. The second category requires human skills, because industrial robots cannot perform tasks perfectly on their own. The HRC is born for the second category.

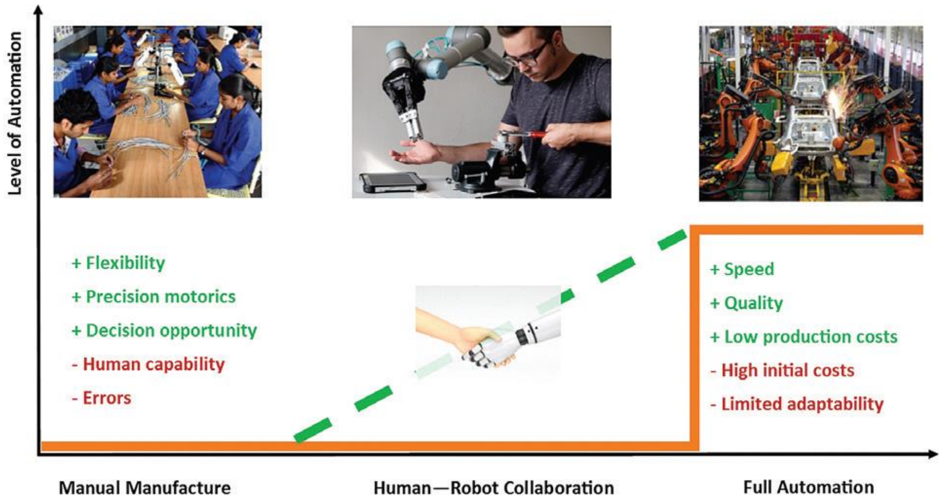


Figure 1.1 standing of Human-Robot collaboration[25]

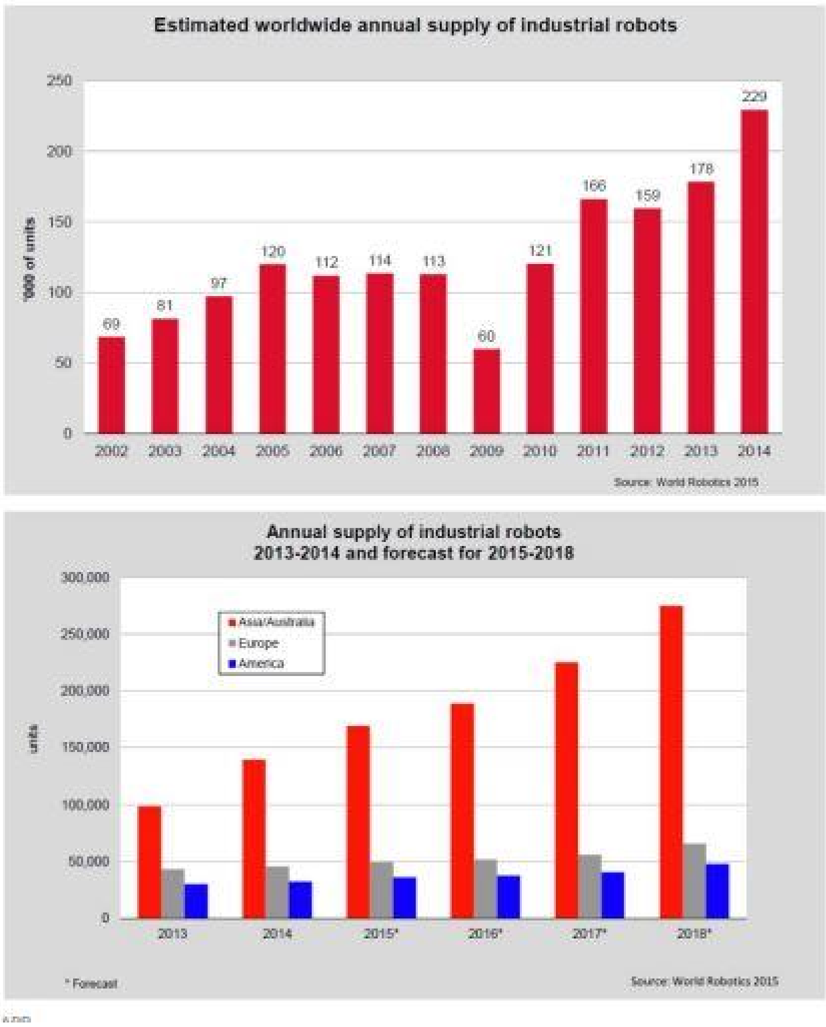


Figure 1.2 world wide annual supply of industrial robots.[25]

From the figure 1.2, we can figure out that the world wide annual supply of industrial robots continue increasing, typically for Asia market. The demand for the developing country such as China is still increasing.

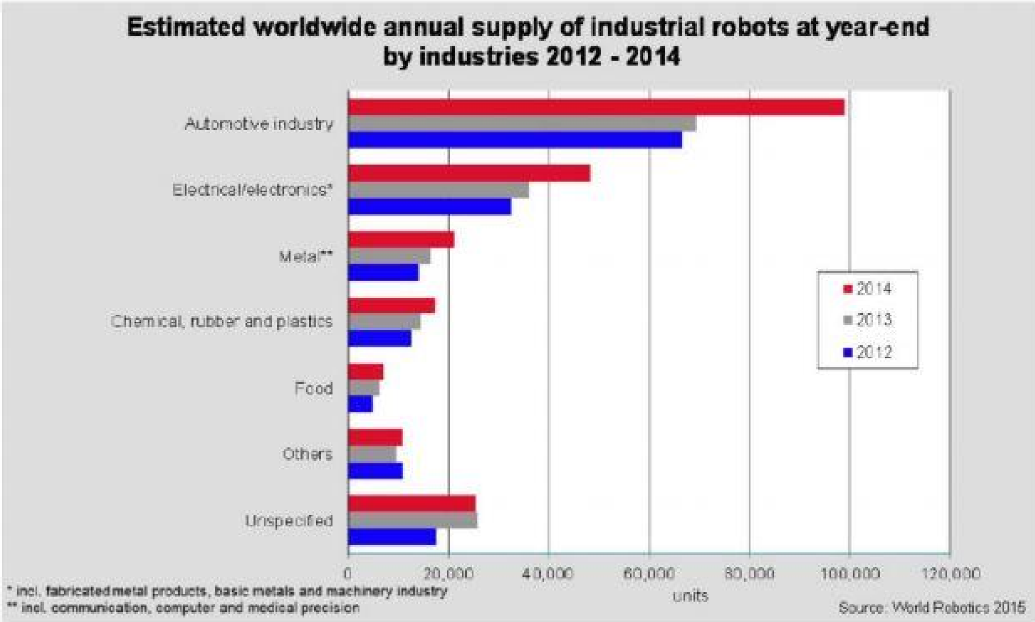


Figure 1.3 the world wide annual supply of industrial robots for the different application[25]

From the figure 1.3, We can find that automotive still dominates numbers and drives industrial robot technology requirement. Many other market, e.g. 3C assembly have very low degree of automation.

Source from International Federation of Robotics (IFR), World Robotics 2015 Industrial Robot, Executive Summary.

1.2 Problem statement

Nowadays, there are still many operations are taken by operators manually, which may have irreversible effect on human health in case of ergonomic issues. Thanks to the development of technology, we could introduce the HRC into the production in order to deal with ergonomic problems. But in the meanwhile, we could face another challenge which is the safety issues.

When human and robot are in a share working area, as the robot moving with high speed, the safety issues become the most important aspect during the system design. The collaboration environment could be extremely dangerous due to possible unpredictable, wrong motion of the robot which can cause severe injuries to the operators.

1.3 Objectives

This thesis is mainly focusing on the safety issue of the Human-Robot Collaboration. The advantage of the HRC will be analysed. Trying to discuss the hazard identification and risk assessment according to a case study. To give some general solutions aiming to improve both safety condition and productivity.

1.4 Overviews of the thesis

Chapter 1 presents the background of the thesis by discussing the reason that why we use the Human-Robot Collaboration solution is that we aim to improve ergonomics and productivity and the problems and objective of this thesis. The problem is that when we introduce the robot in the sharing environment, the safety issue occurs, which is also the most critical aspect for the HRC solution.
In chapter 2, the detail of the HRC will be presented, such as definition, safety, work space characteristic, interaction level and 3 types of the HRC concerning the safety .
Chapter 3 will talk about the robot components. The robot hazard and the risk assessment will be presented.
Some safeguard solutions will be given in chapter 4 according different interaction level. And certain methods which aims to improve production safety and productivity will be presented.
In Chapter 5, a case study will be discussed by using a predefined logic flow. First step is to proof that the system with robot is better than pure manual by applying Analytic Hierarchy Process (AHP) method. Then to perform task specification and assign the operation to the human and robot by using the Hierarchical Take Analysis in order to maximize the benefit of the HRC solution in case of ergonomic and productivity. The next step is to evaluate feasibility of the process and risk assessment by computing the probability of each occurrence by using a software named Integrated Dynamic Decision Analysis (IDDA).
The chapter 6 is the conclusion of this thesis

Chapter2 Human-robot collaboration (HRC)

In the industrial environments, robot applications may respond to fluctuations methods to improve process productivity. Furthermore, in context-aware robot (not completely isolated from the rest of the production line), manufacturing process costs can be reduced in terms of space and time (unfenced robot units and more sub-tasks performed simultaneously).

2.1 Collaborative robots

Collaborative robots are be also called cobots, cooperative robots or robotic assistants. A robot designed for cooperation with humans does not have to need strictly different design from standard industrial robots which are in conformity with safety standard ISO EN 10218. However, robot has to be equipped with other *safety components*. Recommendations for collaborative robots are summarized in a new (February 2016) technical specification ISO/TS 15066 (Robots and robotic devices – Collaborative robots).

Figure 2.1 robot workplace with collaborative robot[4]

Figure 2.2 Robot workplace with conventional robot[4]

To build up production systems with direct human robot collaboration, special robots with integrated safety features are needed. Such robots have become available over the past few years. Nevertheless, robots suitable for collaborative applications are provided only with a “toolbox” of suitable safety features and safety functions. There may be default settings of these that serve to protect against the manipulator-related hazards alone. The proper use of these functions in an application, however, is specific to the application and cannot be anticipated by the equipment supplier. Only the application-level risk assessment can determine which safety measures are required for the specific system. In Table 1 we summarize the features of selected robot types intended for human-robot-collaboration. Examples of other similar robots are Baxter and Sawyer (Rethink Robotics), Speedy-10 (Mabi Robotic), P-Rob 1R (F&P Robotics) and PF400 (Precise Automation).

Robot	Pay-load [kg]	Reach [mm]	No. of joints	Safety functions, monitoring			Safety perfor-mance (ISO 13849-1)	Special features
				Joint Position/ Speed	TCP Position/ Orientation/ Speed	Other		
KUKA LBR iiwa	7 / 14	800 / 820	7	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Torque sensors
FANUC CR-35iA	35	1800	6	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Dual force-torque sensors in base
Bosch APAS	4	911	6	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Uses Fanuc LR-Mate 200iD
Universal Robots	3 / 5 / 10	500 / 850 / 1300	6	Y / Y	Y / Y / Y	Y	PL d, no cat.	
ABB IRB 14000 “YuMi” (Figure 1)	0.5	559	7 per arm	N / N	N / N / Y	N	PL b, cat. B	Inherently safe dual-arm

Table 1 Examples of robots intended for Human-Robot Collaboration[13]

Collaborative robots and other auxiliary devices for improving workplace safety, they are not designed to replace current technology. Robot assistants expand the range of applications of robots in industry and bring several key advantages:

• From a economic point of view, compared with countries where labor is very cheap, the use of robots can improve the competitiveness of enterprises. Even small companies can focus on customer needs and offer products at lower prices.

• The repeatable positioning accuracy and continuous operation of the robot provide better quality and lower requirements for post-processing and quality control.

• Robots can accelerate some operations or adapt to specific conditions, which can lead to improve production.

• Robots can do the repetitive, uncomfortable and large load work which results in lifting the burden from humans which can lead to occupational disease.

•To improve the working environment can result in a decrease in the amount of operator injuries due to poor ergonomic.

• Dangerous situations often result from the circumventing safety rules and simplifying procedures. If safer technology is available, the risk of injury could be lower.

A robot must react to a foreign object, person, or collision with that object -- see figure 2.3. The robot workspace must be monitored. It varies with the levels of the system. For safety reasons, we need use sound and light alarm and stop the robot. The compliance control can be provided in more advanced systems - adjusting motion by pushing. The most complicated is to completely eliminate collisions by adjusting the trajectory by using sophisticated sensors and software.

As the level of cooperation increases, the working area of robots and workers are shared more and more until they are finally completely unified -- see figure 2.4. Standard robot cells have a fixed barrier or a virtual barrier, in the form of scanners or light screens, to prevent human contact with machines. A higher level of cooperation is to share the working space with the monopolistic movement of robots when people are not in their working area. The most advanced is synchronous motion. To achieve these, the safeguard is needed to be applied. According to different interaction level, the safeguard is different obviously. The different preventive solution and related sensor will be discussed in detail in chapter 5.

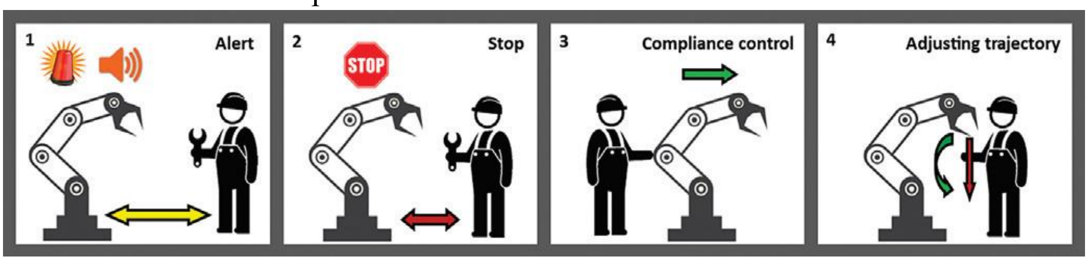


Figure 2.3 Reaction of the robot on a foreign object[4]

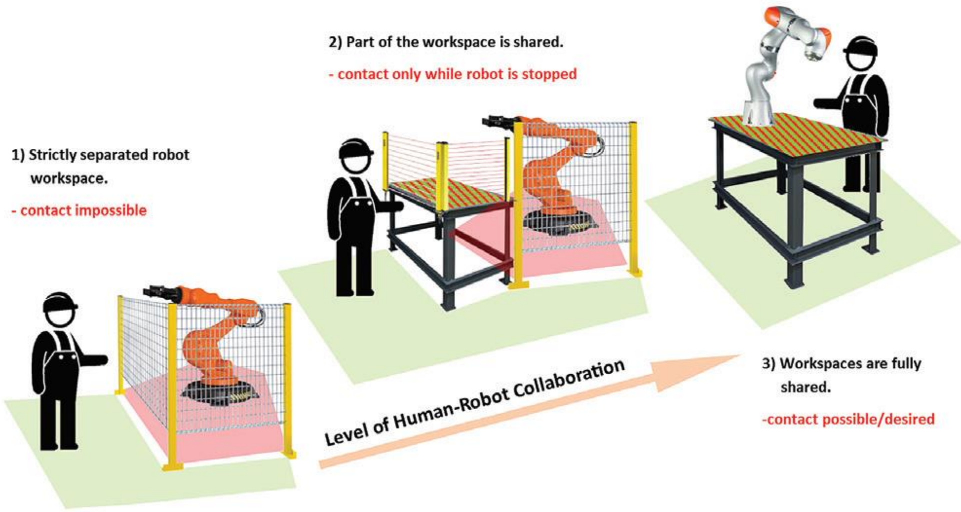
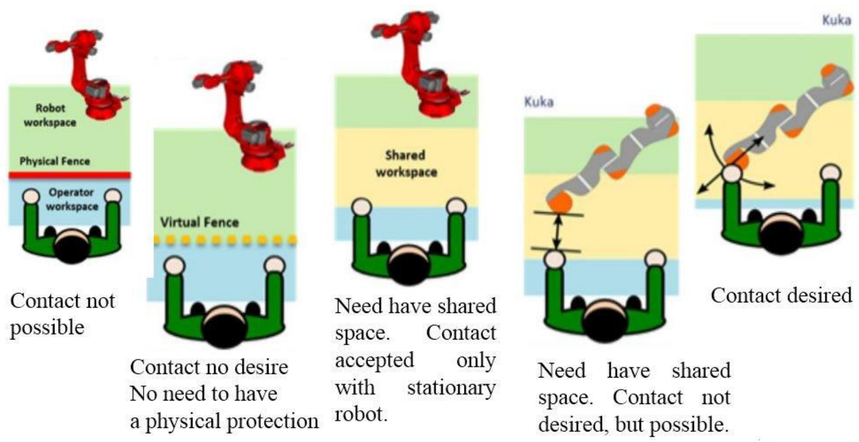


Figure 2.4 Different interaction level[3]

The Human-Robot collaboration scenarios can be categorized into:
Working areas co-sharing in mutual exclusion: "passive" HRC where Robot operates with full power in absence of operator, and apply gradually reduced power if operator exists. The behavior is differentiated a priori according to the working areas and the robot reaches the rest condition when unforeseen presences are detected "close to" the Robot.
Passive robot used as power actuator: Robot is not "autonomous": it can't perform any job and/or run any program in a automatic way; it is totally follow to the command of the human operator. Human and Robots, if not executing autonomous task, might be in contact.
Human-robot "active" cooperation; the robot has an active role in the task operating and/or motion program. The Robot is "active" but not "autonomous": "autonomy" requires "intelligence" and "awareness" of the Robot.
The different level of Human Robot Collaboration are shown on Figure 2.5.



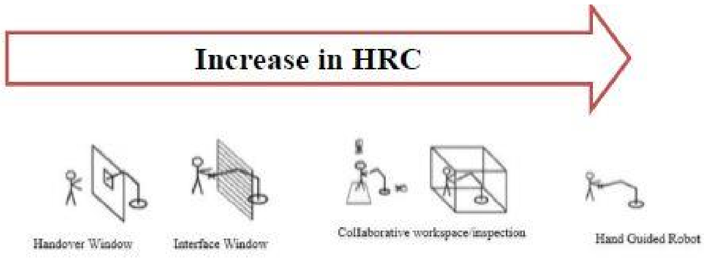


Figure 2.5 Different forms of human-robot collaboration [6]

2.2 Applications with collaborative robots

Although the technology is still in its infancy stage, some companies and universities have already developed applications with collaborative robots. KUKA [KUKA 2015] or Fraunhofer institute [Fraunhofer 2012] are combining collaborative robots and mobile platform into agile robotic assistant which has a wide workspace due to its mobility. Applications are tested in both the virtual and real world and the co-presence of the robot is observed [Weistoffer 2014]. In automotive industry we can figure out collaborative applications by using Power and Force Limiting. AUDI [AUDI 2015] has a PART4you operation, where the robot lifts a component from the box and gives it to the operator so that operator does not have to bend. In BMW [BMW 2013] a sensitive robot is sealing doors in cooperation with operators. Fig. 2.1 shows application in VW engine assembly [BW 2013], where the robot inserts glow plugs into cylinders next to laborer. In SKODA AUTO [SA 2015] there is a collaborative application in Vrchlabi gearbox assembly plant – see Fig-2.6. The robot thanks to its sensitivity inserts the gear actuator piston into a precise hole.

Figure 2.6 Collaborative robots in SKODA AUTO-KUKA LBR iiwa[3]

During calibration of the workplace, the operator can push off the robot and it remains waiting until the workspace is clear. Robot KUKA LBR iiwa is equipped with a safe end-effector that has no sharp edges and even during loading the robot does not harm the human in any way. Another robot is tested for hand guiding application where the robot holds the part for the worker who can adjust its position and mount it.

For the handling of heavy and bulky components in welding tasks, a multi-robot system with collaborative functionality assists the worker. Two robots position the components to be joined in the welding position, at which point the worker is able to carry out the welding task under favourable ergonomic conditions. In comparison to a standard welding bench, the worker need not assume awkward postures or work overhead, as all necessary positioning and orientation of the work pieces can be done by the robots. This also includes presenting the components in an optimal position for the welding process, allowing proper flow of the welding bead. Since the robotic repositioning motion is quite fast, the handling time, which presently is about one third of the total process time, can be reduced to a minimum.

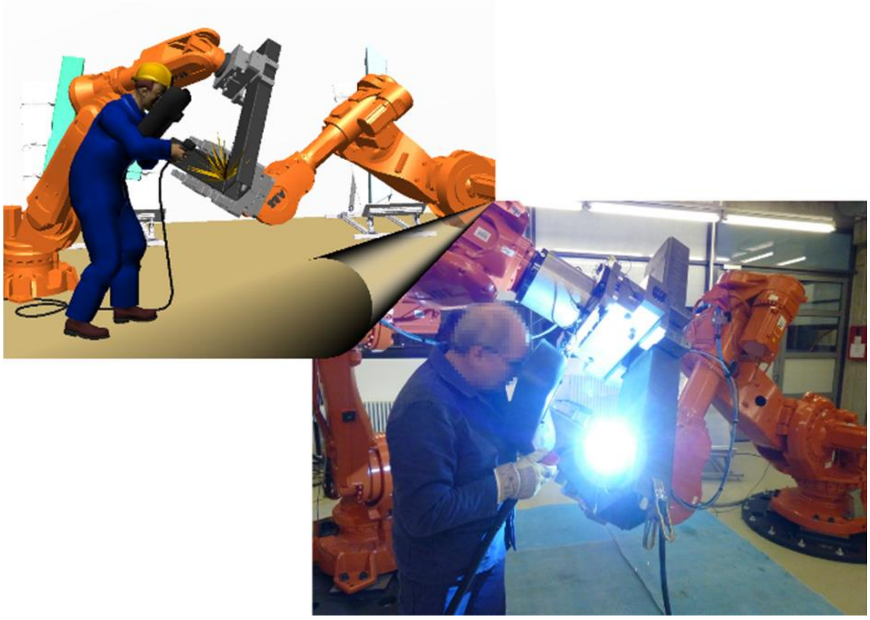


Figure 2.7 Simulated and real HRC in a welding application[3]

Integrated safety elements are a robot controller with safety-rated motion supervision, a safety-rated optical sensor system to monitor the collaborative workspace, and grippers with pressure control and pressure maintenance valve. The integration and the configuration use a combination of the collaboration principles SMS and SSM which will be discussed later. For example the robots can move their wrist axes only at reduced speed, the moving range of the main axes is limited to a minimum of a few degrees.

Another example is a robot-based assistance system is designed to assist workers with temporary or age-related physical limitations. Reference processes are repetitive tasks like tightening screws or even the handling of heavy and bulky parts. For these tasks, intuitive human-robot interfaces will be designed for the operator panel. The worker teaches the first three positions of the screws by hand guiding. The main technical element is the use of a KUKA iiwa with the integrated torque sensors and appropriate options. All remaining screw positions are computed, based on the assumption that all positions are in the same plane.

For a task in the vehicle assembly, a robot can be installed to replace the mechanical handling device. The handling device only compensates for the force in the vertical direction, and the horizontal direction must be moved by the workers. In order to reach the final position without colliding with the coated body, a temporary worker was needed to supervise the process. The robot, on the other hand, will assemble the parts into the car in a predetermined, guided, collision-free path. In addition to control tasks, workers can perform other tasks, such as the cables that guide components.

2.3 Standards for the HRC

Whether one uses HRC or not, all machinery must follow the Machinery Directive (2006/42/EC). The Machinery Directive is converted into national law in all EU member states and provides a uniform European protection level for safety and health of industrial employees working with machinery. All machines that are produced in or imported into the EU are required to meet European technical and safety standards. The EC Declaration of Conformity for the machine and its CE-marking documents this conformity. Essential prerequisite for the CE-marking of a complete robot application is a risk assessment and the implementation of the necessary safety measures thus identified. How to do a risk assessment is described in EN ISO 13849-1 and EN ISO 12100. The basic safety requirements on the robot and the robot system are described in the standards for the safety of the robot EN ISO 10218-1, and for the safety of the robot system EN ISO 10218-2. They also specify four basic protective principles for HRC. These are “Safety-rated monitored stop”, “Hand guiding”, “Speed and separation monitoring” and “Power and force limiting”. The application of these principles can be difficult without guidance more detailed than that given in the two parts of ISO 10218. As a result, the responsible ISO working group has developed a so-called “Technical Specification” document, ISO/TS 15066 to provide additional detail on the safety requirements on collaborative robots and applications. This guidance is aimed both at robot manufacturers and system integrators in their various roles and responsibilities in bringing forth an HRC application. In particular, the TS presents the safety requirements for each of the four basic types of collaborative operation. For each of these, we give a short summary of the relevant risks, the protective principle and comment possible implementation aspects. In all of the cases below, the protective principle applies in the shared, collaborative work space. It is noteworthy that practical applications will often be composed of a combination of more than one of the basic protective principles.

2.3.1 Types of Human-Robot Collaboration based on ISO EN 10218

1. *Safety-Rated Monitored Stop*

The safety-rated monitored stop (SMS) is the simplest form of HRC. In this collaboration strategy, the robot comes to a supervised standstill in the collaborative work space, the space shared by worker and robot. During this standstill, the worker can enter the collaborative work space and carry out his task, such as placing / removing parts into / from the end-effector. When this task is completed, the worker leaves the

collaborative work space and the robot can resume non-collaborative work automatically.
We can see this type of collaboration when operator manually insert objects to the end-effector of the robot. Another application is the visual inspection that may be required during the operation. Some operations may require human involvement, such as finishing or automating complex processes that are costly. Robots can also help operators handle large payloads. For the case study which will be presented in chapter 4 is based on SMS mode.
Applications of Safety-Rated Monitored Stop are as following:
• To Load or to unload of parts by using end effector
• Examinations of work in process
• only robot or operator moves in collaborative workspace.
• To be combined with other collaborative technique

2. Hand Guiding

Collaboration according to hand guiding (HG) puts the worker into direct control of robot motion. The mitigation of the risks associated with robot motion is to effect robot motion only as a result of dedicated input from the operator. This input is given for example via a joystick or by means of direct input of external force onto a compliant robot, which then moves accordingly. Motion can also be constrained by programmed limits, such as "virtual walls", fixed trajectories, and speed limits or similar, as the application risk assessment might require.
For improving the safety, there is an enable button (death switch) in the grabbing area. The robot can only move if the button is pressed, otherwise it will stop. The robot can achieve better ergonomics, when carrying heavy objects, operators only need to deal with a small guiding force. Hand guiding is mainly for a controlled motion of semi-automatic operation or robot programming process. The operator learns the position of the desired trajectory according to the guidance of the manipulator.
Applications of hand guiding method are as following:
•Robotic lift assist
•Highly variable applications (acts like a manually "tool")
•Limited or small-batch production


Figure 2.8 Hand Guiding Method[6]

3. Speed and Separation Monitoring

Sharing a collaborative production task according to the speed and separation monitoring (SSM) protective principle allows for worker and robot to move in the same space. To mitigate the risks of contact, however, the robot must be controlled in such a way that the human cannot reach the robot while it is moving in a hazardous manner. It is clear that this generates the need for safety-related detection of the worker in the collaborative work space by appropriate sensors. Furthermore, this information must be used by the robot controller so that the robot speed is adjusted to avoid moving contact with the worker. Online estimation of the stopping distance of the robot can be of advantage to recover the full productivity potential of this method.

The third collaborative method: "speed and separation monitoring" presented in Equation(1)during Simultaneous tasks and direct operator interface.

Sp(t0)= Sh+ Sr+ Ss+ C+ Zd + Zr Eq(1)

where

Sp(t0) = Protective separation distance

Sh = The operator's change in location

Sr = The robot's change in location

Ss = the robot's stopping distance

C = the intrusion distance that a part of the body can move toward the hazard zone prior to actuation of the safeguard

Zd + Zr = Position uncertainty for both the robot and operator

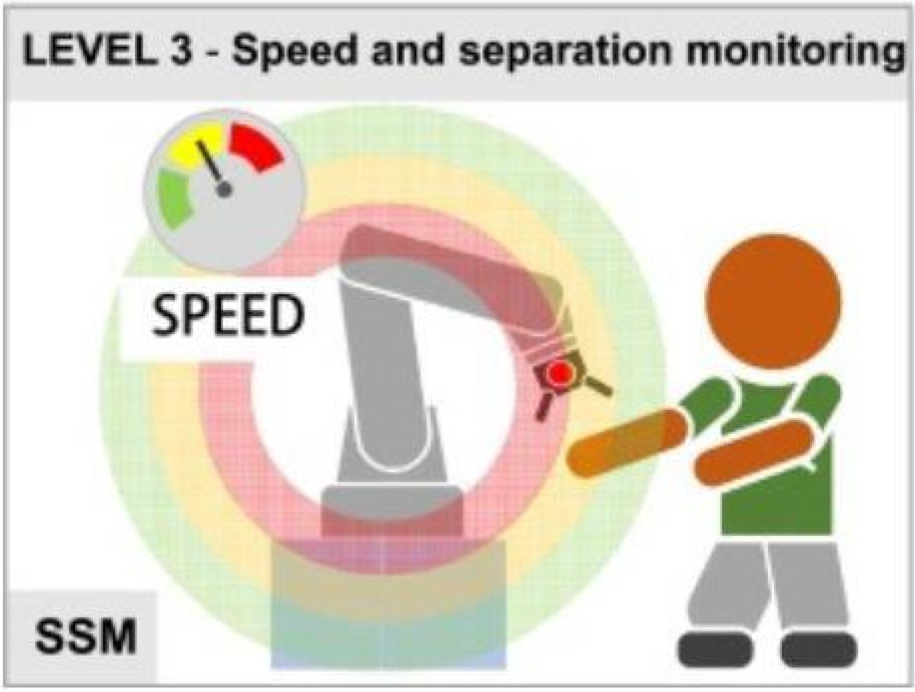


Figure 2.9 Speed and separation method[6]

4. Power and Force Limiting

Power and Force Limiting is a kind of collaborative method which needs special collaborative robot. The motion parameters of the robot are monitored with high precision, and even the tiny deviation between the robot and the actual position can be detected compared with the program control. The high precision encoder and high resolution allow the robot to accurately monitor its speed and position. By analyzing the current generated by the actuator, by measuring the response to the ground, or by using tactile sensors, sensitive torque sensors in the joints of the robot to measure and evaluate the force and torque. Therefore, the robot can recognize the impact of obstacles, analyze and react to them in a very short time. The robot can brake and stop immediately after a collision, or it can move in the opposite direction, minimizing the impact energy.

Most eagerly awaited by the potential user community is the description of the power and force limiting approach to HRC. According to this protective scheme, human and robot are working so closely that incidental contacts can occur. The mechanical and control design of the robot system, therefore, must render such contacts “harmless”.

The proper biomechanical limits for harmless contacts, both for sustained and for short contact, are provided in the TS for the first time. These limit values are based on pain sensation threshold research, a literature study on the estimated onset of minor superficial injury and a simple model-based interpretation.

It is important to stress the need for an application level risk assessment to judge the risks associated not only with the robot manipulator, but also those introduced by the application (e.g. sharp edges on tools or parts). Depending on the outcome, it can be required to install additional safeguarding measures, beyond the proper configuration of the Power and Force Limiting protective scheme of the robot.

It is important to mention that:

• To apply Power and Force Limiting requires that the robot system should be specifically designed.

• Forces that can be applied are obligatory to be limited to robot, end-effector, work piece.

• When contact occurs the robot system should react.

• Quasi-static (pressure) or transient (dynamic) are the kind of contact.

Applications of Power and Force Limiting method are:

• Small or highly variable applications
• Conditions requiring frequent operator presence

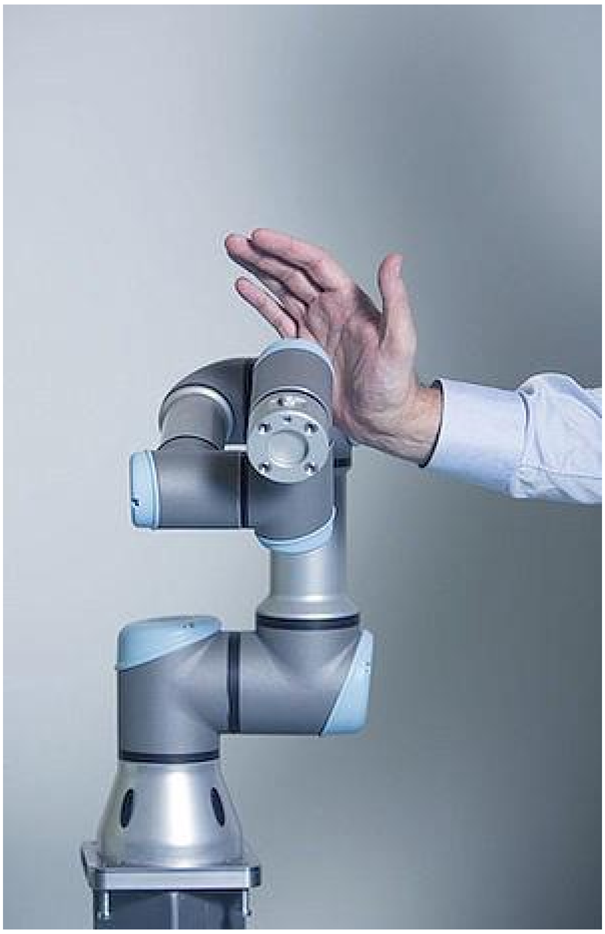


Figure 2.10 Power and force limiting method[6]

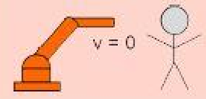
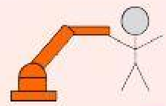
ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	
5.10.5	Power and force limiting by inherent design or control (Example: *ABB YuMi®* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Table 2 Summary of 4 types of HRC[25]

From first type of standards to the last one, the interaction level is increasing, and the operator and the robot are close to each other, in another word, they share more collaborative area. It is obvious that, with the integration level increasing, the HRC system need to be more sophisticated.

So for the different integration level, the corresponding safeguard method is different from each other.

2.4 Introduction of safety issues of HRC

The existence of an operator in an area where the end-factor is moving at high speeds leads to address safety concerns. Standard robots have warning colors and are surrounded by fences. When the robot's operating range is disturbed, it should be stopped immediately to avoid causing injury or even fatal injury. If the robot is operating with a payload of several tons, or an acceleration of 10 g, then it must be sufficiently secure that no human presence is possible. To achieve secure human-robot collaboration, we must compromise. The maximum payload and velocity of motion are significantly reduced. The load capacity of the collaborative robot is about 10kg, and the maximum speed limit is 250mm/s. Because of these limitations, robots can be very light. The lightweight design won't do as much damage after impact as a standard robot. Yet even these restrictions are not enough. Robots must be equipped with sensors to detect or prevent collisions.

Companies have made different strategies to improve safety of their products. On the figure – Fig. 2.9 are a few examples of collaborative robots. First two of them on the left are modified conventional robots equipped with passive and active safety elements. The robot in the middle has similar working range and parameters as a human laborer. The last two are special lightweight robots with embedded sensors.

Figure 2.11 Collaborative robots – MRK-Systeme KR SI, Fanuc CR-35iA, ABB YuMi, UR5, KUKA LBR iiwa

The power and force limiting refers to the active elements of collision detection. A new response control strategy was developed and tested as a sensitive buffer skin. Thanks to capacitive sensors, some robots have a sensor skin that can detect obstacles before a collision. Collisions can also be predicted by the visual system. In this type of application, we need very fast responses.

In case of a collision happens, the robot is equipped with passive protection components designed to minimize damage. Collaborative robots have no sharp edges, and all their dangerous parts are round and smooth. The cooperative robot has no finger pinched parts that rotate. The surface is softened with plastic. Some parts are made of plastic or coated with a soft foam material that absorbs some of the energy produced by the impact. This will improve security. Cables and compressed air hoses are placed in the robot's internal space or they are covered as a consequence of the risk becomes minimal.

In the problem of collaborative robot safety, active safety elements must be established correctly. If it is incorrectly, the robot can achieve standard robot properties. They can travel at high speeds, and their impact energy is many times higher than safe limits. It is necessary to set correct limits during programming. Another important factor is the actual handling load of the robot, as it is calculated from a dynamic model. Robot programmers have an important responsibility for working area safety.

The safety of robot component decides the safety of collaborative robot. Anything that's attached to the robot will make it less secure. This applies to the cable mounted on the surface of the robot, the vision system, but mainly the end-effector. Robots become dangerous when working with objects with sharp edges or sharp parts. Other hazards could be drill holes or welded joints attached to the robot's wrists. In these cases, contact with the technology is prohibited. In order to achieve safe collaborative robot design, the risk needs to be analyzed in detail.

The detail of the solution to increase the safety will be discussed in chapter 4.

Chapter 3 Hazard and risk assessment of HRC system

This chapter will analyze the hazard and risk assessment of the HRC system. The safety issue of the system is mainly due to poor design of the system, failure of the robot and failure of the human. It is better to emphasize that some failures of the robot and operator will cause the problem of production such as quality, productivity, and some failures will cause the safety issues. The failures which cause safety issue are the top priority which must be solved.

3.1 Techniques for hazard assessment

Hazard assessment related to robot implementation is helpful to detect potential weaknesses in design through systematic documented considerations on the following categories[6]:
1. All possible ways in which robot can fail.
2. Causes for each mode of failure.
3. Effects of each failure mode on robot system reliability.
4. Probability of occurrence of each failure mode.
Many analytical methods have been proposed to understand how accidents occur by failures and errors, also to reduce the probability of their happening.
1. Preliminary Hazard Analysis (PHA) is an effective basic system for hazard analysis. The necessary raw data relating to the design, production, and hazard characteristics of the system is first collected. There are four main categories: hazards, causes, main effects and prevention control. Hazard characteristics and corrective/preventive actions are uncertain indicators of potential hazards and their potential solutions.
2. Failure Mode, Effects and Criticality Analysis. FMECA examines the various elements of the system and all the failure possibilities that can occur under various operational conditions. In this analysis, you should identify each task and function of the component. Then, on the basis of historical data, the error and failure reasons of components are identified, the influence of results is listed, and the probability of events is estimated. This type of analysis indicates that elements of a system are therefore potentially dangerous, and failure modes can be listed from the highest probability of occurrence to the lowest. Finally, some measures to improve robot design and performance are proposed.
3. Hazard and Operability Study (HAZOP) is the most systematic form of hazard analysis. In the first step, you define the system and all of its subsystems that require data. Then identify potential interactions and complex hazards in the system, analyze and examine the data, and use potential hazard areas as evidence.

4. Fault Tree Analysis (FTA) is one of the most influential tools for logical analysis of system hazards. FTA uses logical links to quantitatively (and qualitatively) illustrate the functional relationships between different components of a complex system. Then you can start with the basic elements and climb up the tree to assess the probability of failure of the system. The program concludes with a description of the hazards that can occur when relationships between system components fail. FTA uses a pyramidal tree test, starting from a top-level event, i.e. failure that is mainly not desired (for example, accident or injury), all the way to the initial cause of danger, as shown in figure 3. The FTA and FMEA exchange information and consider combinations of driving to risk situations (identified in risk and hazard assessments).

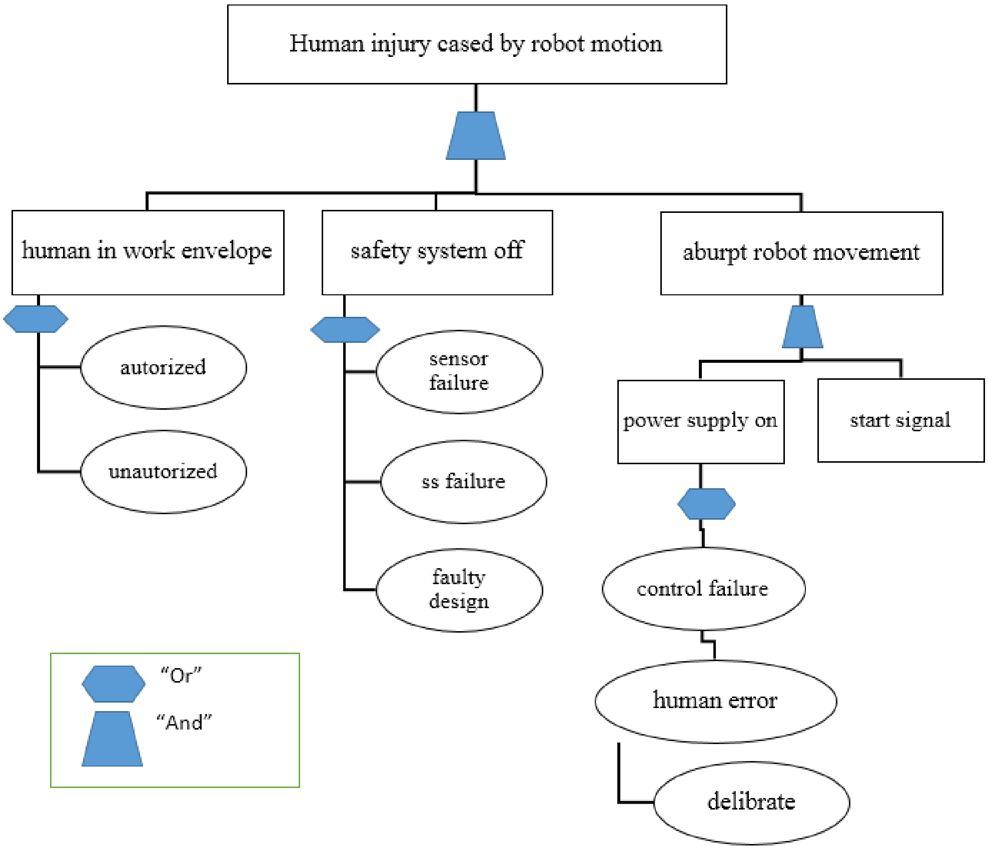


Figure 3 An example of the FTA method is presented for the event "unexpected robot motion".

This method has a top-down fault analysis method. It starts with an unwanted event called top event, and then requires identification of how that top event is affected by a single or combination of low-level failures or events (for example, human actions, security systems, and robot state). For the specific application of FTA analysis, the most important event is a hazard in security, which must be foreseen in advance and identified through the previous technology. FTA analysis can be either quantitative or qualitative, but in most cases, it is not easy to carry out quantitative analysis, because all failure possibilities need to be evaluated (measured in probability), and then the occurrence of top-events can be calculated as the result of qualitative analysis.

First, the fault interaction can be demonstrated in the tree, and second, the protection mechanism can be integrated with events (including human errors).
The objective of qualitative analysis is to study the minimum cut set (the relationship between the top event and the main event) that represents the main event that will lead to the top event. Almost all possible hazards in the human-robot cooperative environment are the result of unsafe conditions and unsafe behaviors.
The FTA and FMECA between other analysis technologies are relatively safe robot safety analysis methods in the field of HRC.

3.2 The basic component of robot

In order to discuss the assessment and hazard of the HRC system, it is better to present the basic component of the robot at first.

3.2.1 The overview of robot system

[8]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.

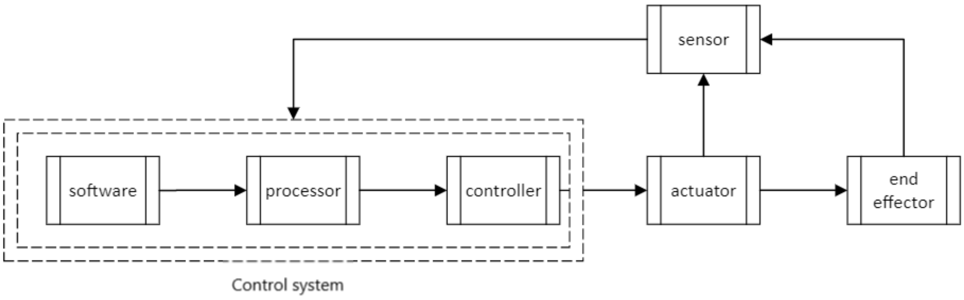


Figure 3.1 Overview of robot system

3.2.2 The 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 described 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.
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.

3.2.3 The sensor

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.

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. *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.

The sensor is the most important component for the safety issue of the HRC system.

3.2.4 The actuator

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.

3.2.5 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:

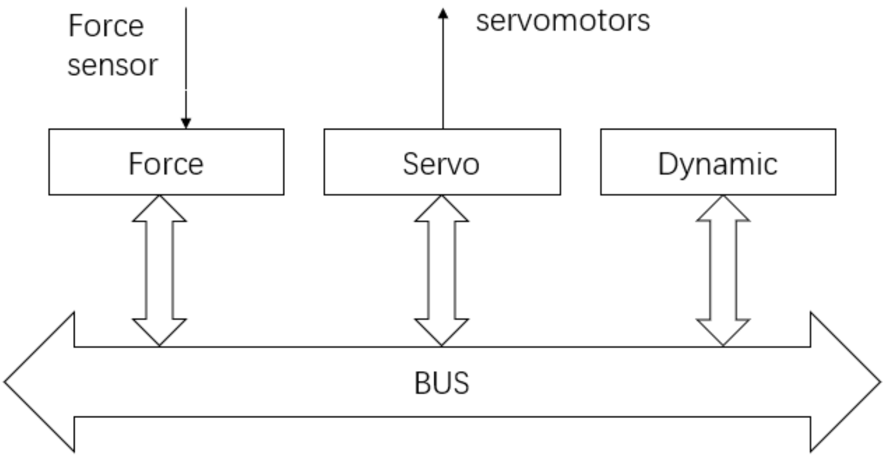


Figure 2.2 Structure of control system[8]

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 disturbance, 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:

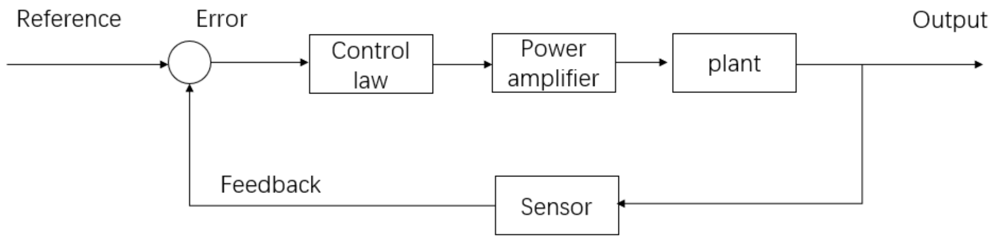


Figure 3.3 Typical block diagram of a close-loop control

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.

3.2.6 The system

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.

3.3 The overall failure frequency of the robot

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 which is the robot that will be used for case study 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:

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

Table 3 Frequency of robot’s failure

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

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):

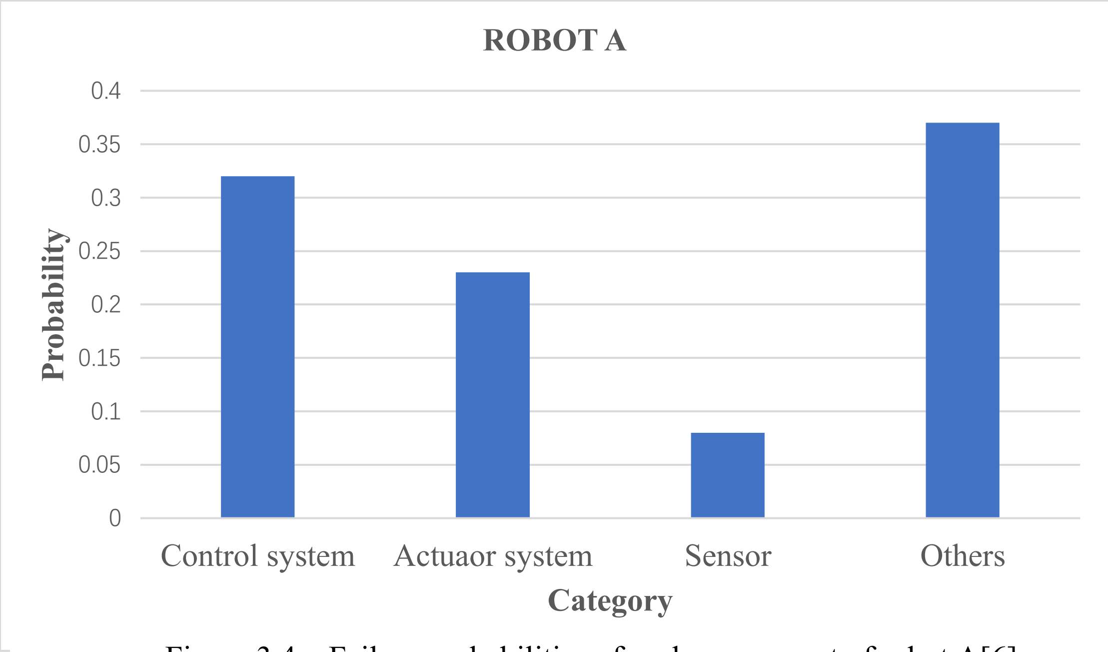


Figure 3.4　Failure probabilities of each component of robot A[6]

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.

3.4 The human effect

Since the system is human-robot collaboration, so not only the robot can contribute failure but also human can generate a large portion of failure.

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.

Also the acceptability is critical. Especially in manufacturing, tasks are transforming from manual work to collaborative work between human and robot. These evolution in the working environment have brought great challenges to training and education. Because the complexity of the task and basic condition are changing, but the tasks themselves have not, the current work profile is unlikely to change fundamentally. In order to prepare employees for increasingly complex tasks, various influencing factors should be taken into account when designing employee qualification schemes.

A lot of researches underline the need for human actors to have specific capacities to meet new organizational and technological development challenges and face the challenges and requirements of production today and in the future. Therefore, contemporary methods of employee qualification assessment should take into account the wide range of capabilities required. This means focusing not only on task-related capabilities, including the transfer of technical knowledge and skills, but also on the development of personal and social capability, thereby increasing individual flexibility and problem-solving skills.

In order to improve safety and efficiency of the system, training plays a vital role to develop and increase the competencies. The result that will be presented later shows that human contributes a lager portion of failure that may result in safety issue compared to robot.

3.5 Tolerance of the human body's injury

[6]Human-robot collaboration increases the possibility of human injury and pain. In the process of human-robot collaboration, it is important to understand the tolerance of human injury to simulate and design collaborative environment. Many experiments and simulations have been completed to examine these limitations. These parameters are determined according to the velocity of the robot, the distance between the operator and the robot, the acceleration and the contact area. Many types of physical pain and injury can be found on the tolerance index. On the basis of static and dynamic simulation, a lot of research on the tolerance limit of body structure is carried out.

In the process of applying stimulation to the human body, the human body's pain tolerance limit is obtained by the body's response. The body's head, arms, back and hands are most often harmed, and their critical forces are 130N, 180N, 240N and 140N respectively. The most important body part is the head.

The human head is a complex system composed of three main parts. These components include the skull and facial bones, the skin and other soft tissues that cover the skull, and the brain. Head injuries are superficial and deep, including bruises, lacerations and abrasions.

When a skull fracture, one or more skull fractures are caused by accident. Skull rupture is caused by the internal part of the skull being hit by the brain or by pressure inside the brain. According to the study [26], the threshold value of brain injury is determined according to the low threshold value of Aran's law, which describes that middle ear fracture is one of the causes of such injury. These types of damage can be divided into constrained impact and unconstrained impact, as shown in figure 3.5.

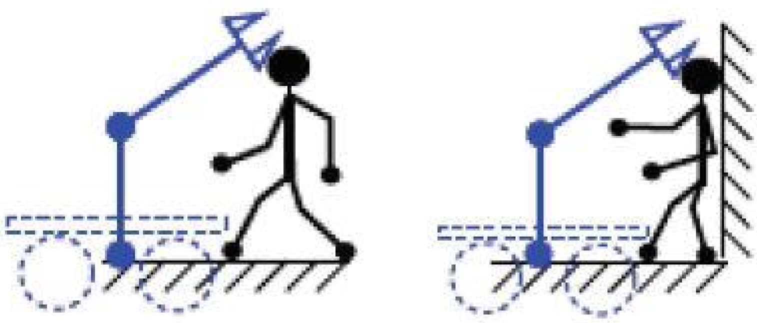


Figure 3.5 Unconstrained impact,(left), Constrained impact(right)

The second type of impact can cause serious injuries because the head is exposed to the maximum force of impact and there is no chance of escaping from the danger zone.
The injury criteria, threshold of brain dysfunction and pain tolerance of skull fracture can be measured by human-robot collaboration analysis. According to different parts of the skull fracture threshold is different; The fracture thresholds of different parts of the skull are shown in table 4

Bone N ame	Fracture Force, KN
Maxilla	0.66
Mandible	1.78
Parietal	3.12
Frontal	4
occipital	6.41

Table 4 Skull bone fracture forces

In mechanical contact and collision accidents, impact force and collision distance are important factors affecting the severity of damage. The physical characteristics, actual configuration, approach speed, direction and contact time of the robot constitute the impact force. Other parameters, such as task specification, robot failure rate, the existence and reliability of safety features, instrument shape and control method, will affect the measurement results.
According to the National Highway Traffic Safety Administration (NHTSA), the maximum allowable value of HIC is 700 representing 25% of serious injury with maximum head acceleration of 70g (3,5KN) during the impact period of 15ms. Based on Canadian Motor Vehicle Safety Regulations Standard (CMVSS), this value was reported as 80g which is related to the fracture of the frontal bone.
To consider HIC value it is necessary to know the robot operating and structural characteristics such as speed, load, braking and idle time. However, it is important to mention that, personnel approaching speed and the reaction time might contribute to this measurement. The maximum authorized head acceleration is limited to 62g (3.12

KN) for interaction levels of L3 and L4.

3.5.1 Proposal of an Injury Scale

In order to classify the safety of robot system according to the injury assessment of the reference contact type, we proposed a new AIS injury scale, referred to as abbreviated robotics injury scale (ARIS), as shown in figure 3.6. Since the injury coding should consider both soft tissue injury and hard tissue injury, the injury coding is reconstructed and enhanced. While maintaining the anatomical structure of the body's classification region and AIS, the specific two-digit code of the structure and nature of the injury was updated by two new numbers, the classification of the injury type and the specification of the soft tissue state. A new severity score has also been introduced to reflect the range of minor injuries (the last digit after the decimal point).

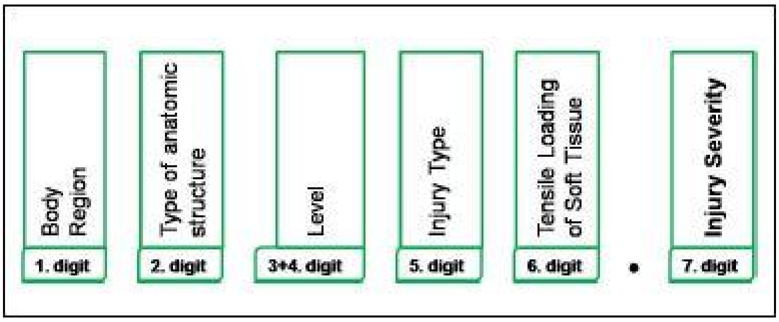


Figure 3.6 ARIS - Abbreviated Robotics Injury Scale[9]

The new number d5 is used to identify injuries associated with human-robot collaboration, such as, abrasion, fracture, fracture, crushing, laceration, and contusion (hematoma).

In addition, the new number d6 is now being considered to determine whether there is a normal tensile load on the soft tissue region. This is necessary information to be able to represent various aspects of the treatment required and the risk of secondary consequences of the injury described, such as infection. Finally, for the last number, d7, we propose a new severity score to reflect the severity spectrum that we think is relevant to describing the injury case, as they may occur during the collaborative operation of robots and humans. It is important to note that you must be able to express a range of severity above and below what can be considered to be the maximum tolerable level. In fact, we've divided AIS-Code 1 into subgroups, ranging from "non-invasive" (beyond the maximum tolerable level) to scores indicating intolerable severity. According to research published by the BGIA, tolerable injuries include hematomas or bruises without lacerations.

At present, we must make it clear that the threshold between tolerable and intolerable injury severity scores cannot be assumed. This level must be the consensus of all relevant stakeholders.[9]

3.6 Related robot hazards

When robots were introduced into industry in the past, the safety of robots was not required by manufacturers or users. With time passing, more and more attention has been paid to the safety of robots. Robots are not designed for specific tasks that are different from other machines. The core design of robots is motor flexibility, which in part leads to the risk of injury. The robot can be freely programmed to carry out different speeds and movements on each individual axis, and can continuously move to n axes, with various motion ranges, and intersect with the activities of human beings and other machines and structures.

In recent years, there have been many accidents, including fatal ones, in the use of robots in manufacturing plants. According to a Japanese robot survey report, 18 accidents were caused by robots and external malfunctioning equipment moving wrong during manual operations (teaching 1, testing 2, maintenance 3, etc.), operations and operators entering robot areas without authorization.

Figure 3.6 illustrates the ratio relationship between these factors, in which the occurrence of accidents can be seen. As shown in the figure, the accident value did not exceed 5,6% in the automatic operation mode of the robot, while in the manual mode, the accident value was 16,6%. This means that robot accidents are most likely to occur during maintenance, teaching or when humans operate tasks near robots.

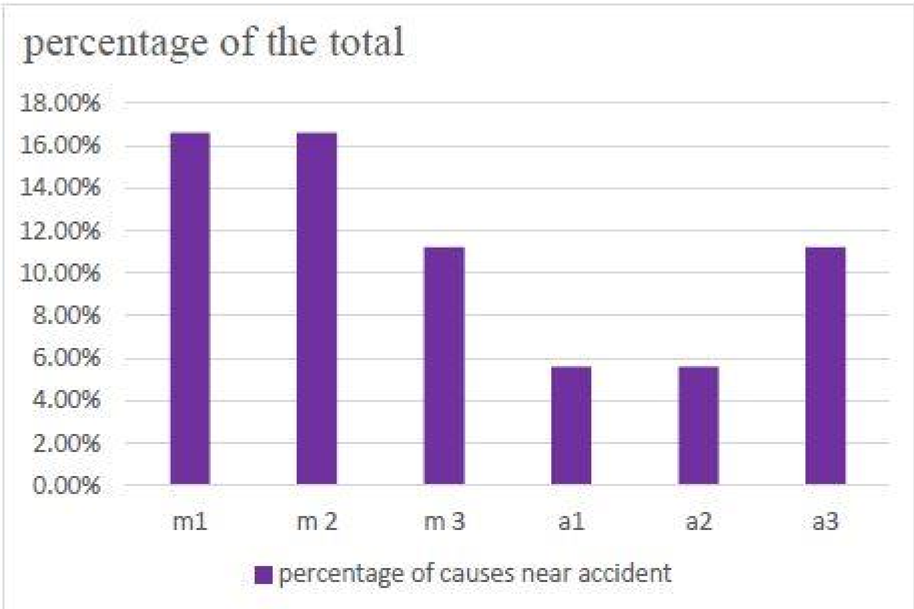


Figure 3.7 The ratios of failure causes near accidents[6]

3.7 Hazard Identification

Hazards of tasks depend on important parameters such as task specification, robot application, and interaction level. Reliable systems should be provided with the necessary information prepared by experts. This information will relate to interaction level specifications, task process times, robot types and characteristics, operating equipment, and workplace sizes. This data is stored in the system database along with the corresponding ergonomics and safety standards.

In the system evaluation, hazards are mainly divided into three categories: cognitive hazards, ergonomic hazards and mechanical or electronic hazards. All levels of interaction are related to their own hazards; These hazards depend on human-robot collaboration process, human-robot cooperation distance, operator responsibility and task specification. However, physical and cognitive parameters should also be considered; If to perform a task requires a great deal of physical and mental effort, this increases the risk of error, which leads to hazards. The assessment results are presented in the form of a task list related to the hazard specification. This list includes potential hazards, causes, and consequences, as shown in table 5.

Hazard	Task / Factor	Description	Causes consequences
Mechanical / Electrical	Welding, Painting, Cutting, Assembling, Drilling, Milling	Crushing Trapping Collision Stored energy Rejection Electrical choke Burn Poisoning Pressure Shearing Cutting Severing	***Cause***: Failure of Robot parts, Instrument failure, Human error, Failure of control, Software Failure, Firmware failure, Safeguarding failure, Incorrect work planning, task design, Incorrect task sharing. Incorrect time process scheduling, inadequate installation, usage. ***Consequence***: Robot (part) sudden movements. Unintended movement of associated machines.

Ergonomic	Assmbling, Loading, Moving, Handling	Strain/Pain Physical fatigue Hearing loss Visual Loss Risk Wrong Protection	***Cause***: Excessive Physical Load, Inadequate TP design (E1, E2), Insufficient work cell design (E4), Poor GUI Design (E3), Incorrect work conditions (E5), Wrong task distribution (E8), Inefficient work planning, failure of Robot parts, other Machinery, Faulty design, installation, usage, spatial arrangements, Safety Features Insufficiency ***Consequence***: Erroneous task performance, Risk Taking behavior, Elevated noise level, and long term exposure. Effect on the hearing and balance, awareness, speech communication, perception of acoustic signals, vigilance, Insufficient lighting, Visual Awareness loss, High Hazard Exposure, Risk Likelihood.

Cognitive	If any Indication from the *Tab. 3.6* (right column); Insufficiency for the Factors: E2, E3, E5, E8 (*from Tab.3.10)*	Fear/Anxiety Mental fatigue Stress	***Cause***: Personnel Hazard Perception, Excessive task cognitive load, Poor Control Panel Design (E2), Poorly designed user interface (E3), Bad work Conditions (E5),Incorrect task distribution (E8) ***Consequence***: Unsafe behavior, Erroneous work, Task misunderstanding, misuse, recognition of Hazards and hazardous situations is obscured, erroneous work, unsafe behavior.

Table 5 List of main hazards, causes and consequences[6]

Hazard from robot collaboration:

1. Hazards from robot characteristics, i.e., speed, force, torque, acceleration, momentum, power etc.
2. Operator dangerous location of working under heavy payload robot.
3. Hazards from end-effector and work part protrusions.
4. Sensitivity of the parts of the operator body that can come in contact in case of collision.
5. Mental stress to operator due to robot characteristics (e,g., speed, inertia etc.)
6. Hazard from trajectory taken by the robot.
7. Physical obstacles against robot operation during collaboration.
8. Hazard from fast worker approach speed and robot's slow reaction time.
9. Hazard from tight safety distance limit in the collaborative workspace.

Hazard from industrial process during process during collaboration

1. Ergonomic design deficiency for operation and maintenance.
2. Time duration of collaboration in the process.

3. Transition time from collaborative operation to other operation.
4. Potential hazards from the industrial process (e.g., temperature, loose parts etc.)
5. Mental stress to operator due to collaborative industrial process.
6. Work material routing during the process.
7. Physical obstacles tackled by worker in order to accomplish process requirement in collaborative workspace.
8. Hazards due to task complexity in collaborative workspace.

Hazard from robot control system malfunction during collaboration
1. Hazards from operator during reasonably foreseeable misuse of the system.
2. Hazards from control layer malfunction and misuse of collaborative system by attacker under a cyber-attack in a connected environment.
3. Physical obstacles in front of active sensors used in the collaborative workspace. (e.g. obstacle in front of camera).
4. Non-provision of transition from collaborative operation to manual system in case of system malfunction.
5. Hazards from multiple workers involvment in the collaborative process.
6. Hazard created due to wrong perception of industrial process completion by the robot.
7. Hazards from obstacles against unobstructed means of exiting the collaborative workspace at any instant.
8. Hazard from visual obstruction for robot in collaborative workspace due to vantage point of operator.

The severity of accident can range from no injury to death. The results fall into two categories: clipping points (body parts compressed between robot parts or between the robot itself and certain external objects) and collisions. The UAW(united auto workers) union reports cited raw data on several injuries related to robot operations. These types of injuries include cuts or abrasions due to contact with sharp or abrasive surfaces, and more serious injuries, including fractures, due to manipulator clamping or direct compression loads.
When the operator is performing tasks near the robot, and the robot has a large workload. If the most potential impact and injury occurs, it is likely to cause casualties. Fingers, hands, head and chest are the most common body parts in potential accidents. (See Figure.3.7.1).

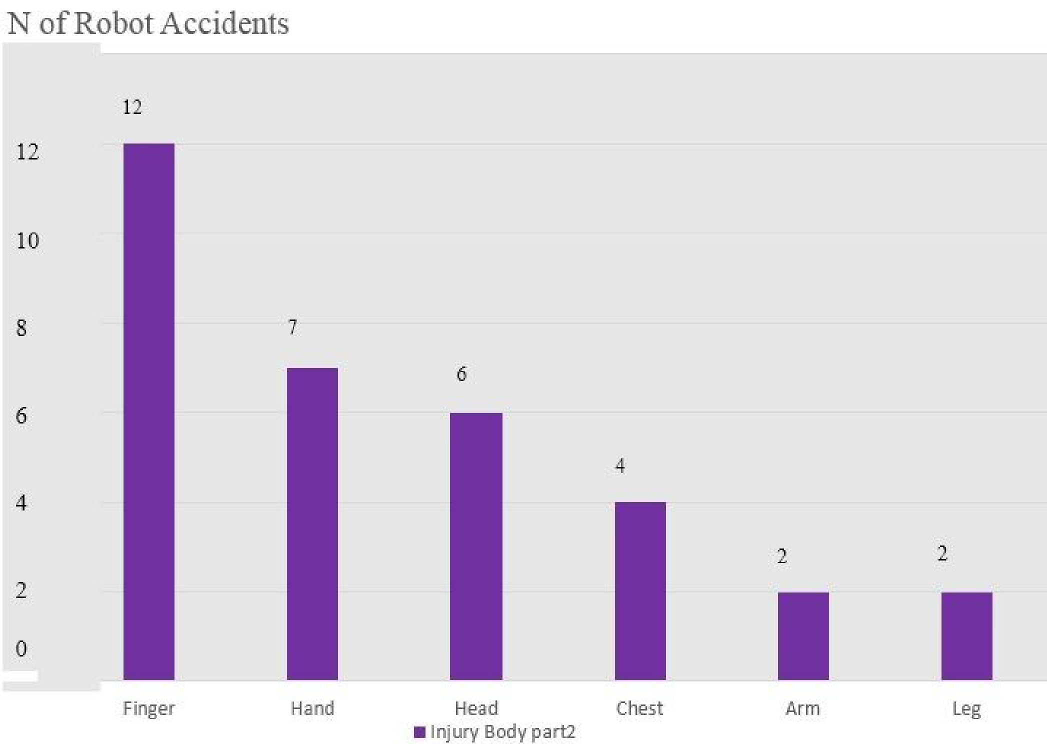
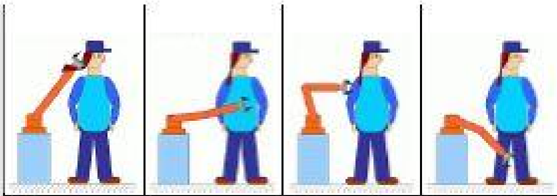


Figure 3.7.1 The 36 robotic accidents failure by types of injury[6]

3.8 Description of Contact Situations and Mechanical Hazards

As long as robots come into contact with humans, there is a risk of injury. There are additional mechanical hazards associated with specific applications, including specific tools. But let's just consider the manipulator itself. We recommend the following classification of contact areas and injury types:

[9]Table 6 Classification of contact region and damage types. Conditions requiring further examined by simulation are marked with ‘S’, conditions requiring examined during risk assessment are marked with ‘A’.



Relevant Hazards, Injury Types	Head and Neck	Torso	Upper Ex-tremities	Lower Ex-tremities
Free Impact	S	S	S	A
Crushing, Trapping	S	S	S	A
Shearing	A	n/a	A	A
Cutting, Severing	A	A	A	A
Entanglement, Drawing In	A	A	A	A

The hazard "Entanglement, Drawing In" is not a type of injury but it immediately causes at least one other type of damage. However, we recommend that it be assessed as a separate and related hazard, so we include it as an additional item.
The entry "n/a" indicates that this situation does not occur since the torso simply is too large to be sheared by a smaller-size or light-weight robot.
More work needs to be done to understand minor injuries such as minor bruises in more detail. We can confidently estimate that those items marked with an "S" are the most likely cases and those that can be further examined by advanced simulations. Items marked "A" are unlikely or currently unlikely to be simulated and therefore need to be addressed during risk assessment.

3.9 Risk assessment

[6] After determining the possible hazards of the system, it should be studied according to its probability and severity. In general, the primary purpose of risk assessment is to gather sufficient information about system hazards to characterize the system safety design. Providing different data for accurate risk assessment; This information may include the application of the robot, the structure and function of the robot, information about the workplace, and how the operator will work with the robot, as shown in figure 3.8.
Risk assessment for human-robot collaboration application based on personnel and ergonomic characteristics. Once the influencing factors reach the value below the designed threshold, these factors may cause a great risk which will be reproduced in hazards identification output.
In general, decision makers can obtain valuable information about existing risks that may jeopardize the realization of system objectives and the effective means of system

control. In this way, you can build an appropriate way to interact with possible system risks. Taking the final output of risk assessment as the input to complete the system decision process. On the other hand, risk analysis has a good understanding of the concept of risk, which will provide an input for risk assessment and help decision makers decide whether risk needs to be considered. In addition, the appropriate strategies for handling the respective risks in each step are spelled out. Risk analysis includes the identification of risk consequences and probabilities, which will determine the effectiveness of system control measures. Risk analysis deals with the consideration of risk sources, risk consequences and probability of risk occurrence. Thus, it is necessary to determine the parameters that affect the risk consequences and probabilities.

Considering the means of risk control and its efficiency, the use of various techniques in complex applications may be necessary. Risk analysis measures the level of risk in a system by assessing the potential consequences and their respective probabilities. It is possible to use a single parameter to make decisions where the results are negligible or the probability is very low.

Risk can be analyzed in different ways; Usually these methods include qualitative, semi-quantitative or quantitative. These methods are selected based on the availability of actual data, the required applications, and the importance of organizational decisions. Qualitative evaluation is to determine the level, consequence and probability of risk according to "high", "medium", "low" and other significance levels. Results and probabilities can be combined to report the level of risk generated according to qualitative criteria; The semi-quantitative method uses the numerical rating scale to report the results and probability, and can combine them and use the formula to obtain the risk level. On the other hand, in quantitative analysis, the specific values of the results and their respective probabilities are calculated and the risk level is reported in specific units on this basis. However, quantitative analysis is not always possible due to lack of information or related human factors.

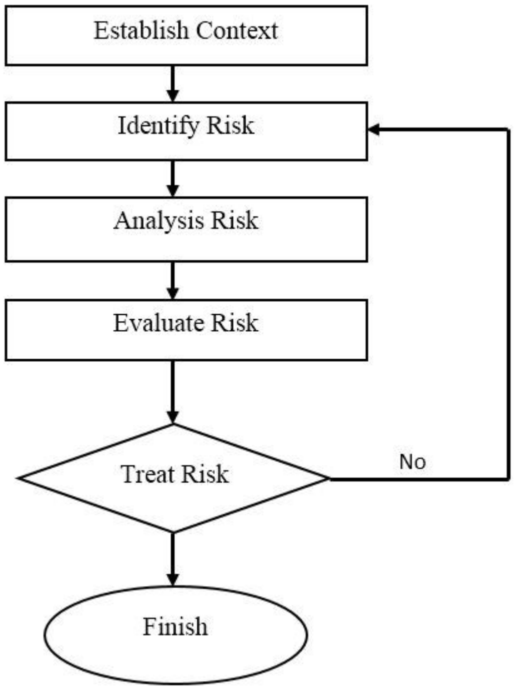


Figure 3.8 risk assessment overview

The purpose of risk assessment is to collect and generate information about robot hazards to design and improve safety designs. The information required for robotic risk assessment also includes the planned and unplanned use of the robot, and the function and structure of the robot (as shown in figure 3.9). In some robot safety standards, risk assessment methods have been widely used and discussed. In risk assessment techniques, there are several steps determined by risk categories and mitigation methods.

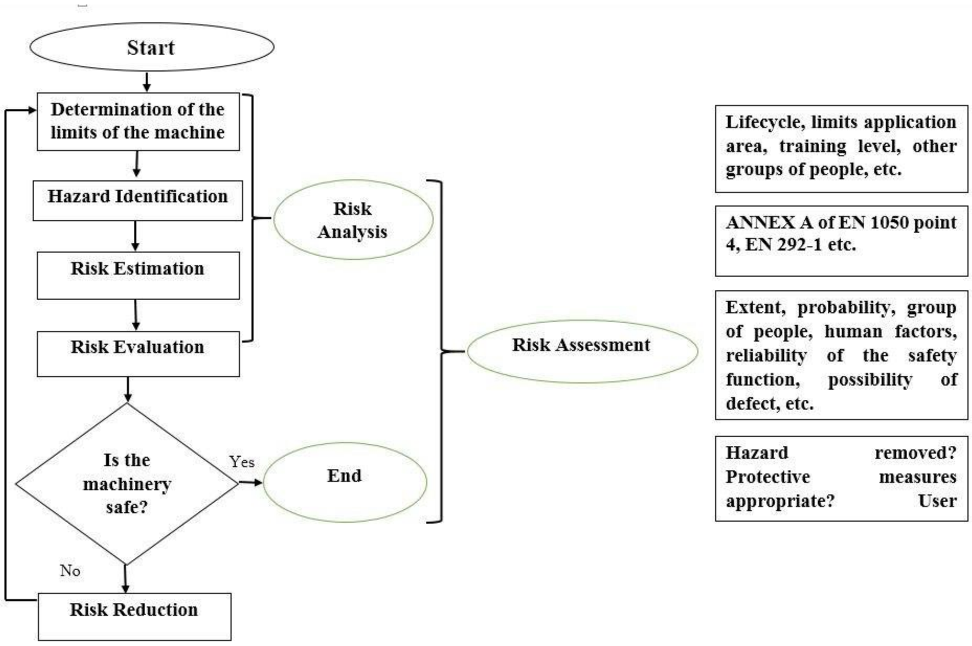


Figure 3.9 Risk Assessment Algorithm

For example, in the Robot Safety Standard ANSI/RIA R15.06 these steps are [6]:
1. Identifying robot application areas and identify all constraints (layout, time, dynamics, kinematics, mechanical constraints, software requirements, etc.) related to the intended use.
2. Conducting hazard identification for each robot task, analyze its operation method, interaction mode with humans and estimate the probability of mechanical failure.
3. To assess the risk category of each hazard according to the probability, probability and severity of injury or damage. This step involves developing a risk assessment matrix consisting of three main categories: severity of hazard (S1, S2), frequency of exposure (F1, F2), and probability of avoidance of hazard (A1, A2).
4. To determine whether the estimated risk is tolerable or not.
5. If not acceptable, the risk can be reduced through appropriate safety protection system installation or standard procedure application.

A standard approach to risk reduction (see Fig. 3.10) requires to application of all necessary hierarchical order of measures. The first step of hazards elimination should be always be the work cell redesign, while the next steps should involve the set-up of safeguarding technologies, training, warning procedures, and personnel safety equipment definition.

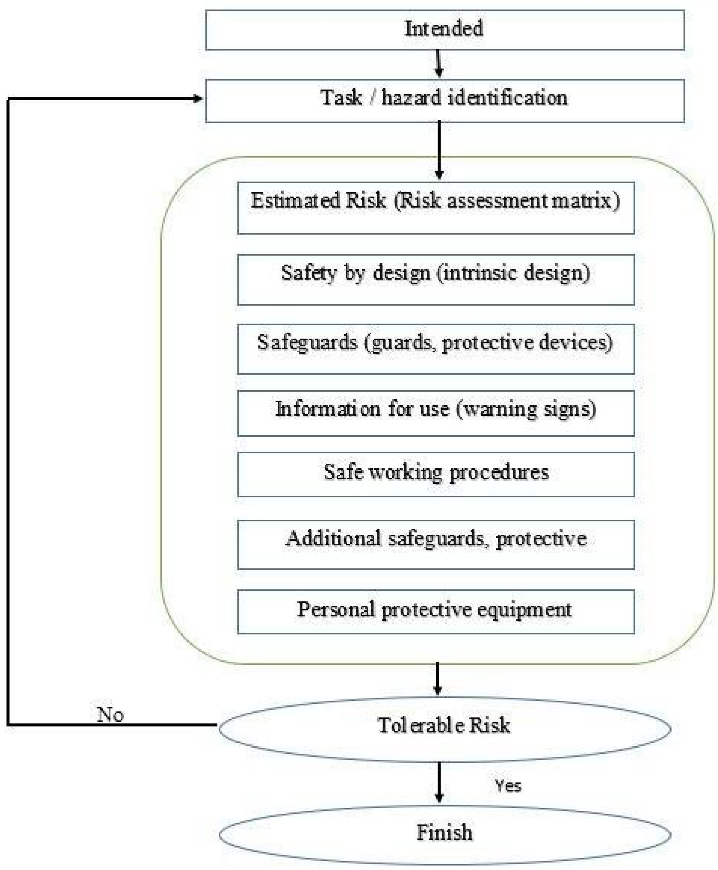


Figure 3.10 Generalized risk reduction algorithm

According to ANSI/RIA, standard suggests a strategy to reduce the risk, this can be approximately categorized into three classifications:

1. Fault avoidance (preventing or reducing the occurrence of faults by selecting highly reliable components); robot system fault tolerance enhancement (in case of failure of components system lose their functionality gradually, not catastrophically by including system redundancy, error correction and recovery) and fault immediate, reliable detection;
2. Select and locate proper safeguarding
3. Implement and determine risk category for safety circuit requirements.

Manually collecting all of these categories is difficult, typically for multi-tasking applications that contain many factors that might influence the final risk category. Furthermore, these methods are mechanically oriented, where the influence of human factors is not very relevant. Then detail of the risk reduction method will be discussed later in chapter 4.

In conclusion, the risk assessment basics are:

1 Use case identification

2 Hazard identification

3 Risk estimation

4 Risk reduction

5 Iterate until acceptable residual risk

1 Use cases

For a systematic approach, we begin by listing the anticipated use cases for the system shown. The information to record includes the task to execute, the lifetime phase of the machinery in which it takes place, the qualification level of the personnel involved, and the frequency of occurrence of the particular use case (see Table 7). A review of these reveals that for use cases UC1 – UC5 there are both the hazard of quasi-static and of transient contact with the hand or lower arm of the operator. Use cases UC6 and UC7, however, take place with the robot system powered down, so that no risk of contact with the moving robot exists.

Use case	Description, Frequency
UC1: Setup and programming	• Specially trained personnel • Rare
UC2: Normal production	• Simply trained personnel • Frequent
UC3: Manual in-tervention	• Simply trained personnel • Infrequent
UC4: Foreseea-ble misuse	• Untrained personnel • Rare
UC5: Mainte-nance	• Specially trained personnel • Infrequent
UC6: Cleaning	• Untrained personnel • Infrequent
UC7: Disman-tling	• Untrained personnel • Rare

Table 7 Overview of use cases

[9A not-isolated robotic cell would expose anyone close to danger. An operator may not even be trained or authorized to work with a robot, but still have access to the robot during daily activities. This will result in stricter safety requirements than traditional robotic devices.
Therefore, we need to describe in detail who might be exposed to risk, his/her skill level, and how often. Our proposed roles are shown in figure 3.11. Table 8 gives a detailed description of the roles.

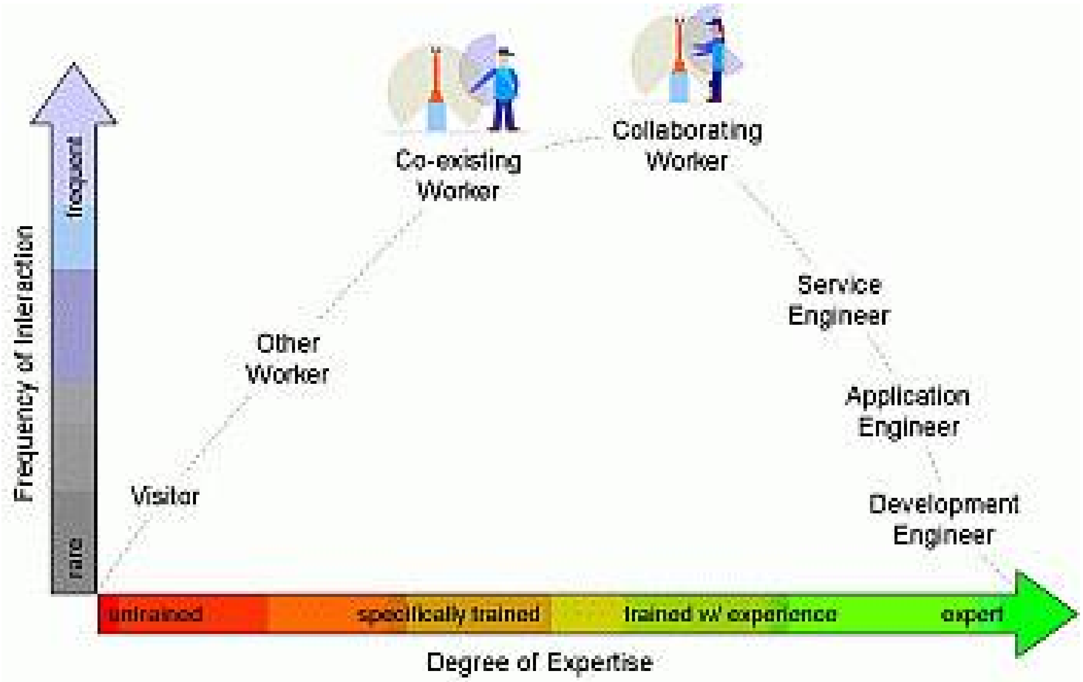


Figure 3.11 Roles of personnel, frequency of exposure and degree of expertise

Role	Role Description	Worst unsafe interaction with robot
Visitor	internal or external visitors, coming to robot for single visit, uninformed about hazards	enters work range although advised not to, and is hit by robot resulting in any of the listed hazards (see below)
Other Worker	employees occasionally coming close to robot, without any particular assignment involving the robot	enters work range although advised not to, and is hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical shock; his hazardous activities can be summed up under reasonably foreseeable misuse
Co-existing Worker	employees working physically in an overlapping workspace with robot; assignment does not comprise any interaction with robot	hits or is hit by the robot accidentally, resulting in any of the listed hazards
Collaborating Worker	interacts with robot (manipulator, end-effector, work pieces, fixtures, part tray, etc.) in regular operating mode	hits or is hit by the robot due to error in procedure or machine, resulting in any of the listed hazards
Service Engineer	interact with robot, reconfigure, repair and exchange and replace devices, reprogram, recalibrate robot and sensors, execute service routines	safety systems may be disabled, insulation protection may be removed; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical shock
Application Engineer	same as service engineer plus collaborating worker plus installation, introduce new production processes, decommissioning, retooling, switching on/off	interacts with robot when safety systems may be disabled; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical
Development Engineer	develop machine hardware and control, commission and test machine	safety system may be disabled or not working properly, unexpected behavior of robot is likely to happen during tests; hit by robot resulting in any of the listed hazards; plus additional hazards such as electrical

Table 8 Description of interacting personnel[9]

1 Hazzard identification

For the hazard identification, we must analysis the contact situations which are quasi-static(constrained) contact and transient(unconstrained) contact.

	Transient Contact	Quasi-Static Contact
Description	• Contact event is "short" (< 50 ms) • Human body part can usually recoil	• Contact duration is "extended" • Human body part cannot recoil, is trapped
Limit Criteria	• Peak forces, pressures, stresses • Energy transfer, power density	• Peak forces, pressures, stresses
Accessible in Design or Control	• Effective mass (robot pose, payload) • Speed (relative) • Contact area, duration	• Force (joint torques, pose) • Contact area, duration

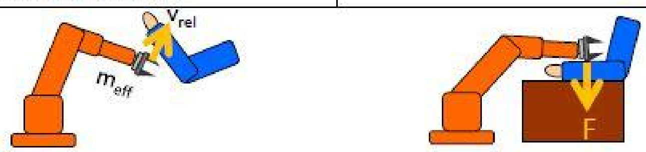


Table 9 contact type[10]

3 Risk estimation

Then overview of the risk assessment is shown in figure 3.12.

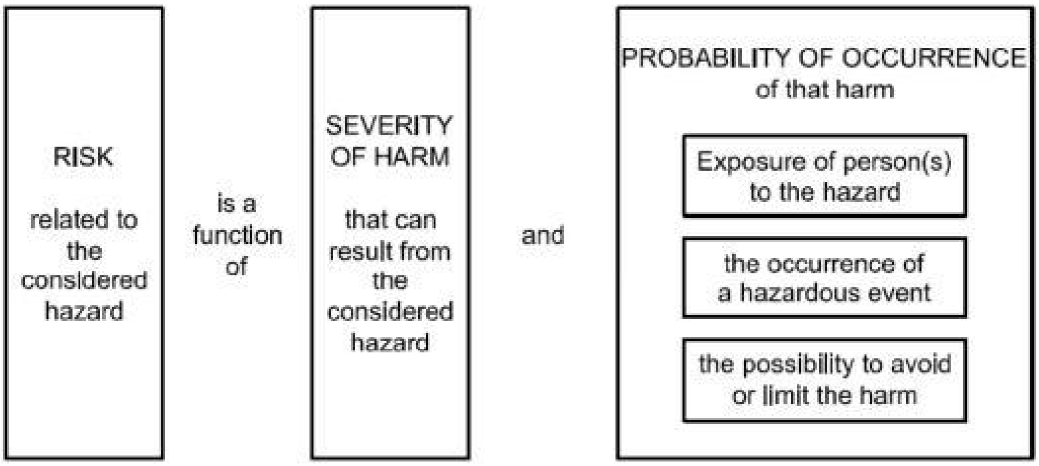


Figure 3.12 Overview of risk assessment

It is not possible today to use standardized quantification values to clearly estimate the risk of injury in human-robot collisions. This is due to the lack of basic statistics from robots and limitations in fully understanding the human body mechanisms of systemic injury under all possible load conditions.

[10] In recent years, many researches work on providing injury criteria for the classification of collision injury effects, which has been carried out mainly in the field of automobile. In particular, the lack of knowledge about low levels of harm has a higher correlation than the survivability ratio in the human-robot-collaboration case, because it can be assessed using artificial intelligence. There is still a long way to go before these low-level injuries (mainly soft-tissue injuries) can be systematically classified to assess the severity of the associated low-level hazards.

At present, the first experimental measurements are possible only in the worst-case condition, as e.g. carried out with crash-test dummies by Oberer-Treitz et al. and

Haddadin et al. So even though they provide a good basis for specifying how to design test procedures, they lack the proper injury criteria and prescribe the appropriate limitations in human-robot interaction.
As we can see, the risk is a function of severity and probability of occurrence of harm. It is better to discuss how to measure these two quantities.
According to the research[11], We can estimate the severity of the harm by establishing a impact model between robot and human body regions with the input which are mass of the robot, mass of the human, impact velocity, robot's radius curvature(sharp edge), stiffness of human and robot. The output is power flux density. Then we combine the power flux density with the corresponding injury criteria to estimate the severity.
As for the probability of occurrence of the harm, We can use the software named Integrated Dynamic Decision Analysis (IDDA) to get a probability of incident with the input of evet tree of the specific production process. This software can also evaluate the production process feasibility. The case study which will be presented in chapter 5 will use this software to check the feasibility and the safety of the system.
At the design phase of the HRC system, the severity and probability that mentioned above are two factor that must be checked for the risk evaluation. If the risk assessment result is not feasible, we need to improve the system design until the result is acceptable.

Chapter 4 Risk reduction

4.1 Interaction level of HRC

To identify the method and safeguard of collaboration between human and robot 4 levels of interaction are suggested, in which the interaction of each level needs different methods to provide security, installation of security means, application of safety standards and compliance with different security requirements., etc. Since for the different level of the interaction, the corresponding safeguarding method is different.

Interaction Distance	Description	Human Task
L1	Inside the robot operational work space (physical contact)	Guiding
L2	Outside the operational zone, within immediate space in the restricted one (in close vicinity)	Teaching Assembling
L3	In safeguard space, within the arm maximal reach	Verification Monitoring
L4	Outside the robot maximal reach	Observing

Table 10 HRC interaction level[6]

Level (L1) represents tasks in a shared working area that allow physical contact between the robot and the operator. Level (L2) refers to the task that separates the operator from the robot based on different task assignment or control strategies. Although the operator can work in close proximity to the robot and is authorized to enter the working area, the operator shall not enter the working area of the robot under the supervision of safety measures. At level (L3), the distance between the operator and the robot is large. However, he may be within reach of the robotic arm, and will require enormous precautions. At level L4, humans work completely outside the robot zone,

but there may be a risk of throwing objects in the robot workspace.
In other words, these levels determine the probability of injury to the operator, with L1 being the most dangerous region and L4 the least dangerous region. In each process, the damage probability of each interaction level is determined, and appropriate methods for dealing with different levels of damage are selected from table 10. A schematic of these levels is shown in figure 4.1.

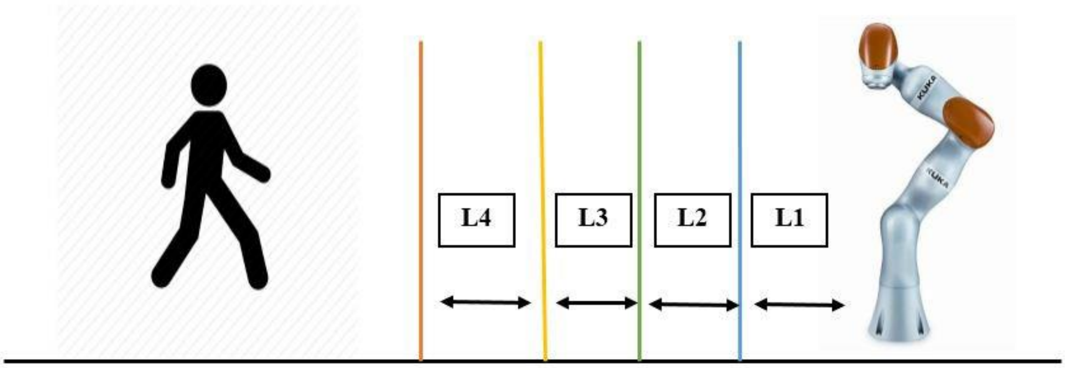


Figure 4.1 interaction levels in collaboration workspace[6]

The different interaction levels are based on the different safety strategy selected. For example, for the level 1, the HRC type is Power and Force limiting, while for level 4, the type is speed and separation monitoring.

4.2 Introduction of safeguarding and protective zones

In order to better identify hazards, the robot workstation is usually divided into two parts: the robot movement zone (the area around the end-effector) and the approach zone. An analysis by the US national institute for standards and technology (NIST) provides a more detailed distinction, identifying three areas of security:[6]
Zone 1- A safety area outside the work area accessible to the robot, within which safety is achieved in an industrial environment using physical barriers and perimeter sensors;
Zone 2-A secure area of the robot's accessible workspace, intruders are within the robot's reach, but there is no imminent danger of being hit.
Zone 3- A safety zone is defined as the volume immediately around the robot.
Human-centered design (HCD), in which humans play a vital role in systems and development, defines all tasks and responsibilities at each interaction level in the process of cooperating with robots. The areas were divided into: peer to peer, supervisory, mechanic or maintenance and observation zones. Therefore, in each area the method involves and defines the role of the person during collaboration with the robot system.
For instance, peer-to-peer roles refer to the human presence as an aid to the robot, and the abilities and skills provided to each person according to the performance of the task

will change their contribution. The role of the supervisor can be viewed as control and monitoring of the overall situation. This means that the supervisor evaluates a given situation and monitors the situation against a predetermined target. In the mechanical aspect, attention should be paid to the characteristics of the robot, electrical and mechanical parts.

The interaction is very limited and, perhaps, it’s the most isolated in the role of *bystander*. The two approaches can be combined to give a concept that is not used in interactive hierarchical propagation, where the relevant areas of the robot can be connected to the human part of the cooperative task execution. From a security perspective, each layer's interaction implies the meaning of its set of protection declarations. In the standardization of robots, the third level is well explored and elaborated due to its obvious correlation with the safety of tactical equipment.

A reasonable set of safeguard solutions at last two levels require more complicated protection measures and policies, because the risk for people being injured by the robot is very high.

4.3 Risk reduction solution

Safeguarding systems as most efficient standardized level are categorized into 5 classes[6]:

1. Present sensing devices. Laser scanner, light curtain and pressure sensitive mats are often used for robot safety (see figure 4.2a and b). This device are used for detecting human movement in robot area and stopping robot movement when human enters dangerous areas. For contactless monitoring of a freely programmable area, a laser scanner can be used. Body detection is usually applied to these types of sensors: ultrasonic detectors, passive and active infrared sensors, capacitors and pressure sensors. Robot grippers can also be equipped with photoelectric transducers, cameras, capacitances, radars, rangefinders and other sensors to control their own working state and enhance the "perception" of the surrounding environment.

2. Fix perimeter guards. Including the non-sensor safety devices which are usually installed around a robot in order to cover the safety system, such as: fixed barriers (fences) and interlocked barrier guards, (see Fig.4.2 c).

3. Awareness system Including the video, audio alarms (flashing, muting lamps), warnings and awareness barriers.

4. Personnel protection indicates hand, foot switches, teach pendant equipped with enabling switches and emergency stop. Also other task required special protective clothes or some wearable equipment’s protective.

5. The safety circuit relies on all safety system levels to connect all safety devices to safety and robot controllers. Control systems can be integrated safety systems or safety relays that are directly or remotely monitored by programmable logic controllers (PLC) or security modulators (see figure 4.2d). Robot control is usually limited to a standard common boundary control device (the basis of mechanical switches or software), overloading, and motor temperature, speed, and acceleration monitoring.

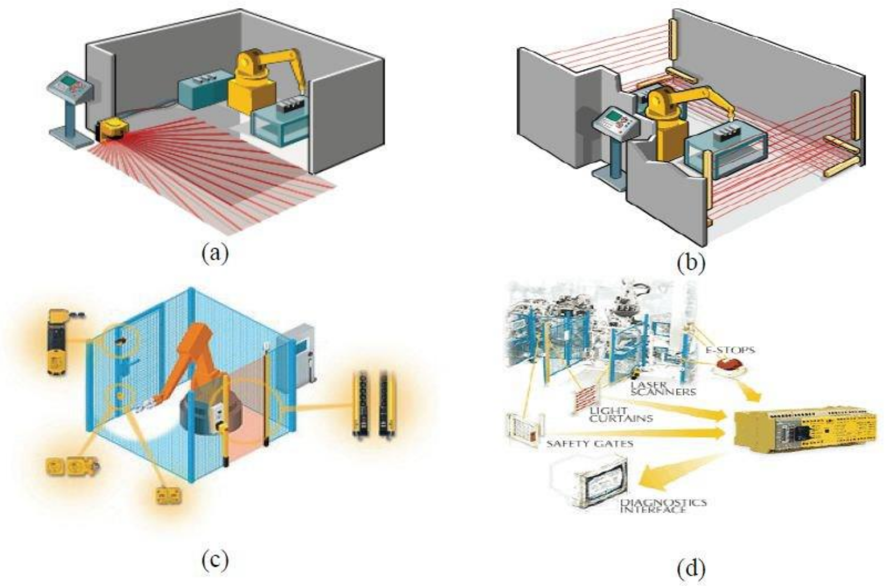


Figure 4.2 Safeguarding Solutions for the Robotic Systems: a) scanning system, b) light curtains, c) guard fence with safety switches integrated into the gates, d) safety controller.

For some solution for improving safety of HRC, the results of the KUKA Roboter GmbH can be highlighted. they have developed a safety system for industrial robots incorporating the safety-related fieldbus (SafetyBUS p) in cooperation with Pilz GmbH. The Electronic Safety Circuit (ESC) coupled with SafetyBUS p and Pilz Programmable Safety System (PSS) safety controllers. Fieldbus network is widely used in the transmission of control data, but the data related to security is not widely used. Traditional fieldbus technology is generally prohibited for security-related purposes unless the bus system is designed to meet the requirements of the security system

“KUKA Safe Robot” is a technology developed by same group. This robot is more intelligent and sensitive allowing the worker to enter the robot area to interact and guide the robot manually. The “Safe Operation” and “Safe Handling” are most important functions of robot. They monitor the speed and acceleration of the robot axes, enabling a safe operational stop of the robot. Pliz group has introduced other safety attitudes into industry. A camera system for three-dimensional safety monitoring was developed in cooperation with DaimlerChrysler. The Safety EYE is located in customized place, three-dimensional protective area around a dangerous zone. Using a single system. This area can be configured and detected on a PC flexibly and quickly.

Similar in the Team@work project, It was developed as a 3D monitoring system to prevent humans and robots from coming into contact with each other. To detect operator/robot position, three CCD cameras are used and signals are sent to the robot control unit to change its position and operating characteristics. Another proposed security solution, including a camera mounted on the robot's hand, computer image processing and a laser screen to change the robot's actual position.

The safety and autonomy of a robot is entirely dependent on ability to manage unexpected events, such as failures or unforeseen environmental changes. Fault handling and fault-tolerant control are essential functions in the safe interaction between robot and human. Reliability depends on the framework's ability to handle disappointment. In the paper [Caccavale and L. Villani, Fault Diagnosis and Fault Tolerance for Mechatronic Systems: Recent Advances, Springer Tracts in Advanced Robotics, Vol. 1, Heidelberg, Germany, 2003.], finally, a fault classification model is presented. It is worth mentioning that the picture of human-computer interaction applications is more complex. In HRC, it is very important to identify the fault types that affect the acceptability of robot reliability and should also be considered in the development and use process.

In fact, to prevent all possible scenarios can never be fully achieved. In the interactive process, the robot system is monitored, events or faults are detected, and its location and type are identified. Proper programming of the behavioral robot system, such as different control strategies, can ensure safe interactions and high tolerance for collision prevention. In the event of an eventual collision with a human, the robot should move as much as possible in a safe configuration. In order to check whether the technologies adopted are appropriate and sufficient, appropriate combination of analysis (such as FMECA, FTA) and evaluation are needed to obtain reliability.[6]

4.3.1 Visual and sensor monitoring

For improving the safety of human-robot collaboration and providing feedback signals for robot movements, it is necessary to provide valuable information for monitoring human movements. Mechanical forces and displacements are the simplest ways to monitor human-robot collaboration. Human monitoring communication signals is another kind of monitoring system. The system is divided into physiological monitoring and visual monitoring. One application that can read human intentions from mechanical signals is in tasks where robots can power human movements. For instance, Yamada et al. in [27] applied a Hidden Markov Model to the operator’s purpose estimate from early motion of the operator. The visual monitoring system uses the camera to track people in the interaction process, and uses these data to guide the interaction, and realizes the visual monitoring through the user's eye gaze and head position. [28] to provide reading with gestures or facial expressions. Due to improved security, human-robot collaboration in the workspace can be managed by fixed cameras. [29] different image methods are adopted to detect obstacles moving in the robot. When a collision is detected, the robot's motion changes their path. It is an important issue that physiological responses vary greatly from person to person.

The other is that the same physiological signals are triggered in a series of psychological states; For a controller, it is difficult to determine the subject's emotional state, or whether the response is caused by the system's actions, or by external stimuli.[6][12]

4.3.2 Trajectory planning

Safety control and trajectory planning are important in human-robot collaboration, especially when there are additional obstacles in the environment. Trajectory planning is considered safe when the degree of potential danger can be minimized and the target can be reached. In this context, various trajectory planning methods are proposed, most of which are based on heuristic variation or algorithm and artificial potential field. This method does not need to search in the global path, has the possibility of online operation, and is easy to modify the sensor according to dynamic obstacles and trajectory planning. When redundant of robot is applied, the method can be extended to avoid the impact of obstacles while executing tasks. A similar method is proposed when the trajectory target and task are global positioning and dedicated to redundant manipulator. In this method, a force is generated to avoid obstacles, and the redundant manipulator is positioned to the null space, so that the robot can continue the target trajectory while avoiding the collision of redundant dof obstacles. The problem of this robot planning method is local search, which cannot reach the minimum value of global position, which is not the optimization goal.

Another problem in the workspace is the large force of deriving formulas. The jacobian matrix is required to convert these forces into joint torques and introduce the position and velocity errors near the singularity of the robot.

At present industrial robots are position controlled. Precisely planned tasks are required for successful human-robot collaboration. For unstructured human domains, this detailed description of the environment is very difficult. Therefore, mere motion control may lead to an unnecessary increase in contact forces. Force/impedance control is important in HRC. The ability to sense and control exchange forces is critical in HRC tasks.

The research [30] proposed a robot manipulator that uses equivalent mass spring damping system for impedance control, with contact force as input (impedance may change in different directions of task space and is usually nonlinear coupled). The dynamic equilibrium interaction system between human and robot is studied. The weight of human and robot structures affects balance. In general, the interaction task requires an exact value of the contact force. Robots with joint torque sensors offer the possibility of measuring contact forces. Like DLRIII lightweight robot, joint torque control combined with high performance drive and lightweight composite structure can meet the requirements of safety performance. The manipulator may be close to the obstacle. In addition, in the article[31], the author used the mobile manipulator for path planning, and measured the distance between the robot and any obstacle as "safety degree" in the cost function. The genetic programming method was used to generate the path according to several optimization criteria, such as the actuator torque minimization, joint distribution, obstacle avoidance and maneuvers.[6][15][16]

4.4 Training and maintenance

As the result that presented in chapter 3 shows that the human failures contribute to the safety issues are with a larger portion than robot failure. So training becomes significant. Employee qualification should mainly consider the needs of different target groups while involving the whole company. Thus, it is important to invest in:
(1) into the job trainings for apprentices and trainees as they represent future operative workers and managers within the manufacturing context,
(2) along the job trainings for present employees to learn and develop new competencies, as their tasks will be supplemented with new technologies, and
(3) out of the job trainings to enhance the knowledge transfer between older and younger employees or to support the flexibility within a company through job rotation measures.
In order to meet the challenges of working with robots to accomplish current tasks, it seems most likely that the overview requirements for developing capabilities will be met during the job training process. So far, several "methods of work" have focused on the general requirements for employee qualifications in industry 4.0. Most of them consider new possibilities through continuous technological progress, such as digital learning environments or simulation training in hybrid reality systems through augmented reality (AR) or virtual reality (VR). In order to understand the mechanism of different methods, more in-depth study is needed.
Training through the use of equipment and techniques for real-time solutions, such as AR tools, allows learning on demand, such as in the event of a failure, which can be an example of work measurement. These methods relate theoretical knowledge to practical application [19]. In addition, they provide a customized learning process for each learner, so they can be used independently of time and learning speed.
Measures such as the digital learning factory (IFA), which is near the workplace, are carried out internally, but not directly in the workplace. The digital learning factory includes a real learning environment, including the real production process in the physical and digital environment. They can be used for different target groups and learning purposes. The adaptability of the learning factory is related to the upcoming changes in production settings, which can be realized through several equipment modules.
Since not every company is likely to set up such factories in its own workspace, companies often send employees to different workshops or manufacturers for training, which is considered non-job training. The training often provides knowledge about machine use, but lacks portability to specific production processes for different companies. As Acatech points out, practical relevance is a key factor in the success of eligibility programmes.
All in all, employee qualifications seem to be a promising approach to human-robot interaction. To date, there has been no experience-based advice on whether on-the-job training or training adjacent to on-the-job training is more successful in preparing employees for future tasks.

Also the maintenance plays a vital role in HRC system. An advanced maintenance solution not only improve the productivity by increasing MTBF(mean time between failure), but also improve the safety condition by maintaining the performance of safety control system such as sensor. For the maintenance of HRC system, we should give priority to the component related to the safety. [13][14]

4.5 Conclusion

To reduce the risk, different solutions should be considered for different interaction level. The interaction level of system is based on the type of the HRC system which can be decided by the application, cost, process etc.

Types of HRC	Possible solution to reduce risk
Safety-rated monitored stop	1. Safety button to authorize the operator to enrter and exit from collaborative working area 2. Cammera or other sensors to monitorthe working area 3. Training and maintenance
Hand Guiding	1. Traject planning 2. Emergency stop 3. Controls close to the end-effector 4. Training and maintenance
Speed and separation monitoring	1. Sensor monitor the distance and speed 2. Protective stop if minimum distance or speed limit reached 3. Consider braking distance in minimum separation distance 4. Training and maintenance
Power and force Limiting	1. Sensor monitor the end-effector speed, torque and force. 2. End-effector brakes when contact with operator 3. Low inertial 4. Avoid sharp edges 5. Soft skin where can contact with operator

Table 11 Summary of risk reduction methods

Chapter 5 Case study

In this chapter, the introduction of analytic hierarchy process (AHP) approach will be represented in order to prove the effectiveness of the human-robot collaboration system compared to the purely manual process. Then then the hierarchical task analysis (HTA) method will be introduced which aims to allocate the task for the human and robot of the system. The case study model is a assembly process of brake disc which based on the research [6]

The main purpose of this case study is to analyze the procedure of the brake assemble process by using software named Integrated Dynamic Decision Analysis (IDDA) to evaluate the production process and risk assessment. In the end, some modification will be made in order to improve the system both safety level and production efficiency.

5.1 Manual assembly process of a brake disc

Brake disc is a rotating part of the wheel brake disc assembly used on brake pads. It produces friction force to the rotation of the shaft, as it does on the axle, to slow down the speed and keep it stationary. The material is cast iron, generally gray iron. Brake disc designs are different, some are simple solids, but some have complex designs attached to fins or blades. The size of the brake disc depends on the weight and power of the vehicle. In order to make the brake disc have better heat transfer, noise reduction, quality reduction and surface water dispersion, the design of the brake disc through the hole or groove.

In order to remove gas and dust, the disc is designed as a thin channel called a slotted disc. This type of disc is used in racing environments to eliminate gas and water and deglaze brake pads. Another type of brake disc is the floating disc, which splines to prevent thermal stress and cracking. This feature will allow the disc to expand in a controlled symmetrical manner and optimize the unwanted transfer to the hub.

The assembly process of the brake disc is accomplished through five sequential steps. In the first step, semi-finished products, such as snap rings, stand upright, bearings, from the previous station or from the shelf. Second, the operator will remove the dustproof board from the board box and place it on the semi-finished products. Then the operator takes out 3 M6 screws from the screw box and inserts them into the dustproof plate. The third step, the operator will remove the hub from the hub box, put it on the dust board, the assembled parts to the pressure machine, and put it in place. At this point, the press inserts the hub under pressure into the previously assembled parts, which the operator then takes back to the production unit. Fourth, the operator will remove the brake disc from the brake disc box and place it on the assembled parts. In the final step, the operator removes two M8 screws from the screw assembly, inserts them into the assembled part and screws them tightly.

In order to describe the operator's work in more detail, it is better to clearly define the working conditions. Each operator works 8 hours/shift every day, and each brake disc weighs 5 kg. It takes about 3 minutes to assemble one brake disc. Considering the shift time of operators and the assembly cycle of brake discs, operators should assemble about 160 brake discs with a lifting weight of 800 kg every day. Obviously, traditional manual processes bring many ergonomic issues. It is clearly that traditional manual process will bring many ergonomic problems. This is also the reason why we introduce HRC solution into the industry.

5.2 Introduction of Analytic Hierarchy process(AHP)

It is not an easy task to qualitatively evaluate the efficiency of the process according to various criteria to find the optimal solution. However, using quantitative analysis, such as analytic hierarchy process (AHP), provides a good solution to meet this goal. In the current brake disc assembly case study, the evaluation criteria considered are productivity, ergonomics, safety and quality. The comparison solution adopts the pure human system and the comparison solution based on the human-robot collaboration system, and the evaluation method adopts the analytic hierarchy process. The four standards of production efficiency, ergonomics, safety and quality are considered the most important by factory managers and experts involved in this activity. Other criteria are ignored because they do not significantly affect the human-robot collaboration process. In order to implement this activity, three experts participated in decision-making and planning, and they supported the authors' choice of AHP methods to evaluate the effectiveness of human-robot collaboration[6].

The AHP analysis proposed by References [20–24] is defined in eight general steps, as follows:

1. Identifying the problem and defining the goals.

2. Construct the general framework of the AHP analysis in a hierarchically descending order; this means that the objective set at the highest level is followed by the criteria set at the intermediate levels, and then solutions, which are set at the lowest levels.

3. Use the pair-wise comparison scale for AHP preference from References [20–24], ranging from 1–9 (intensity of importance). In this scale, 1 expresses the equally-preferred status and 9 expresses the extremely-preferred status.

4. Construct the pair-wise comparison matrix for the four criteria

5. Construct the pair-wise comparison matrices of alternatives for each specific criterion; this means that if there are n criteria and m alternatives available in the procedure, there should be n matrices with the size of $m \times m$.

6. Construct the synthesized comparison matrices of alternatives for each specific criterion to calculate the priority vectors; each value of the synthesized matrix is calculated by dividing the same element by the summation of its column. Each priority

vector is then calculated as the average of the new matrix row.

7. Calculate the consistency ratio for the pair-wise matrix of the four criteria to check the consistency of the analysis comparisons.

8. Construct the priority matrix of alternatives (solutions).

In the research [6]. The AHP method is applied for comparing the effectiveness between human and human-robot process considering productivity, quality, ergonomics, safety. The result shows that human-robot solution is more effective with overall priority equal to 0.5365 while the priority for the human solution is 0.4638.

5.3 Introduction of hierarchal task analysis (HTA)

After we decide to use HRC solution, the next step is to allocate the task to the human and robot in order to maximize the advantage of human-robot collaboration and fulfill both productivity and safety demands.[6]
There are several ways to analyze operational tasks. These methods include hierarchical task analysis (HTA), goal-oriented task analysis, and cognitive tasks for modeling human-computer interaction. HTA method is a scientific method to allocate human tasks, involving different ergonomics and human factors. The HTA has extensive applications in entertainment, police and military, space exploration, manufacturing, mining and agriculture. In order to form an HTA diagram, all tasks should be defined as goals and sub-goals; They all have to complete in order to reach the ultimate goal. In this specific human-robot collaboration research, HTA will be a very effective method to determine human-robot collaboration tasks. The same scenario applied to AHP is applied to the HTA approach. In research [8]. The author use HTA method to allocate the task to the human and robot for the brake assembly process. In order to complete this activity, the same three experts were involved in the planning and identification of tasks; One is responsible for management and consulting, with more than five years of experience, and the other two are responsible for programming and running applications. Two people trained in robot programming and safety procedures perform collaborative activities, working with prototypes in laboratory environments; One is responsible for working directly with and assisting the robot, while the other is responsible for monitoring tasks and shutting down the robot in case of emergency. The robot programmer received a year's training in Java programming, specifically for KUKA robots. Another expert is a doctoral researcher who has studied the challenges and difficulties of human-machine collaboration for more than three years. The first step is to obtain data in the actual production environment through direct observation. After recording all necessary information, the sequence of operations is classified according to relevant skills and abilities to clarify the framework objectives. Once the sequence of operations is determined, the general process should be decomposed into separate unified tasks according to the hierarchical task analysis (HTA) method.
This method is helpful to distinguish the roles of the human and the robot in the

assembly process. However, the operator's primary task involves inserting screws and hubs, while the robot's task is to perform the assembly process and tighten the screws. In the fourth step, HTA is applied to combine operator tasks and robot tasks in a collaborative order to form a new task table. Finally, the hybrid task algorithm is evaluated to verify the feasibility of the proposed method. Using the HTA approach, tasks are defined as sub-goals with process time cycles of related tasks. In order to constitute the HTA algorithm of the brake disc assembly, the main target of the system is considered to be equal to the target of the robot master and manipulator. Thus, in the HTA algorithm, the assembly of the brake disc is recorded as the supercoordinate target 0. In order to achieve the main goal, the sub-goal should be completed. The sub-target is subdivided into three groups: sub-target 1(to assemble dustproof board); Sub-target 2(to place the hub on the board, to replace the roof and tighten it); Sub-goal 3(to complete assembly of brake disc). Sub-goals are then divided into small goals. It is important to add lower-level goals to the model when more detail is needed.
The result of the HTA method done by [6] are shown in Figure 5.1(original process human only) Figure 5.2 (process for HRC).

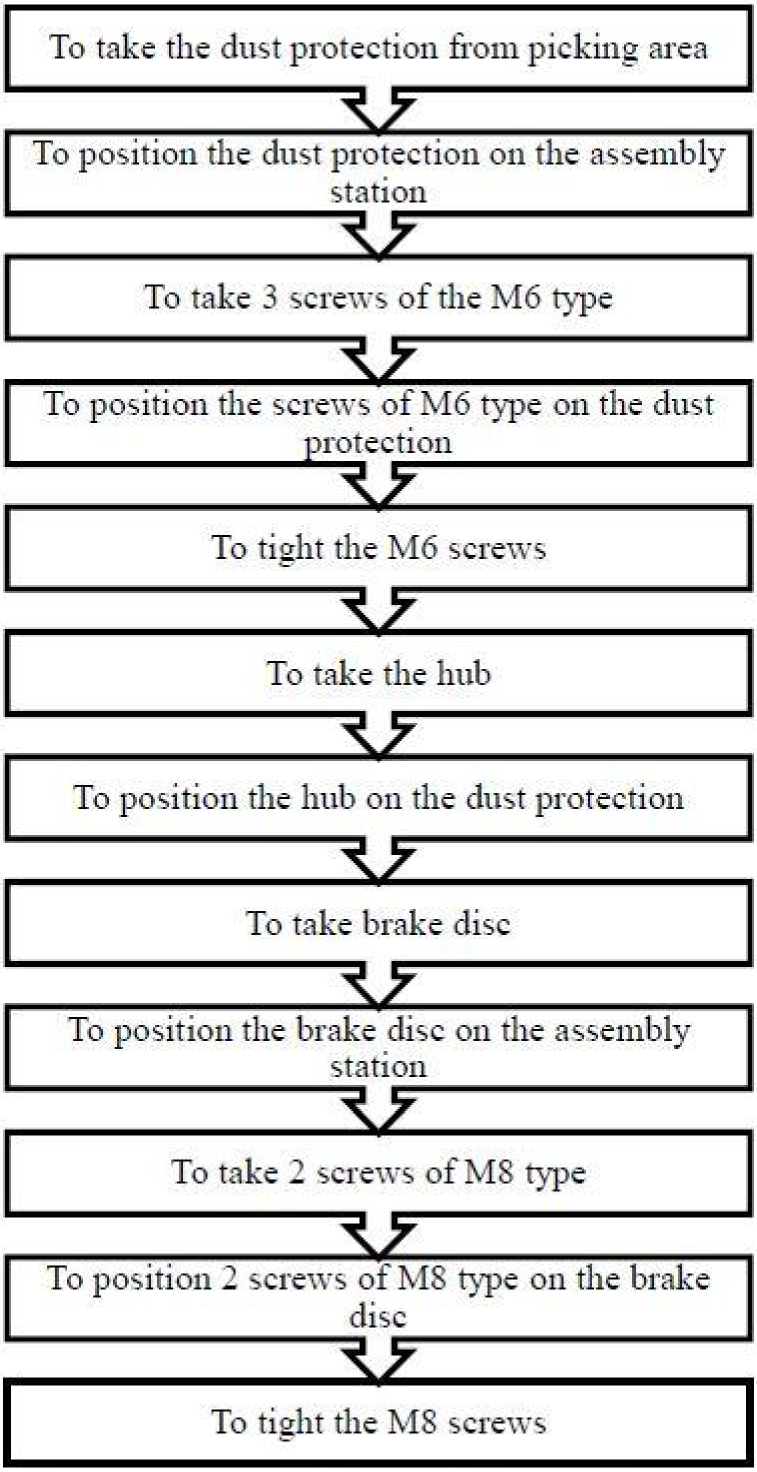


Figure 5.1 purely manual process[6]

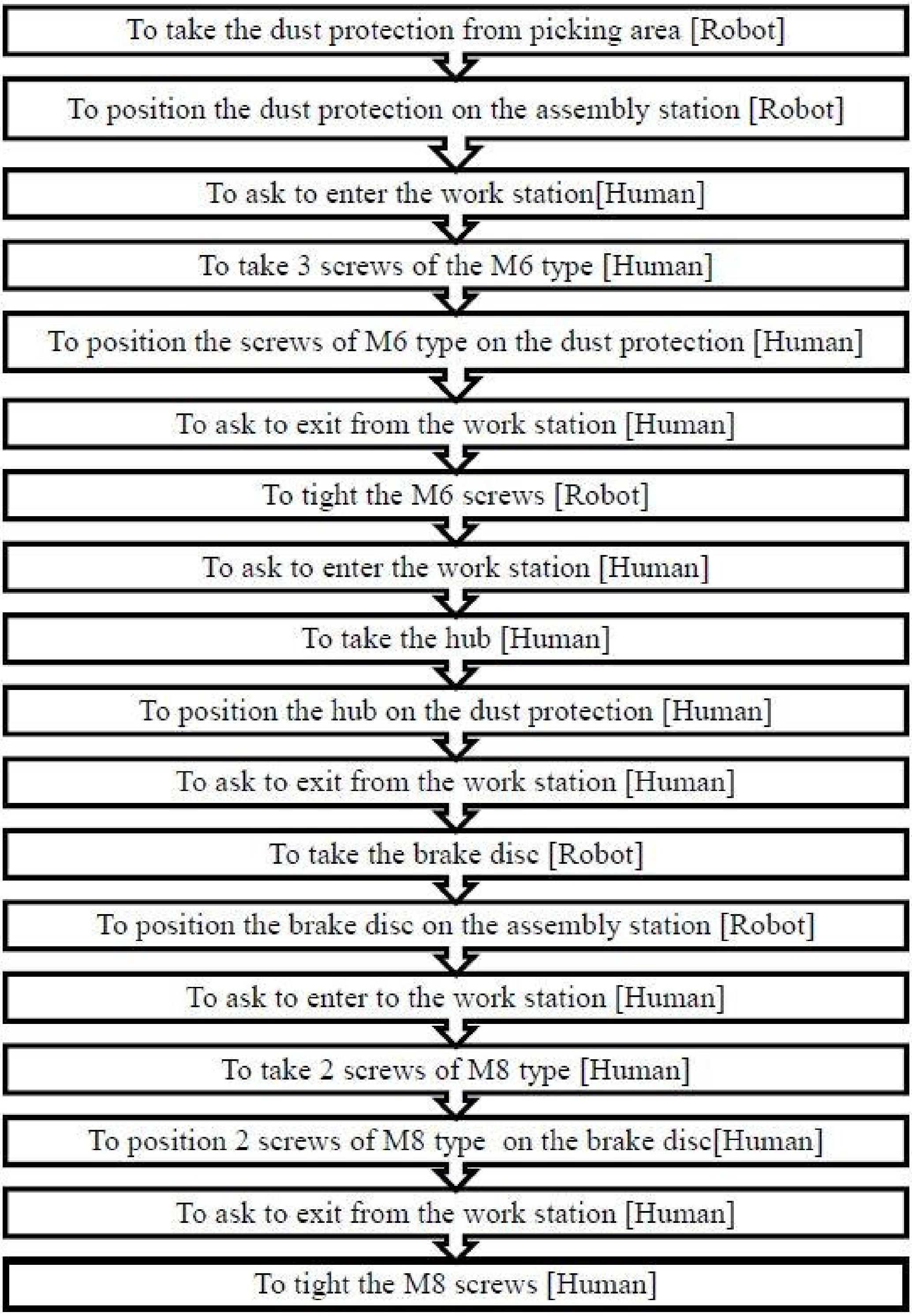


Figure 5.2 Process for HRC[6]

According to this application, The safety-rated monitored Stop type has be chosen for this assembly process.

This result will be a input for the IDDA simulation which will be discussed later on.

5.3.1 IDDA software

IDDA is a Computing Environment for Integrated Dynamic Decision Analysis. As Decision Analysis tool it is based on a rigorous application of Logic to define and to depict all the possible alternative incompatible scenarios among which the choice has to be done: that is, the field where the decision has to be taken. [7]
Each alternative scenario is developed and presented according to a Cause-Consequence logical approach. In this approach both logical rules and probability evaluations are applied dynamically in that each piece of information progressively received can be used to define the successive logical path and the conditional probabilities of the following events, according to a sound application of the inductive reasoning.
As we discussed before in chapter 3, for the risk assessment of the HRC solution, we need to get severity of harm and probability of occurrence of the harm. We compute the energy flux to represent the severity. While for the probability, we can use IDDA to calculate its value. This software also can evaluate the production process feasibility by checking the probability that finish the production correctly.

5.3.2 Events tree, the input for the IDDA

For using the IDDA software, 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.[8]
According to the description of the procedure from chapter 5.3, the event tree is shown

in Table 12

Table 12 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

The failure probability of each level is calculated by[W. Jiaqi 'Human-robot interaction, analyzing the risk in collaborative environment] based on failure mode of the robot component, corresponding bathtub curve, operating time and meantime before failure(MTBF).

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

The input data for calculating failure probability of each level is from an experiment by recording the failures of this robot in three years. As shown in Table 13

Table 13 Frequency of robot's failure

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

The final result of event tree with corresponding failure probability as show in Table 14

Table 5 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
150	operator takes the three M6 screw and position them on the dust protector	11	0.02
200	operator exits the working station	2	0.0004
250	screwing	35	0.000486
300	go back to the home position	4	0.0000556
350	operator enter the working station	3	0.0004
400	changing the robot tool	12	0.02
450	take the hub and position it on the dust protection	10	0.0004
500	operator exist the working station	2	0.0004
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
650	operator takes two M8 screw and put it on the brake disc	17	0.02
700	operator leave the working station	2	0.0004
750	screwing	24	0.000333
800	go back to the home station	4	0.0000556

Before doing simulation with software, we should distinguish two types of failure. For level 1, 50, 100, 150, 250, 300, 350, 400, 450, 550, 600, 650, 750, 800. The failure will cause production process cannot finish correctly which means production is not efficient. These failures will not cause the operator in accident by robot, since there is no collaborative working condition for these levels.

While for the combination of level 200 and 250, 500 and 550, 700 and 750, according to sequence-consequence logic, the operator safety should be analyzed. Since for those level, operator and robot may share the working area. Since we decide to use SMS types, which means if the operator is inside the collaborative working area, the robot must stop. For example, if level 200 fails, which means operator doesn't exit from working area and if level 250 doesn't fail, which means robot screws. In this situation, we need to evaluate the probability of accident. This is a worst case analyze in order to have a more conservative result.

5.3.3 Hazards identification

As we discussed in chapter 5.4.2, The incident happens when operator doesn't exit the working area, and the robot still works. We can analyze the hazard when human is inside the working area as robot working.

Possible hazards are:

1. Hazards from robot characteristics, i.e., speed, force, torque, acceleration, momentum, power etc.
2. Hazards from end-effector and work part protrusions.
3. Sensitivity of the parts of the operator body that can come in contact in case of collision.
4. Mental stress to operator due to robot characteristics (e,g., speed, inertia etc.)
5. Hazard from trajectory taken by the robot.
6. Physical obstacles against robot operation during collaboration. -
7. Hazard from fast worker approach speed and robot's slow reaction time.
8. Hazard from tight safety distance limit in the collaborative workspace.

5.4 Simulation and results

There are 5 alternative solutions of brake disc assembly process are simulated, which are:

1. Original work process
2. With a safety button based on SMS
3. After training
4. Applying advanced maintenance
5. Integrated solution of 2,3,4.

After simulation of these 5 alternatives, we can evaluate the process both in terms of efficiency and safety. Meanwhile we can figure out that how these factors can effect the system performance.

1. Original work process

There is no safety related software and hardware applied. Operator just follows the instruction of production.

The corresponding events tree as follow:

Table 6 The events tree of original work process

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
150	operator takes the three M6 screw and position them on the dust protector	11	0.02
200	operator exits the working station	2	0.0004
250	screwing	35	0.000486
300	go back to the home position	4	0.0000556
350	operator enter the working station	3	0.0004
400	changing the robot tool	12	0.02
450	take the hub and position it on the dust protection	10	0.0004
500	operator exist the working station	2	0.0004
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
650	operator takes two M8 screw and put it on the brake disc	17	0.02
700	operator leave the working station	2	0.0004
750	screwing	24	0.000333
800	go back to the home station	4	0.0000556

The result is as follow
The probability of finishing production correctly (this means both no failure of production and no accident) =0.937
The probability of having accident =1.148e-03

2. With a safety button based on SMS

According to standards SMS, we introduce a safety button to authorize the operator to enter or exit. When operator exist in working area, the robot must stop. When the operator wants to enter the cooperative area, he should push the button to command the robot to stop moving until the task is completed. When the operator completes his task, he should push the button again, which means he wants to leave the collaboration area. In addition, after the operator completely quit, the robot can continue to work and complete the task.

The corresponding events tree as follow:

Table 7 The events tree with safety button

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	operator asks to get into the working area	4	0.0004
101	Button status	0.5	0.0002
150	operator takes the three M6 screw and position them on the dust protector	11	0.02
200	Operator asks to exit from the working station	2	0.0004
201	Button status	0.5	0.0002
250	screwing	35	0.000486
300	go back to the home position	4	0.0000556
350	operator asks to get into the working area	3	0.0004
351	Button status	0.5	0.002
400	changing the robot tool	12	0.02
450	take the hub and position it on the dust protection	10	0.0004
500	Operator asks to exit from the working station	2	0.0004
501	Button status	0.5	0.0002
550	taking the brake disc and position it on the hub in the assembly station	27	0.000375
600	operator asks to get into the working area	2	0.0004
601	Button status	0.5	0.0002
650	operator takes two M8 screw and	17	0.02

	put it on the brake disc		
700	Operator asks to exit from the working station	2	0.0004
701	Button status	0.5	0.0002
750	screwing	24	0.000333
800	go back to the home station	4	0.0000556

The safety button plays a role of double checking that operator is exist or not. The reliability of safety button system becomes critical. Since it not only effects the safety performance but also the production efficiency. Since this procedure is series connected to the original production process, we sacrifice the efficiency of the production for safety performance.
The result is as follow
The probability of finishing production correctly =0.936
The probability of having accident =5.73e-04

3. 4. Training and maintenance

As we analyzed in chapter 3 and 4, the human errors contribute to the failure of production both in terms of efficiency and safety. So training is a critical factor which effect the HRC system performance.
Regarding for maintenance, its aim is to maintain the reliability of component and reduce the failure probability of failures of robot component. With advance maintenance to the HRC system, not only increase the production efficiency but also the safety performance since we reduce the failure probability of safety system.
According to some experience from automotive industry field, and in order to be more conservative, we could say that the probability of failure both contributed by human and robot reduced by 25%.
The event tree is same as the one of original work process by reducing failure probability by 25%.
The result of training is as follow
The probability of finishing production correctly =0.947
The probability of having accident =8.67e-04
The result of advanced maintenance is as follow
The probability of finishing production correctly =0.9374
The probability of having accident =9.74e-04
From the results, we can figure out that the training has more effect than maintenance in terms of both production efficiency and safety performance.

5 Integration of 2, 3, 4

For the alternative 5, is a integration of training and maintenance based on SMS type by applying a safety button.
The result of integration is as follow

The probability of finishing production correctly =0.951
The probability of having accident =4.35e-04
With this solution, the safety performance of system is increased by 62%.

A table to summary the result:
With P=probability of finishing process correctly, S= Probability of accident

Table 17 summary of the results

	P	S
Orininal work process	0.937	1.148e-03
Safety button based on SMS	0.936	5.73e-04
Traing	0.947	8.67e-04
Maintenance	0.938	9.74e-04
Intergration	0.951	4.35e-04

From table 17 we can figure out that training plays a vital role in performance of the system, this factor has a lager effect on the system behavior both in terms of productivity and safety. Since training will make the operator to better follow the instruction which is designed aiming to improve the productivity and safety. The maintenance aims to reduce the failure probability of the system component. If the failure probability of the normal component reduces, the productivity will increase. The maintenance of the component which is in charge of the safety, should be given priority, since it not only effects the production efficiency but also the safety performance. With the integrated solution, the safety performance of system is increased by 62%. By introducing visual sensor (laser scanner, camera, ultrasonic sensor) and trajectory adjusting, the probability of having a low level of accident could drop to order of 10^{-5}, and the probability of having a fatal accident could drop to order of 10^{-6}.
We can estimate the severity of the harm by establishing an impact model between robot and human body regions with the input which are mass of the robot, mass of the human, impact velocity, robot’s radius curvature (sharp edge), stiffness of human and robot. The output is power flux density which can be calculated through CAE software. Then we combine the power flux density with the corresponding injury criteria to estimate the severity. There is especially a lack of knowledge in the area of low-level injuries, which will be of higher relevance in the case of human-robot-collaboration than the ratio of survivability, as it can be rated with the AIS. There is still a long way to go, to classify these low-level, mainly soft-tissue injuries in a systematic way that allows for an evaluation of the severity of the relevant low-level hazard.

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	Extreme	Extreme
Possible	Medium	Medium	High	High	Extreme
Unlikely	Low	Medium	Medium	High	High
Rare	Low	Low	Medium	High	High

Table 18 Risk matrix

The original process which without any safety software and hardware have a moderate consequence and possible likelihood. The residual risk is not acceptable.

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	Extreme	Extreme
Possible	Medium	Medium	High	High	Extreme
Unlikely	Low	Medium	Medium	High	High
Rare	Low	Low	Medium	High	High

Original process

After applying integrated solution which mentioned above, the consequence becomes minor and the likelihood becomes unlikely.

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	Extreme	Extreme
Possible	Medium	Medium	High	High	Extreme
Unlikely	Low	Medium	Medium	High	High
Rare	Low	Low	Medium	High	High

Integrated solution

By introducing visual sensor monitor and trajectory adjusting method, we could reach ‘low’ level.

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	Extreme	Extreme
Possible	Medium	Medium	High	High	Extreme
Unlikely	Low	Medium	Medium	High	High
Rare	Low	Low	Medium	High	High

With central safety controller(continues monitoring the load, velocity, temperature, human, trajectory adjusting etc.)

Chapter 6 Conclusion

Chapter 1 presents the background of the thesis by discussing the reason that why we use the Human-Robot Collaboration solution is that we aim to improve ergonomics and productivity and the problems and objective of this thesis. The problem is that when we introduce the robot in the sharing environment, the safety issue occurs, which is also the most critical aspect for the HRC solution.

In chapter 2, the detail of the HRC will be presented, such as definition, safety, work space characteristic, some examples of application, HRC standards and 3 types of the HRC concerning the safety, and introduction of safety issues.

Chapter 3 will talk about the robot components. The robot hazard and the risk assessment will be presented.

Some safeguard solutions will be given in chapter 4 according different interaction level. And certain methods which aims to improve production safety and productivity will be presented.

In Chapter 5, a case study will be discussed by using a predefined logic flow. First step is to proof that the system with robot is better than pure manual by applying Analytic Hierarchy Process (AHP) method. Then to perform task specification and assign the operation to the human and robot by using the Hierarchical Take Analysis in order to maximize the benefit of the HRC solution in case of ergonomic and productivity. The next step is to evaluate feasibility of the process and risk assessment by computing the probability of each occurrence by using a software named Integrated Dynamic Decision Analysis (IDDA).

The chapter 6 is the conclusion of this thesis

In conclusion. During designing phase of the HRC system, first step is to use AHP method in order to prove that HRC is more efficient than purely manual solution considering productivity, ergonomics, quality, safety. Next step is to decide the safety strategy based on the application. By making trade-off between cost and performance, the safety system can be designed in detail. Then, the HTA method should be applied in order to allocate the task to human and robot. The final step is evaluation the production process, by checking the result of production feasibility and risk assessment. Training plays a vital role in system performance, this factor has a lager effect on the system behavior both in terms of productivity and safety. Since training will make the operator to better follow the instruction which is designed aiming to improve the productivity and safety. The maintenance aims to reduce the failure probability of the system component. If the failure probability of the normal component reduces, the productivity will increase. The maintenance of the component which is in charge of the safety, should be given priority, since it not only effects the production efficiency but also the safety performance.

For the case study which considering the assembly process, the cycle time is around 3min if the assembly process is manual. While for the HRC solution, after applying the HTA method, the cycle time is 203s. Here is a question need to be further discussed.

For the cycle time of the manual one, it is measured through experiment, the operator may be in normal or best performance, since we didn't consider the ergonomic effect. weighs around 5 kg, and the assembly of one brake disc takes around 3 minutes with large deviation. Considering the shift time of operators and the assembly cycle of brake discs, operators should assemble about 160 brake discs and lift 800 kg every day. Considering at least 200 working days a year, he should lift around 160,000 kilograms. In other words, it will carry a load of 1600kN. This annual workload can affect fatigue accumulation and fatigue of the operator, and may cause serious damage to the operator's muscles. This can also affect productivity and quality, as operators sometimes feel tired or have muscle aches; This may result in improper disc insertion or insufficient screw tightening. This will result in reducing quality and productivity. Although the collaborative procedure increases the total assembly time during experimental tests in laboratory environment (210 seconds) in comparison with the manual procedure in production line (180 seconds), operator ergonomics are improved and the risk of injury is considerably reduced. By making trade off productivity, ergonomic, quality, safety the HRC solution is better that purely manual one obviously. For other application like welding and painting etc, due to the collaborative is faster and more precise, not only the ergonomic and quality are improved but also the cycle time is reduced dramatically.

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Appendix

Input file for IDDA

1. Original work process

1 1, 0.000180591 1., 50 2000, ‘carrying dust protection?’ ‘Yes’ ‘no’
L 1 1, 2000 1

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

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

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

200 1, 0.0004 1., 250 250, 'the operator exits from the working station?' 'Yes' 'No'
A 200 1, 250, 2001 2000
L 200 1, 2001 1

250 1, 0.000486207 1., 300 2000, 'start screw?' 'Yes' 'No'
L 250 1, 2001 0
L 250 1, 2000 1

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

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

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

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

500 1, 0.0004 1., 550 550, 'The operator exits from the working station?' 'Yes' 'No'
A 500 1, 550, 2001 2000
L 500 1, 2001 1

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

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

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

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

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

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'

2. With a safety button based on SMS

1 1, 0.000180591 1., 50 2000, ‘carrying dust protection?’ ‘Yes’ ‘no’
L 1 1, 2000 1

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

100 1, 0.0004 1., 101 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 100 1, 2000 1

101 1, 0.0002 1., 150 2000, 'button satus?' 'Yes' 'No'
L 101 1, 2000 1

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

200 1, 0.0004 1., 201 201, 'the operator pushes the button to exit from the working

station?' 'Yes' 'No'
A 200 1, 201, 2000 2001
L 200 1, 2000 1

201 1, 0.0002 1., 250 2000, 'button status?' 'Yes' 'No'
L 201 1, 2000 0
L 201 1, 2001 1

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

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

350 1, 0.0004 1., 351 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 350 1, 2000 1

351 1, 0.0002 1., 400 2000, 'button satus?' 'Yes' 'No'
L 351 1, 2000 1

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

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

500 1, 0.0004 1., 501 501, 'the operator pushes the button to exit from the working station?' 'Yes' 'No'
A 500 1, 501, 2000 2001
L 500 1, 2000 1

501 1, 0.0002 1., 550 2000, 'button status?' 'Yes' 'No'
L 501 1, 2000 0
L 501 1, 2001 1

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

600 1, 0.0004 1., 601 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 600 1, 2000 1

601 1, 0.0002 1., 650 2000, 'button satus?' 'Yes' 'No'

L 601 1, 2000 1

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

700 1, 0.0004 1., 701 701, 'the operator pushes the button to exit from the working station?' 'Yes' 'No'
A 700 1, 701, 2000 2001
L 700 1, 2000 1

701 1, 0.0002 1., 750 2000, 'button status?' 'Yes' 'No'
L 701 1, 2000 0
L 701 1, 2001 1

750 1, 0.000333 1., 800 2000, 'start screw?' 'Yes' 'No'
L 250 1, 2000 1

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'
20010. 1., 0 0, 'The operator incidents?' 'No' 'Yes'

3and 4 Training and maintenance

File is same as file 1 by reducing failure probability by 25%.

5 Integration solution

1 1, 0.00013544 1., 50 2000, ‘carrying dust protection?’ ‘Yes’ ‘no’
L 1 1, 2000 1

50 1, 0.0001666 1., 100 2000, 'position the dust protection?' 'Yes' 'No'
L 50 1, 2000 1

100 1, 0.0003 1., 101 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 100 1, 2000 1

101 1, 0.00015 1., 150 2000, 'button satus?' 'Yes' 'No'
L 101 1, 2000 1

150 1, 0.015 1., 200 2000, 'the operator takes the screw?' 'Yes' 'No'
L 150 1, 2000 1

200 1, 0.0003 1., 201 201, 'the operator pushes the button to exit from the working station?' 'Yes' 'No'
A 200 1, 201, 2000 2001
L 200 1, 2000 1

201 1, 0.00015 1., 250 2000, 'button status?' 'Yes' 'No'
L 201 1, 2000 0
L 201 1, 2001 1

250 1, 0.0003645 1., 300 2000, 'start screw?' 'Yes' 'No'
L 250 1, 2000 1

300 1, 0.0000417 1., 350 2000, ' go back at home position?' 'Yes' 'No'
L 300 1, 2000 1

350 1, 0.0003 1., 351 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 350 1, 2000 1

351 1, 0.00015 1., 400 2000, 'button satus?' 'Yes' 'No'
L 351 1, 2000 1

400 1, 0.015 1., 450 2000, 'replace the robot tool?' 'Yes' 'No'
L 400 1, 2000 1

450 1, 0.0003 1., 500 2000, 'take the hub on dust protection?' 'Yes' 'No'
L 450 1, 2000 1

500 1, 0.0003 1., 501 501, 'the operator pushes the button to exit from the working station?' 'Yes' 'No'
A 500 1, 501, 2000 2001
L 500 1, 2000 1

501 1, 0.00015 1., 550 2000, 'button status?' 'Yes' 'No'
L 501 1, 2000 0
L 501 1, 2001 1

550 1, 0.000281 1., 600 2000, 'The robot take the brake disc in the hub?' 'Yes' 'No'
L 550 1, 2000 1

600 1, 0.0003 1., 601 2000, 'the operator pushes the botton to enter in the working area?' 'Yes' 'No'
L 600 1, 2000 1

601 1, 0.00015 1., 650 2000, 'button satus?' 'Yes' 'No'
L 601 1, 2000 1

650 1, 0.015 1., 700 2000, 'the operator takes the screw?' 'Yes' 'No'
L 650 1, 2000 1

700 1, 0.0003 1., 701 701, 'the operator pushes the button to exit from the working station?' 'Yes' 'No'
A 700 1, 701, 2000 2001
L 700 1, 2000 1

701 1, 0.00015 1., 750 2000, 'button status?' 'Yes' 'No'
L 701 1, 2000 0
L 701 1, 2001 1

750 1, 0.00024975 1., 800 2000, 'start screw?' 'Yes' 'No'
L 250 1, 2000 1

800 1, 0.0000417 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'

Results

1 Original work process

Event sequences number : 21
Event probability : 1

Seq.N.	Event Tree N.	Probability
1	1	9.369576e-01
2	2	5.209774e-05
3	3	3.121282e-04
4	4	3.749539e-04
5	5	1.249012e-07
6	6	1.913667e-02
7	7	3.828866e-04
8	8	3.590908e-04
9	9	3.830398e-04
10	10	1.436938e-07
11	11	3.833368e-04
12	12	1.955800e-02

13	13	3.913166e-04
14	14	5.439603e-05
15	15	4.759100e-04
16	16	3.914949e-04
17	17	1.904402e-07
18	18	1.998395e-02
19	19	3.998389e-04
20	20	2.222259e-04
21	21	1.805910e-04

2 With safety button based on SMS

Event sequences number : 27
Event probability : 1

Seq.N.	Event Tree N.	Probability
1	1	9.361147e-01
2	2	5.205087e-05
3	3	3.118474e-04
4	4	1.404929e-04
5	5	3.747413e-04
6	6	5.621963e-08
7	7	1.912232e-02
8	8	1.434389e-04
9	9	3.826569e-04
10	10	3.588754e-04
11	11	1.435717e-04
12	12	3.829536e-04
13	13	5.745166e-08
14	14	3.831644e-04
15	15	1.954920e-02
16	16	1.466410e-04
17	17	3.911992e-04
18	18	5.437971e-05
19	19	4.757672e-04
20	20	1.468012e-04
21	21	3.915679e-04
22	22	5.874399e-08
23	23	1.998095e-02
24	24	1.498796e-04
25	25	3.998389e-04
26	26	2.222259e-04
27	27	1.805910e-04

2 Training

Event sequences number : 21
Event probability : 1 - 2.22045e-16

Seq.N.	Event Tree N.	Probability
1	1	9.471111e-01
2	2	5.266230e-05
3	3	3.155106e-04
4	4	2.842344e-04
5	5	9.468158e-08
6	6	1.443295e-02
7	7	2.887456e-04
8	8	3.610674e-04
9	9	2.888322e-04
10	10	1.083527e-07
11	11	3.854083e-04
12	12	1.966369e-02
13	13	2.950438e-04
14	14	5.468450e-05
15	15	4.784338e-04
16	16	2.951488e-04
17	17	1.435732e-07
18	18	1.498946e-02
19	19	2.998792e-04
20	20	2.222259e-04
21	21	1.805910e-04

3 Advanced maintenance

Event sequences number : 21
Event probability : 1

Seq.N.	Event Tree N.	Probability
1	1	9.374522e-01
2	2	3.909339e-05
3	3	2.341969e-04
4	4	3.751466e-04
5	5	9.371626e-08
6	6	1.914491e-02
7	7	3.830515e-04
8	8	2.691693e-04
9	9	3.832048e-04
10	10	1.077108e-07
11	11	2.875706e-04
12	12	1.956263e-02
13	13	3.914091e-04

14	14	4.080610e-05
15	15	3.568165e-04
16	16	3.915821e-04
17	17	1.427837e-07
18	18	1.998596e-02
19	19	3.998792e-04
20	20	1.665774e-04
21	21	1.354400e-04

4 Integration

Event sequences number : 27
Event probability : 1

Seq.N.	Event Tree N.	Probability
1	1	9.514937e-01
2	2	3.967894e-05
3	3	2.377048e-04
4	4	1.427871e-04
5	5	2.856170e-04
6	6	4.284898e-08
7	7	1.450050e-02
8	8	1.450268e-04
9	9	2.901406e-04
10	10	2.718414e-04
11	11	1.451328e-04
12	12	2.903092e-04
13	13	4.355291e-08
14	14	3.872919e-04
15	15	1.474462e-02
16	16	1.474683e-04
17	17	2.950251e-04
18	18	4.101020e-05
19	19	3.586011e-04
20	20	1.475946e-04
21	21	2.952335e-04
22	22	4.429167e-08
23	23	1.498872e-02
24	24	1.499097e-04
25	25	2.999094e-04
26	26	1.665774e-04
27	27	1.354400e-04