Verification and Visualization of Safe Human Robot Collaboration for Robotic Cell

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Robotics and Automation field is booming in today’s scenario. Researchers and Technologist comes up with new ideas in the robotics field to achieve a higher productivity, flexibility and efficiency. To achieve the above goals, it shall be required that human and robot share their work space with each other and works in a collaborative nature. Safety is a main concern and in focus. Robot should not injure the operator in any way during working in robotic cell. In this master thesis main focus is to create a various test plans and validate them to ensure the safety level in robotic cell. The test plan should be validated in a real robot environment. The test plans consist of functional and individual verification of safety devices which are being used in a robotic cell at PTC which is known as smart automation lab. Apart from that it includes design simulation of robotic cells with manikins to ensure validation of safety in virtual environment. Design simulation of robotic cell with manikins are created in RobotStudio 6.06. However, smart components, trap routines, SafeMove and offline program in RAPID have been created. Various test results are incorporated in the results section to ensure the verification and validation of safe human robot collaboration of virtual environment in RobotStudio 6.06.
I gratefully acknowledge University West for providing all the support during my study. I am very thankful to my examiner Bo Svensson and supervisor Mattias Ottosson for guidance throughout the period. I am also very thankful to Anders Appelgren for technical assistance, discussions and fruitful information to accomplish the master thesis project. My special thanks to Hanna Tullock, Julie Portal, and Sai Sumanth to support me during project work. I highly appreciated my honour to Björn Lindqvist and Johannes Jinder (SICK AB, Sweden) for given me a permission to use special figures in my master thesis report.
This master degree report, *Verification and Visualization of Safe Human Robot Collaboration for Robotic Cell*, was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work has been included in this degree project has not previously been published or used for obtaining another degree.

Signature by the author 18-06-15

Kuldeepsinh Gohil
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<td>ANSI</td>
<td>American National Standard Institute, has coordinated the development of voluntary consensus standards in the United States and has represented the needs and views of U.S. stakeholders in standardization forums around the globe.</td>
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<tr>
<td>Collaboration</td>
<td>Interactive co-operation of two or more persons or machines</td>
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<tr>
<td>EU</td>
<td>European Union, a cooperation between most European countries.</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization, ISO creates documents that provide requirements, specifications, guidelines or characteristic that can be used consistently to ensure that materials, products, process and service fit their purpose.</td>
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<tr>
<td>Industrial Robot</td>
<td>An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications</td>
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<tr>
<td>I/O</td>
<td>Input and Output signals of controller in robot studio</td>
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<tr>
<td>Manikins</td>
<td>A model of human body</td>
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<td>OSHA</td>
<td>Occupational Safety and Health Association, to assure safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education and assistance.</td>
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<td>OPC-UA</td>
<td>Open Platform Communication Unified Architecture. It is machine to machine communication protocol.</td>
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<td>PTC</td>
<td>Production Technology Center</td>
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<tr>
<td>TCP</td>
<td>Tool Centre Point, is the point around which the orientation of the tool/manipulator wrist is being defined</td>
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<tr>
<td>RAPID</td>
<td>Programming language of ABB robots</td>
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<tr>
<td>RobotStudio 6.06</td>
<td>Robot Simulation Software by ABB</td>
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1 Introduction

Nowadays robotics and automation field emerging. In the new era, the concept of Industry 4.0 is booming and more advanced production technologies are installed with robotics application to get higher flexibility, reliability and productivity [1]. In 1960's and 1970’s robots were used for rigid application which humans could not performed [2]. Robotics work cells and areas were isolated at that time and it was dangerous for humans to enter the work cell. Safety has been main concern at that time to till now [3] [4]. Revolution in the technology and Adopting new concept of Industry 4.0 in Europe. Industry 4.0 is name used by German government strategy for fourth industrial revolution. The concept of smart factory can work, where each operation in production is connected [1]. It is necessary for humans to work with robots [5]. Robots are programmed to handle more complex situation accurately. It is an advantage to get humans flexibility to enhance the efficient production. In past, many accidents had happened and robots killed or hurt humans. During investigation it was concluded that mistakes had done by humans directly or indirectly while performing tasks with robots [6]. Design consideration is most important which can prevent accidents. Safe practise methodologies allow to humans to work with robot in collaborative way. Moreover, design of robots and its applications are developed by engineers who have deep knowledge about performance, limitation and safety of robots. Real task performer are the workers who operates the robots to get desire output [7]. The proper safety guidelines must be shared perfectly to the real operators of robots to avoid any accidents in case of lack of knowledge. There are many safety devices available which can prevent accidents while interacting with robots [8].

1.1 Background

The Twenty-first century is recognized as a technological revolution for the robotics and automation field [1]. New innovations, start-ups and ideas are turning up on industrial platforms to become a better and better manufacturing and developing new process [2]. In last three decades many rigid conventional processes have been carried out by humans themselves. Some of the processes are risky in nature of weight carrying, improper environment, and fumes-hazardous places and ultimately productivity and efficiency could be less [5]. From the 1960’s, those kinds of processes have carried out by industrial robots. Robots hold a wide capacity to perform tasks repetitively with desired accuracy. Looking at those advantages many industries (i.e. automotive, manufacturing, assembly) have been installed robots in their plants to achieve higher productivity and efficiency [8] [9] . Technology revolution, the smart factory concept is adopted. Robotics and automation are key players in an industrial scenario to boost up the technology rapidly [10]. The main fundamental’s to achieve productivity, efficiency and flexibility in a short time [11]. To achieve the above parameters, it is imperative for humans to work with robots. Before robots had worked alone and not sharing the work space with humans but nowadays requirement of the process to share the work space between robots and humans and can give desired output where robots are more accurate and humans have more flexible in nature of work [12] [7]. This concept is called
flexible automation. For that most important concern is safety. Precaution is most important for human while working with robots in robotics cell or collaborative workspace [12]. The objective to keep human safe in any conditions. There are special rules and regulation for “robot and its devices” exist in the ISO 10218-1 part 1, and “robot system and integration” ISO 10218-2 part 2 [13] [6] [14]. Furthermore, many countries have own safety standards (i.e. Europe, Sweden, Spain, USA) to ensure that human keeps safe at all time during interaction with robot.

1.2 Description

The development of a robotic cell at PTC (smart automation lab) is lead by University West and GKN aerospace. This robotic cell is recognized as a “smart automation lab” [15]. It is a unique robotic cell which consists a special feature under project name of FIA (environment for innovative and flexible automation). The cell should demonstrate a concept for how flexible and fast-changing industry automation can be built up. The term "Plug and Produce" is used. The main goal to prepare a unique flexible automation which partly changeable in a required operation for production including measurement and inspections methodologies through wireless communications or OPC-UA. The robotic cell also relates to working environment. For instance: - on ergonomics, for developed interface between man and machine. Furthermore, there is aim to create a security solution (i.e. Safety) in a collaborative work space in a robotic cell between operators and robots.

1.3 Aim

The robot cell consists of advance techniques as it works based on “Plug and Produce” concept. This robotic cell has more special features including multi agent systems and various operations will be performing together by OPC-UA. This Robotic cell commissioning work is still going on in PTC Trollhättan. One main consideration area in this master thesis project is about safety and to examine security solutions for this robotic cell. For security solution certain tests and scenarios are considered in a simulation environment to ensure satisfying safety level in the robotic cell. Following are the aims for this master thesis project.

- Create a test plans and perform the tests to verify implemented safety solution in robot cell at PTC (smart automation lab)
- Design a simulation of robot cell with manikins in RobotStudio 6.06.

1.4 Limitation

This robotic cell consists of unique features since it is a part of university research and innovation work. It is different from real production cells. This cell becomes a more flexible in terms to perform the various operations including safety solution. This is a unique robotic cell and such kind of cell has never built up as before to work on concept of “Plug and Produce”. Consideration of above scenario, it would be a lack of comparative results to similar one. Cost of the robotic cell must not be considered. Limited to selected robotic cell at PTC.
2 Literature Study

2.1 Design considerations for safe human robot collaboration

Advancement of interaction between human and robots are necessary to increase productivity and flexibility [1]. The concept to utilize human skills as well as robot skills provide desired results since robots are fast, accurate, perform the same work precisely [14]. Whereas human is more flexible in nature so combination of work together and sharing the work is more efficient in today’s scenario. There would be a certain design consideration strategy to make things happen to share work space and keep safe human during assignment work with robots. It could be an industrial robot or collaborative robots too. Design considerations are as below [2].

- Robot stop function: Each robot has that function as protective measure and separate emergency stop function
- Speed control: Speed of the end effectors and TCP should be controllable
- Visual indication: There would be a clear guideline formulated while sharing collaborative work space with human and robot. (i.e. speed and motion control, hand guiding device, force monitoring device)
- Limitation of robot motion: It is necessary that robot detects the human presence and act accordingly in collaborative work space to ensure the safety at all time.
- Minimum separation distance: - Layout would well organized and Minimum safe distance should be defined between human and robot in advance. Also, it depends on application to application.
- Collision detection: - Safety function includes to measure the correct distance and velocities of human and robot to avoid collision.
- Ergonomically requirements: - Working space well organized considering human work behaviours. It is ensuring that no sharp edges, cutting edges, sharpen points and rough surfaces available in the contacted area.

2.2 Existing Safety standards (ISO)

There are many various safety standards available in ISO [13] [13] and in EU directives by product to product. In this section more, emphasis on general standards [Table.1] and especially for the robotics standard [Table.2]. Safety standards are most important for any process [13]. A standard defines the design, safety measures, guidelines of the do and don’ts, nature of work, precaution, product services, methods etc. [16] [3]. Standards area guidelines and standard operating procedure to understanding the process, evaluating and validating of the process. There are many various organizations exist to release the standards (i.e. ISO, OSHA, ANSI)

What are standards?
Standards are guidelines that are determined by non-governmental in the region and it is applicable all over the world. One organization manages the standards is the ISO [13]
Table 1. General Standards

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
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<tbody>
<tr>
<td>EN ISO 12100</td>
<td>Safety of Machinery – General principal for design – Risk assessment and risk reduction</td>
</tr>
<tr>
<td>EN ISO 13849-1/2</td>
<td>Safety of Machinery – Safety related parts control system – Part 1: General principles for design, part 2: Validation</td>
</tr>
<tr>
<td>EN 60204-1</td>
<td>Safety of Machinery – Electrical equipment of machines – Part 1: General requirements</td>
</tr>
<tr>
<td>IEC 62061</td>
<td>Safety of Machinery – Functional safety of safety related electrical, electronics and programmable electronic control system</td>
</tr>
</tbody>
</table>

Table 2. Robotics standard

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
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<tbody>
<tr>
<td>EN ISO 10218-1</td>
<td>Robots and robotics devices – Safety requirements for industrial robots – Part 1: Robots</td>
</tr>
<tr>
<td>EN ISO 10218-2</td>
<td>Robots and robotics devices – Safety requirements for industrial robots – Part 2: Robot systems and integration</td>
</tr>
<tr>
<td>ISO/PDTS 15066</td>
<td>Robotics and robotic devices – Collaborative robots</td>
</tr>
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2.3 History of an accidents of human with robots

In any industries safety is main concern for human. Life of human is more valuable than any asset of industries. It is always in focus either in robotics field or other industries (i.e. metal cutting, wood industries, casting, textile etc.). Few accidents in automotive industries which are stated below. These are an eye-opener for technocrats and once again question against the safety practises. However, safety is prime attention area in today’s technological world.

1. Worker at Volkswagen plant killed in robot accident [17]
2. Worker killed by robot in welding accident at car parts factory in India. The man was reportedly stabbed by a metal arm and electrocuted [18]
3. Factory worker killed by rogue robot in USA [19]
4. Bride-to-Be (Regina Elsea) crushed to death by Car-Factory robot [20]

Above are a few major accidents considered for an example to focus on safety measures in the automotive industry. In their investigation it has been stated that few of the accidents had occurred due to human errors and also to failure of the sensors part. It means still due to lack of knowledge of the safety, by pass the guidelines of the standards and improper function of the sensors and machine control that kind of incidents happed in the automotive factory. OSHA identifies seven potential hazards within robotic work cells: Human errors, Control errors, unauthorised access, Mechanical failure, Environmental sources, Power system, improper installation [21].
2.4 Common safety devices

Many safety devices are introduced in the robotics and industrial environment to make betterment of safety [12]. In this section more, focus on common or traditional safety devices which are mentioned herewith. In the above mentioned various common safety devices which are very basic in the nature and in the preliminary level. It is also being used in the robotics cells and production area but while considering safe human robot collaboration and sharing the work space between human and robot still require many full proof improvements. Following are the common safety device exist in the industrial environment.

- **Light curtain sensor:** It consists of several photos electric sensor. Assembling several transmitters and receivers close to each other requires some consideration of interruption errors between light beams. Humans could be prevented hands, fingers or feet while entering in a hazardous area with the use of light curtain sensor. Resolution limit for the fingers is 14mm, for the hands 30mm and for the body protection 40mm [3]

- **Safety mats:** Safety mat is known as mechanical device. The output from the mat generated when users keeps step on it. It usually made from industrial rubber and thickness would be 10 to 15 millimetres. Compressed air, optical fibre and electromechanical solution is being used in safety mats [3]

- **Safety limit switches:** It is a very common safety device is being used with fences in the robotics cells. Whenever human enters in the robotics cells this device allows to stop all function immediately [3]

- **Enabling devices:** It is known as dead man switch too. Teach pendants used to program an industrial robot’s movement are equipped with enabling switches [3]

However, there is a limitation of those safety devices. For example: - Light curtain sensors are available in the various sizes and application of different in respect of distance of the sensing too. It is also fixed at one place therefore it cannot be an appropriate solution for particular robotic cells [5] [9]. Generally common safety devices cannot be a more relevant solution of collaborative work space between human and robot [12] [5].
2.5 SafetyEye

Comparing advantages with common safety devices solutions have their limits. Optoelectronic protective devices such as light curtains, safety mats, limit switches and enabling devices merely monitor planes and complex structure [22]. There is no visual contact to secure protection. All sensors are co-ordinated and aligned, a whole series of cables are laid and safety fences are often erected for further protection. Pressure sensitive mats takes time to install in the plant. Following are special features of SafetyEye over common safety devices. Common safety devices have some drawbacks. It creates more complex structure and no secure protection is provided. There is a lack of visual contact to the workstations. To fulfil this gape by new emerging device which is known as “SafetyEye” by M/s Pilz (Pilz 2006) [3] [8] [2]. SafetyEye is three-dimensional monitoring and control with one safe camera system. A basic principle of SafetyEye is monitors 3D zones of the robotics cells or where it is installed. Powerful camera and software system monitors human behaviours, motion, directions of the human workspace and accordingly it controls the robots speed and motion to keep human safe at all time [14] [9]. If human reaches to near the robot, robot should stop at a moment without interrupting plant shutdown. SafetyEye (refer figure.1) works as humans guarding and protect them while sharing the work space with robots. SafetyEye consists two various zones (i.e. warning zone and other is detecting zone) and based on zones sensing device monitors and control unit controlling the behaviours of the human. The control device
consists an analysis unit and programmable safety unit in which it analyses image data and it generates signals [9]. Based on the receiving signals detects zones is activated and send necessary information to controller to stop the robot movement immediately see figure 1 [3]. This safety device is a kind of emerging technology and open new horizons in industrial environments. SafetyEye is gives a very convenient and secure protection of human and robot or machine. It sets a good example of ergonomics processes.

2.5.1 Advantages of SafetyEye

SafetyEye covers robotic cell and envelop to ensure the protection. Following advantages are listed here below.

- Latest 3D monitoring technology provides unique solution to interaction with human and robot [22]
- This device fulfils full prof safety requirements [22]
- Best suited for ergonomic work station [22]
- Zones detection easily and control effectively without stoppages
- User-friendly device in real sense [22]
- Flexibility and overall productivity improved [22]

2.5.2 Disadvantages of SafetyEye

SafetyEye is an appropriate solution in an industrial environment but still some factors would be considered over common safety devices. Following are disadvantages of SafetyEye compare with common safety device.

- Setup and installation cost an expensive compare with common safety devices [3]
- Need to install SafetyEye for various location as per requirement which can add extra cost [3]
3 Method

This section consist briefly on literature study which is carried out based on existing safety practise following in the automotive industries. Furthermore, it should be focused on existing hazardous work place and few major accidents held in automotive industries. It also includes about detail introduction about traditional safety device and Safety eye. Second and third part of the method is focus on real project work which include design of simulation in RobotStudio 6.06 and smart components features including more emphasis on machine directives, risk assessment process, Collaborative work spaces, laser scanner and SafeMove2 features for ABB robots. Result section is covered outcome of safety test plan and design of simulation of the project work.

- **Literature study**
  Literature study based on to visualize the safe human collaboration methods while using various traditional safety devices. To investigate a fool proof safety solution in industrial robot cells is still under research. At present various safety devices are being used in robotic cell which is covered in part of literature study. The most important is ISO safety standards which should be in practise at any circumstances. However Design consideration for safe human robot collaboration is also important. It emphasis overview and function of traditional safety devices as well as SafetyEye.

- **Experimental test plans**
  This section covers a real test plan to ensure a safety level of real robotic cell at PTC. Test plans consists several methods to validate the safety devices are working as per requirement individually and together in a setup. Generally test would be carried out on various methods. It consist three methods 1) Functional test plan, 2) manual mode and 3) auto mode. Several check points must be verified to validate optimum level of safety in a robotic cell. Furthermore, Design a simulation with manikins in RobotStudio 6.06 is also created for same robotics cell and verify and visualize safety levels in virtual environments. Verification is carried out with various possibilities with manikins to enter the robot cell on different predefined entry points. Simulation is based on detection of warning zone and protective zone and accordingly robots follow the instruction by RAPID program. Interrupt, Trap routines, inputs and outputs signals are created in a simulation in RobotStudio 6.06.

- **Smart components**
  Smart component provides a unique features in RobotStudio 6.06 to visualize a whole simulation in virtual environment. Various zones (i.e. warning zone, protective zones) can be defined in RobotStudio 6.06. Also movement of the manikins would be controlled by smart components features to simulate the task. Virtual controller in RobotStudio 6.06 facilitate to develop I/O signals and based on necessary input and output signals are created in a smart components which is connected with station logic to perform the simulation task for visualization and verification for safe human robot collaboration.
**Results**

This section consist validation of various tests plan of simulation with manikins in RobotStudio 6.06 and experimental test plans in real robotic cell. Test results are based on collection and evaluation of data in form of tables, figures, simulation movies, RAPID program or diagrams. Results leads to conclude the process of verification and validation of simulation results and scope for further discussion and investigation upon future requirements.
4 Design of Simulation with Manikins and Test plans

This Chapter emphasis about robot specification which is installed in PTC (Smart automation lab). It focus on machine directives, risk assessment process which is primary requirement for safe human robot collaboration. In addition it emphasis on function of laser scanner, collaborative work space in robot cell, SafeMove2 features. This project also consists a design of simulation with manikins and visualization it in virtual environment in RobotStudio 6.06. It focus and describe more on smart components features, Rapid programme (Interrupt and Trap routine) and station logic features which are being used for verification in simulation environments. It covers an experiment tests plans are carried out for safety in real robotic cell for specific ABB robot. Various testing scenario for validation of safety is considered for robotic cell at PTC. However this chapter includes overview of machine directives, Safe collaborative operations including information on various standards.

4.1 Robot Specification
The experiment test plan for safety carried out on ABB robot at PTC. There numerous robots are available in the market. It can be classify in terms of small, medium and large robot. The most important things is payload capacity of the robot. Various robots has a special feature as per application and based on operations selection criteria is exist. For this project ABB robot is considered and detail specification of ABB robot as described below. Refer figure (20) in Appendix A.
- IRB 6700 – 235/2.6
- Type IRC5 M 2004
- Voltage 3 x 400 V
- Frequency 50 – 60 Hz

4.2 Machinery directive levels
The machinery directives, Directive 2006/42/EC European parliament and of the council of 17 May 2006 is a European Union directive concerning machinery and certain parts of machinery [23]. It main intention to ensure the safety of machinery which are placed on the market in all member states. This body regulates the guidelines of essential health and basic safety requirements to all manufactures who wants to their products in the European market. However, only those products placed in the market which meets requirement by Machinery directives norms. It provides detail information and clear definition about all kind of machinery, medical equipment’s, military equipment’s, various types of tools, agricultural products including transportation requirements. It covers all the information likewise single parts, assemble, rotating parts including drive and control system. Safety parts are also covered in a machine family. The main aspect of machinery directive is security and for that it is interconnected to certain levels of ISO standard. Levels are designated as A, B1, B2, C. Refer figure (2). Level A
is general description about machine and its fundamental concept [24]. Level B relates to safety (i.e. safety distance, safety device, noise and vibration level whereas level C covers security of particular type of machine (i.e. Robots). Machine directive insists to all machine manufacturer to ensure the risk assessment process to enhance the health and safety requirement applicable to the machines. The machine should be then design and produced based on test result of risk assessments. Manufacture can utilize their own method for risk assessments. Following five steps of priority orders are more general to consider for risk assessment process [25].

- Create a design and construction which eliminate risk
- Move possible works out of the risk area
- Ensure to use protection and safety devices
- Develop safety routines, sop’s and educate the staff
- Use signs and warnings for visualization

![Machinery Directive 2006/42/EC](image)

**Figure 2 Machinery directive levels**
4.3 Risk assessment of robotic cell

Risk assessment is most indeed process now a day for each machinery. It is mandatory for machines to conform a safe in nature to mitigate the ISO standard requirement. There is no any special regulation about Risk assessment process. All manufacture can release their own risk assessment methods which is in lines with machine directives and ISO standards. Risk assessment process includes SOP’s, guidelines and safety audits etc. In robotics world it could be defined as identification, evaluation and estimation of the levels of risks which is involved in the process. The same levels of risk would be compared with standards or benchmark. Risk assessment is most important and crucial process to ensure the safety in process and application in spite of manufacture is release the safety certificates. Following is the more general risk assessment process which is accepted in the industries refer figure (3) [26].

1. **Determine the system scope:** - This is the stage in which necessary information would be collected. (i.e. where will be the robot used? Which tools will be used?). However, robot working speed, payload capacity and working area to be considered while risk assessment process.

2. **Identify risk:** - This stage is very crucial and include to identify all the necessary operation involve of danger. This stage covers from installation to robot operations (i.e. delivery of robot from truck to moment of commissioning). It includes analysis of various robot motions and actions to validate the safety level.

![Image of Risk Assessment process flow chart](image)

**Figure 3 Risk Assessment process flow chart**
3. **Estimate the risk:** - After completion of above two stages, third step to make observation about the risk based on identification. Risk is estimated using the Performance Level Rating (PLr). This analysis uses three different parameters: severity of injury (S), frequency of exposure to hazard (F) and possibility of avoiding hazard (P). It is known as S, F and P.

However, to estimate a risk based on each parameter and a risk estimation tree to observe what the risk level is. On the risk evaluation diagram, the top case represents the lowest risk and the bottom case represents the highest risk.

Following parameters have to be evaluated for S, F, P refer figure (4).

**S: Severity of injury**
- S1: Slight (normal reversible injury)
- S2: Serious (normally irreversible injury or death)

**F: Frequency and/or exposure to hazard**
- F1: Seldom to less often and/or exposure time is short
- F2: Frequent to continuous and/or exposure time is long

**P: Possibility or avoiding hazard or limiting harm**
- P1: Possible under specific conditions
- P2: Scarce possibility

4. **Evaluate the risk:** - What are the actions needed to reduce the risk? There is a correspondence between the Performance Level Rating (PLr) and the PL explained in figure (4). If estimation concerning robotics cell or application has a high risk (PLr = high) than need to ensure that the safety features that will secure this application will have a Performance Level equal or greater than d (PL ≥ d). This ensures that the risk will be monitored or secured by a device that will be able to accept the level of danger.

5. **Is this acceptable?** The questionnaires are being prepared to quantify the risk in this stage. The criteria should be negligible to low level to ensure that employees are safe. If results are satisfactory then it seems to be done in the risk assessment process. In case results are not as per requirement then further steps are needed to eliminate the risk in process.

![Figure 4 Risk PLr chart showing required safety function](image)

*Figure 4 Risk PLr chart showing required safety function [25] with permission from B. Lindqvist*
The most important step is to focus on the risks and its elimination process during this stage. If the risks are reduced then it refers from risk identification chain to ensure that risk has been reduced does not create any further risk in the process. The cycle seems to repeat all the time as shown in the figure (5). For instance: robotic cells cover with the guarding to prevent collision but in case the guarding increase the severity and chances to crushing an employee during maintenance operation then evaluation of guarding is necessary to relocate it and again possible change should be reevaluate in the application to quantify the risk.

6. Risk Reduction process: - This stage validates above stages from risk identification, reduction and avoidance do not conflict while performing operation in robot cell. It also necessary to cross check it does not create bigger risk for employees during robot cell working application. This process should be performed very carefully with considering all potential risk of the process.

4.4 Collaborative operations and Safety

Collaboration operations are necessary to increase flexibility, productivity and efficiency of the operations. Collaboration between industrial robots and humans can be considered into two groups. In first group the robot and human would be in physical contact with each other and sharing the same workspace, or else there is a separation between both of them where they do not share the same working space. Normally there are five various conceptual process of collaborative robots. Application according to ISO 10218-2. The definition of a collaborative operation is, a state in which purposely designed robots work in direct cooperation with a human within a determined workspace. In addition, it should be necessary that it meets all the requirement of protective measures to enable the active the collaborative application [25] [27]. Following are the five various conceptual applications: -

a) Hand-over window
b) Interface window
c) Collaborative workspace

d) Inspection, and

e) Hand-guided robot

Moreover refer Figure (6), Illustrated the Hand-over window (a) is characterised by an autonomous operation within the safeguarded work space. When the interaction is to be occurred, the robot moves to the window and standstill for the operator to perform the defined in-tended task. While an access, no interruption is made of the automated operation. In the Interface window (b) illustrated, the robot stops at a predefined interface window, and to be moved manually outside that interface. There are similarities with the hand-over window, but most important in Interface window there is a hold-to-run control for guided movement [27]. These applications are being used for automatic stacking, guided assembling, testing. Collaborative workspace (c) illustrated is an autonomous operation within a same work-space that is shared by both robot and operator. The most common and indeed concept of collaborative workspace is when operator enters the common workspace, the robot should be reduced its speed and/or stop. This function is carried out by an object detection system with one or more sensors and devices. It could be a laser scanner, light curtain sensors or safety eye. That kind of conceptual application is being used while collaboration assembling, common handling and testing in robotic cells. Inspection (d) emphasis an application where the robot continues perform the operation with decreased speed when person enters the collaborative workspace. It is also work on a principle of an object detecting system. This application is being used for inspection and tuning of processes and welding applications. Hand-guided robot (e) is kind of an application where in specific workspace, robot is moving with support of the operator's hands to guide it along with a path. It works based on hold-to-run control and reduced the robot speed. Each conceptual application illustrates collaborative methods of various operations. This method seems to focus on a way of monitoring the security and risk and safe

Figure 6 Conceptual application of robotic cell [25] with permission from B. Lindqvist
collaborative interaction on shared work space [26]. Each method is described in ISO/TS 15066/2016 and are as follows:

- Safety-rated monitored stop
- Hand guiding
- Speed and separation monitoring
- Power and force limiting

In safety-rated monitored stop, the objective is to make the robot stop or standstill its movements when an operator enters in the collaborative workspace. The primary concept to resume the robot and moving again while person existed the collaborative workspace.

Hand guiding is nothing but the person or operator uses a handheld device for transmitting motion commands to the robot. This method emphasis on safety-rated monitored stop. Person or operator enters the collaborative workspace to perform the hand guiding, the robot stops immediately. The hand guiding task is interrelated to safety rated monitor stop.

Speed and separation monitoring is a used to avoid risk reduction and it keeps safety separation distance at all the time. This method comes in picture while operator and robot shall move at the same time inside the collaborative work space. It is known as protective separation distance between operator and robot.

Power and force limiting is a method to observe a physical contact with operator while performing work with robot system. Robot system specifically designed for this type of operation. The contact can be intentional or unintentional [26].

### 4.5 Safety Laser Scanner

There are many safety monitoring devices are available nowadays and all are described briefly in a literature review section. In this section more, emphasis on external safety device which is known as laser scanner. The safety laser scanner is an optical sensor

![Figure 7 Basic structure of laser scanner [23] with permission from J. Jinder (SICK AB Sweden)](image)
As an optical radar, the system scans its surroundings and measures the distance using the principle of time and light velocity. It monitors a hazard zone on a machine or robotic cells or vehicle by scanning the area around it on a single plane with infrared light beams [23]. Using the integrated rotating mirror, a two-dimensional scan of protection areas is created that can be defined as desired with infrared laser beam. The sensor emits a pulse beam that is reflected by the object being detected; refer to Figure (7). There are two types of monitoring ranges provided by the sensor: protective field and warning field. The protective field shuts down the robot immediately when it detects an object in its predefined area. After a protective field infringement, a reset signal from the control system is required. The warning field forewarns people entering the robotic risky zone. However, it can impact on the robot's behavior because laser scanners are programmable with the controller to monitor the work area should be secured at all times as per requirement. At present, scanners from SICK (Microscan 3) are likely to be used in the robotic cell at PTC (Smart automation lab). It keeps four monitored protective fields in eight fields. The others are warning fields. Additionally, the scanning angle is 275° so it avoids a safety blind spot of almost half a meter as compared to the common scanning angle of 270°. The maximum radius of the protective field is 5.5 meters and the warning field range is 4.0 m. The resolution range is from 30mm to 200mm [15].

4.6 SafeMove2

Robot is feasible and sustainable components of flexible automation solution. It is capable of performing numerous applications from welding to packing in a most efficient way. Since long fences and cages have been used to separate the man from machine or robot to keep them out of harm way. In this section SafeMove2 is explained briefly. This feature introduced in 2008 by ABB [15]. SafeMove2 performs safety certified monitoring of robot motion, tool and standstill supervision as well as speed limitation. It allows for the creation of more efficient and flexible production scenarios and integrates safety fieldbus connectivity into ABB's IRC5 robot controller family. SafeMove2 consists of the following features [27, 28]:

- **Safe Zones:** A safe zone consists of a safe tool zone. It is a supervision function of SafeMove2 which monitors the robot TCP. If it is within its allowed zone, while moving at allowed speed otherwise SafeMove2 stops the robot. The tool orientation can also be limited and working area is defined precisely.

- **Safe Axis range:** It is a feature which replaces electro-mechanical position switches and increases control and flexibility, also reduces maintenance requirements. Safe Axis Range can be used to control up to nine axes.

- **Safe Standstill:** Another feature of SafeMove2 is Safe Standstill. There is no requirement to switch the robot's motors off for overseeing the standstill of robot axes. This operation is carried out while operators close to the robot.

- **Safe Robot speed:** It supervises robot speed. However, SafeMove2 is most secure supervision option available by ABB [28]. For instance, a safety laser scanner is being used for monitoring three zones: warning speed reduction, effective speed reduction, and effective standstill. If person or object enters the first zone, robot speed is reduced by a Rapid program and SafeMove2 is not yet notified. While entering the second zone, SafeMove2 is notified and verifies that the...
robot moves with decreased speed. If not, SafeMove2 stops the robot at a time. Concerning the third zone, SafeMove2 verifies the robot. If it is not moving and it does, a hardware stop is immediately activated prohibiting any robot motion [28].

4.7 Robot Simulation in RobotStudio 6.06

This chapter consists the design of manikins and simulation of robotic cells in virtual environment to ensure verification and visualization of safe human robot collaboration. Design a simulation with manikins in RobotStudio 6.06 for same robotics cell to verify the safety levels in virtual environments. Verification is carried out with various possibilities with manikins to enter the robot cell on predefined entry points. Simulation is based on detection of warning zone and protective zone of predefined entry points and accordingly robots follow the instruction by RAPID program. Input and output signals are generated in a simulation environments. It includes several methodologies as following.

1. Importing 3d model of manikins and laser scanner device
2. Design a simulation with manikins of robotic cell in RobotStudio 6.06
3. Simulated manikins for visualization of safe human robot collaboration with using smart component features and I/O signals
4. Creating collision detection environment with use of smart components in RobotStudio 6.06
5. Adding highlighter features to recognize the collaborative work spaces of robotic cells
6. Generate a Interrupt and Trap routine program in RAPID
7. Performing various tests in simulation with manikins of each predefined path in robotic cell and visualize it for safe human robot collaboration.

4.7.1 Design a simulation with manikins of robotic cell in RobotStudio 6.06

The first task is to import the manikins as a 3d model in RobotStudio 6.06 to create a virtual environment for the simulation. There are three various manikins CAD models imported from the open source library. Each manikins is placed at predefined entry

![Figure 8 Manikins in Robotic Cell](image)
path in robotic cell to create a simulation seems to be a real environment. The aim to import manikins and create a simulation in RobotStudio 6.06 for visualization of safe human robot collaboration. In this section creation of simulation of robotic cell with manikins to verify and visualize various conditions of safe human robot collaboration.

In first step, to import the whole robotic cell station which is already developed in the RobotStudio 6.06. Refer figure (8). All simulation activities are being done in RobotStudio 6.06 simulation software. Once first step is finished then next step to import the manikins in RobotStudio 6.06 station and placed it pre-determined path for further experiment purpose. There are three manikins imported in this project. However all three manikins are placed on the various predefined entry places. The purpose to import the manikins in RobotStudio 6.06 and given them motion to move to collaborative work place to validate a safety level which is defined in a Simulation (virtual) environment. How to move the manikins in RobotStudio 6.06! Which is explained in below sections in details.

4.7.2 Smart component features and I/O signals

RobotStudio 6.06 provides a simulation facility to create a virtual environment. It can be possible to create real environment with using special features in simulation for study and investigation purpose. This concept is highly efficient in aspect of cost and time saving and it is beneficial to avoid risk of collaborative robot cell in advance. Smart components are feature which provide various application (i.e. linear mover) in simulation. Linear mover works on principal to move object in a liner path. Axis direction (in X, Y, Z) and speed can be optimized as per requirement. However, manikins converted as a linear mover and require data would be inserted to create motion of manikins on desired path for robotic cell. Linear mover can optimize the forward and reverse direction of manikins in simulation. I/O is equally important to visualization of simulation of manikins with robot in RobotStudio 6.06. I/O is nothing but the signals of robot controller which is created in RobotStudio 6.06. It gives signals to linear mover or manikins to move in to and out from collaborative work space during playing a simulation. Refer figure (9) (10).

![Figure 9 Smart component of linear mover for red and green manikins](image)
4.7.3 Creating collision detection environment with use of smart component in RobotStudio 6.06

However, robot simulation is an active source to validate the safety and risk assessment process before it harmful in a real robotic cell. To validate safety and risk assessment is complex process in a real robotic cell and it takes time and require of many equipment. Whereas in robot simulation another smart component feature is collision sensor. It works as detector while any object (i.e. Manikin) collide with collision sensor, it generates high signal (digital) while collide any object with it. Refer figure (11). In other words it seems to work like laser scanner in simulation. The principle of laser scanner is described in early section, refer section (4.5). Collision sensor normally is being used with highlighter. The brief explanation of highlighter shown in next section (4.7.4).

4.7.4 Highlighter feature to recognize collaborative work space of robotic cell

Highlighter is another special feature of smart component in RobotStudio 6.06. It provides facility to temporarily change the color of selected an object. It is activated during high signal 1 (digital) and deactivated with low signal 0. Most important things is color.
There is also facility to create a desired color while inserting special color code for visualization. (i.e. code [255 255 0] for yellow, code [255 0 0] for red). Color code seems to be based on [RED, YELLOW, and BLUE]. It could be possible to change color code as per requirement of the color for visualization. Moreover numerous highlighter is being used as needed in the simulation refer (11).

4.7.5 Generate a Interrupt and Trap routine in program

It is kind of instruction which is being used in RAPID program to obtain all information about interrupt that caused the trap routine to be executed. To generate an interrupt and trap routine program, smart components and I/O signals to validate simulation for visualization of safe human robot collaboration. Basic requirement of trap routine program is interrupt the movement of robot in simulation environment while manikins collide the near miss or predefined object with collision sensor. To create a safety solution for investigation purpose is possible by interrupt and trap routine program in various scenario. Inputs and outputs signals are created on profibus device in the controller. And all signals are connected in a station logic. Refer figure (12) for station logic and for details of interrupt and trap routine program, refer appendix (B) (C) (D) in RAPID program.

4.7.6 Performing tests of simulation with manikins in each predefined path in robotic cell and visualize it for safe human robot collaboration

The aim of testing to verify the all functions are up to date and work as per requirement. After completion of above work, finally it would be a task to run a simulation for further investigation purpose to cross check and validate a safe human robot collaboration in simulation or virtual environment. For Experiments of simulation on manikins, various criteria and tests scenario are considered and carried out to ensure that safe human robot collaboration in simulation environment in same robotic cell in RobotStudio 6.06. In this task all three manikins can be fixed at their original position to validate the simulation all the time. Following features are being used to create a simulations in RobotStudio 6.06 and perform it for the validation and visualization purpose again and again as per requirement. For instance:- Manikins CAD models, Sick laser scanner CAD
model, smart components (linear mover for each manikin, NOT gates, collision sensors, highlighters, I/O signals, station logic), Interrupt and trap routine, SafeMove2.

4.8 Experimental Test Plan

This section covers a real test plan to ensure a safety level of real robotic cell at PTC (Smart automation lab). Test plans consists several methods to validate safety devices are working as per requirement individually and together in a setup. Generally, test would be carried out in three stage (i.e. Functional test, verification of manual mode and auto mode in a real robotic cell). Several check points must be verified to check optimum level of safety in a robotic cell as per tests.

4.8.1 Functional test

It consists general check points of various safety devices which are being used in robotic cell. It is test format of primary check points to validate listed safety device in order or out of order in the robotic cell. Refer table (3) for detail reference.

Table 3. Description of Functional test

<table>
<thead>
<tr>
<th>Working Condition of safety device</th>
<th>In Order</th>
<th>Out of Order</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light curtain sensor</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Laser scanner</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Safety PLC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Emergency switch</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Safe move</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Robot condition (Calibration)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Robot condition (Programming)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.8.2 Experimental test plan in manual mode

This section emphasis test plan in manual mode in a real robotic cell. When the functional test procedures have been carried out after that Experimental manual test plan in manual mode to be performed. The first thing should be checked that robot controller switched on manual mode. At the time of test, the teach pendant shall be held by one person, and other person enters to the robot cell, or the operator holds the teach pendant and move in the direction of the robot cell. This section records the whole process of the real experimental test plan in manual mode to verify safe human robot collaboration. It focus on following steps to perform step by step to validation of the test. Also refer Appendix E for detail reference.

- Step 1. Enter the person in the direction of robot cell
- Step 2. Enter the person in the direction of collaborative workspace
- Step 3. Going back from collaborative workspace
- Step 4. Going back from the robot cell
4.8.3 Experimental test plan in auto mode

However, functional test and manual test procedures are finished after that Experimental test plan in Auto mode is carried out. It should be required that robot controller is switched to auto mode. The procedure of experiment in auto mode are recorded as per following steps. Refer Appendix F for detail reference.

Step 1. Enter the person in the direction of robot cell
Step 2. Enter the person in the direction of collaborative workspace
Step 3. Going back from collaborative workspace
Step 4. Going back from the robot cell
5 Results and discussion

This section containing the tests results of design of simulation in RobotStudio 6.06 and outcome of experimental tests plan based on functional test, manual and auto test of robotic cell as mentioned in a previous section. However, design of simulation of manikins in RobotStudio 6.06 for visualization and verify various methodology to validate safe human robot collaboration in virtual environment. Following briefly explanation about methodology and respective outcome of simulation shown in Appendix A, B, C, D, general discussion of the result is covered at end of the section.

5.1 Visualization of Simulation with manikins in RobotStudio 6.06

RobotStudio 6.06 is platform to create simulation of real robot cell in virtual environment. There are many unique features which allows to user to take certain experiments in simulation environment. Following tests of visualizations are carried out with manikins in RobotStudio 6.06 to ensure safe human robot collaboration in virtual environment.

5.1.1 Test 1 - Create a one manikins and placed collision sensor and highlighter

However, an objective of simulation of this project is to validate safety operation performing appropriate way in a simulation environment. There are many safety devices installed in a real robotic cell to ensure the safety level by detecting person or object in a collaborative work place or near robotic cell. Light curtain, Laser scanner are most common type of safety devices which are being used in a robotic cell. The purpose of this design simulation with manikins in RobotStudio 6.06 is to validate same function which is being used in real robotic cell. In test 1, one manikins (white) Human male 3D CAD model imported in simulation. To create a real environment in RobotStudio 6.06, it is necessary to apply motion of manikin by smart component feature of linear

![Figure 13 Result of one manikin detection by collision sensor and highlighter](image-url)
mover. Linear mover is used to move any object in desired direction either in forward or reverse. Furthermore collision sensor is fixed in the direction between collaborative work space and robotic cell. Highlighter is being used to show the color temporarily. Once all setup is as explained in previous section. The most important thing is to run the simulation and validate it. The aim of test 1 when playing the simulation manikins walks to the robotic cell. There have already provision created when manikins enters the collaborative space, it collide with part and Collison sensor is activated. High signal is raised and based on highlighter shows yellow color which indicates warning zone as per laser scanner works in a real environment. In addition manikins still walk to the robotic cell, again it collide with another part which shown red color. This zone indicates the protective zone with red color and at a time robot movement is stopped immediately by using interrupt trap routine function in rapid program. Refer figure (13). And appendix B.

5.1.2 Test 2 - Create two manikins (Red & Green) and validate it from various predefined entry point of robotic cell

In test 1, it seems to detect like a laser scanner. In test 2, created two various manikins (Red & Green) and placed it various predefined way to ensure the safe human robot collaboration. Both are operated by one output signal at a time (di_Execute1). Speed and direction of movement can be set individually as per requirement. In test 2, it acts on basic principle of light curtain sensor. Normally, light curtain sensor activates once it detects the person or object in its sender and receiver zone of light beam. In this methodology same concept works when both manikins, either red or green walks to the robotic cell. Any one reaches to the robotic cell and collide with parts which is created by collision sensor. While colliding it gives high signal and highlighter shown red color and robot stops immediately. Once manikins starts to go back to the normal position then robot works normally in a robotic cell. Test results figure are illustrated in respective appendix. Refer figure (14) and appendix A, figure (19) and appendix B.

![Figure 14 Results of detection by Red and Green manikins by collision sensor and highlighter](image)
5.1.3 Test 3 - All three manikins operated individually to examine simulation in robotic cell

In test3, all manikins operates individually by digital output signals. This test verified solution, which creates for security is still active and secure in the simulation environment. In first case green manikin enters the collaborative work space collision sensor detects and highlighter shown the red color and robot must be stand still until green manikin in a collaborative work space. Refer figure 15 (a) and appendix C. When green manikin returns back to his original position robot moves as per set speed and on its normal path as per set parameter in RAPID programme. Refer figure (b). However, white manikins moves in a collaborative work spaces, it collide with fixed part and indicates yellow color by highlighter. When it collide with another part it indicated red color and robot should be standstill at a time. Refer figure (b) (c). To keep the robot standstill, various inputs and output signals are generated in smart components and in station logic. All inputs and outputs signals are synchronized in appropriate way to communicate with each other based on above condition. The same input and output signals is being used in RAPID program to create interrupt and trap routines.

Figure 15 (a) (b) (c) Verification and Visualization of Test 3 in Simulation
5.1.4 Test 4 - Green manikin enters in predefined area robot moves to another work station

In this test, validation of safety criteria is different way. This simulation test consists a similar environment as per real robotic cell. This test is quite different than above three tests. In above three tests, if any manikins enters in robotic cell collaborative work space from any of the predefined area. Robot must be stand till until manikins' stands in the area. However, this test consideration is different. It is based on once green manikin enters from his predefined area. Collision sensor detects the manikin and highlighter indicates a red zone, Refer figure 16 (a) and then robot does not stand till but robot must leave this work station and move to another work station on red manikin side. Refer 16 (b). However, it also monitors, if white or red manikin enters the collaborative work space robot must be standstill in both of the cases. Refer figure 16 (a) (b) (c). When one of them move back robot works normal as per given data in the RAPID programme. In this scenario interrupt and trap routine is modified in the programme to enable to perform the above mentioned procedure in simulation environment. Refer appendix D. There are two different purpose of this test. First purpose is to identify security or safety level of the robotic cell in various two predefined areas. Second purpose is to increase flexibility, productivity and efficient operations to avoiding delay events in the robotic cell.

Figure 16 (a) (b) (c) Verification and Visualization of Test 4 in simulation
5.1.5 Test 5 - SafeMove implementation in simulation

In this test SafeMove features is validated in a simulation environment. It is require to get SafeMove configuration to perform the test in RobotStudio 6.06. It is a special unique feature which is provided fully integration solution in real robotic cell and in simulation environment. It consists safe zones, refer figure 17 (a), safe stand still, monitor axis range refer figure 17 (b) and cyclic break check. It can be used according to application and requirement in the simulation and in real robotic cell. However this test implemented SafeMove feature and verified safe standstill and monitoring axis range. While entering the white manikins in to direction of robotic cell. Manikin is collided with part and it indicated colours yellow and red respectively. Once it enters the robotic cell which is cover by SafeMove zone robot stops immediately. Refer figure 17 (c).

Figure 17 (a) (b) (c) SafeMove implementation in simulation of Robotic cell
5.2 Test result of experimental test plan

Experimental test plan consist three various tests plans of real robotic cell including functional test plan, verification in manual mode and verification in Auto mode. All three test plan tables are prepared. Refer Table (3) and appendix (E) & (F) respectively. Results of experimental tests plan have been not carried out since real robotic cell commissioning work is still going on and probably it will complete in near future. It is difficult to guess exact time line of completion of commissioning date of real robotic cell since it is a unique robotic cell and need to validate others solution step by step. Moreover, verification and visualization of safe human robot collaboration in simulation environment which guide the end user to implement appropriate solution for reference purpose. Also prepared safety test plans could be useful for future requirement to validate security or safety solution in a real robotic cell at PTC (Smart automation lab). Refer figure 18 (a) (b).

![Real robotic cell at PTC (Smart automation lab)](image-url)
5.3 General discussion

The robotic cell is a unique cell and recognize as a smart automation lab at PTC. Nowadays Robotics and Automation applications are booming. The Flexible automation is indeed to get more efficient work while performing numerous operations in the cell. However, to create a collaborative work space and integration is still challenging task for researcher and innovators because of the security or safety of humans is concern. There are many researches are going on to keep the humans safe while working with robot in a collaborative work spaces. Above mentioned work of design simulation with manikins and various test results scenario shown the security solution and safety level in a virtual environment. So far, the test results of experimental test plan show the result in real environment. Furthermore, it covers possible hazardous condition of collaborative interaction between human and robot on collaborative work spaces. It is prime requirement for all robotic work cell to consider the possible hazardous condition and rectify it through with planned safety strategy.
6 Conclusion

The goal is to keep safe human robot collaboration depending on the results of verification and validation of implemented security or safety solution in robotic cell. This robotic cell is unique in all aspects and covered with various safety devices. For instance: light curtain sensor at each entry points, laser scanner at various locations, safety PLC and by including SafeMove2 function. The most important part is verification and visualization of safe human robot collaboration. In this project, design of simulation with manikins in RobotStudio 6.06 and experimental tests plans for safety are prepared. Results of design of simulation with manikins, smart components, interrupt trap routine in RAPID program and safe move function are carried out in RobotStudio 6.06. Results of Simulations in various scenario indicates a security and safety level of implemented solution in a robotic cell and how become a better and better solution could be established. Simulation provides various aspect to verify and visualize a safety level and it gives an advantage to apply appropriate safety solution in a real robotic cell. However, experimental test plan equally necessary to validate all the function including safety device are in proper order and output of their result as desired.

6.1 Future Work and Research

The project work is carried out in robotic cell at PTC, it is belonging to smart automation lab. This robotic cell sets the higher measures of flexible automation methodology of “Plug and Produce”. It keeps higher flexibility and work on a concrete solution of security or safety of human while sharing the work space with robot in collaborative work space. The cell consists higher safety standards and using special features of safety device to avoid any hazardous environment within robotic cell. The new concept of “Flex cell” is rolling on and the same concept will be applicable in GKN group. However, GKN is global engineering company so same concept will be utilized in other subsidiaries (i.e. might be in Asia, Europe, and in USA) with applying same safety standards or practices. Moreover, the existing location of the robotic cell is not permanent, and it might be replaced as per future requirement. An interesting and most important things to evaluate safety features based on real test plan for future work. In this project SafeMove feature is also applicable in simulation environment. However, it can be useful to validate in a real robotic cell when robotic cell will be in fully operation.

6.2 Critical Discussion

The project work seems to fascination as it includes to create and validated safety solution of real robotic cell at PTC (Smart automation lab). This work is carried out in virtual environment (i.e. simulation of Robotic cell) as well as in real environment too. Design of simulation in RobotStudio 6.06 is good experience with creating and using special features of smart components, interrupt trap routine program and manikins. Challenging task in simulation to create a similar safety solution based on working principle of light curtain and laser scanner. There are various concept exists for safety solution, but it is new concept and indeed nowadays in robotic cell to keep human safe
while working in collaborative workspace with robot. Moreover, real test plan could not be carried out in real robot cell due to robotic cell commissioning work is still going on. Prepared test will be useful as a ready reference to validate results of the robotic cell once robotic cell will be in operation. However, there are three various entry points in this robotic cell and it seems to be interested to apply SafeMove2 feature in a real robotic cell and note the result from each entry points.
7 References


References


A. Appendix : ABB Robot IRB 6700 and Top view of Robotic Cell

Figure 19 Top view of Robotic cell

Figure 20 ABB robot IRB 6700
B. Appendix : RAPID program Test 1 & Test 2

2. VAR intnum intno1:=0;
3. VAR intnum intno2:=0;
4. VAR intnum intno3:=0;
5. VAR intnum intno4:=0;
6. PROC main()
7.   CONNECT intno1 WITH Routine1;
8.   CONNECT intno2 WITH Routine2;
9.   CONNECT intno3 WITH Routine3;
10.  CONNECT intno4 WITH Routine4;
11.  ISignalDI di_Stop_Moving,1,intno1;
12.  ISignalDI di__Resume_Robot,1,intno2;
13.  ISignalDI di_Stop_Moving_Red,1,intno3;
14.  ISignalDI di__Resume_Robot_Red,1,intno4;
15.  reset di_Execute1;
16.  Path_10;
17.  ENDPROC
18. TRAP Routine1
19.   StopMove;
20.   reset di_Execute1;
21. ENDTRAP
22. TRAP Routine3
23.   StopMove;
24.   reset di_Execute1;
25. ENDTRAP
26. TRAP Routine2
27.   STARTMOVE;
28. ENDTRAP
29. TRAP Routine4
30.   STARTMOVE;
31. ENDTRAP
32. PROC Path_10()
33.   SetDO di_Execute1,1;
34.   MoveJ Target_180,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
35.   MoveJ Target_190,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
36.   MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
37.   MoveJ Target_190,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
38.   MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
40.   MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
41. ENDPROC
42. PROC Path_60()
43. MoveJ Target_120,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
44. MoveJ Target_130,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
45. MoveJ Target_140,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
46. MoveJ Target_150,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
47. MoveJ Target_160,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
48. MoveJ Target_170,v200,z1.tcpSpindelmotor\WObj:=wobj_Perform;
49. ENDPROC
50. EMDMODULE
C. Appendix: RAPID program Test 3

51. **MODULE** Module1
52. **VAR** intnum intno1:=0;
53. **VAR** intnum intno2:=0;
54. **VAR** intnum intno3:=0;
55. **VAR** intnum intno4:=0;
56. **VAR** intnum intno5:=0;
57. **VAR** intnum intno6:=0;
58. **PROC** main()
59. **CONNECT** intno1 WITH Routine1;
60. **CONNECT** intno2 WITH Routine2;
61. **CONNECT** intno3 WITH Routine3;
62. **CONNECT** intno4 WITH Routine4;
63. **CONNECT** intno5 WITH Routine5;
64. **CONNECT** intno6 WITH Routine6;
65. ISignalDI di_Stop_Moving,1,intno1;
66. ISignalDI di__Resume_Robot,1,intno2;
67. ISignalDI di_Stop_Moving_Red,1,intno3;
68. ISignalDI di_Resume_Robot_Red,1,intno4;
69. ISignalDI di_Stop_Moving_Green,1,intno5;
70. ISignalDI di_Resume_Robot_Green,1,intno6;
71. reset di_Execute1;
72. SetDO di_Exe_Red,1;
73. SetDO di_Exe_Green,1;
74. Path_10;
75. **ENDPROC**
76. **TRAP** Routine1
77. StartMove;
78. reset di_Execute1;
79. **ENDTTrap**
80. **TRAP** Routine3
81. StartMove;
82. reset di_Exe_Red;
83. **ENDTTrap**
84. **TRAP** Routine5
85. StartMove;
86. reset di_Exe_Green;
87. **ENDTTrap**
88. **TRAP** Routine2
89. **STARTMOVE**;
90. **ENDTTrap**
91. **TRAP** Routine4
92. **STARTMOVE**;
93. **ENDTTrap**
94. TRAP Routine6
95. STARTMOVE;
96. ENDTRAP
97. PROC Path_10()
98. SetDO di_Execute1,1;
99. SetDO di_Exe_Red,1;
100. SetDO di_Exe_Green,1;
101. MoveJ Target_180,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
102. MoveJ Target_190,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
103. MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
104. MoveJ Target_190,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
105. MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
106. MoveJ Target_190,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
107. MoveJ Target_200,v2000,z1,gripTCP\WObj:=Workobject_Manikins;
108. ENDPROC
109. PROC Path_60()
110. MoveJ Target_120,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
111. MoveJ Target_130,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
112. MoveJ Target_140,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
113. MoveJ Target_150,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
114. MoveJ Target_160,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
115. MoveJ Target_170,v200,z1,tcpSpindelmotor\WObj:=wobj_Perform;
116. ENDPROC
117. ENDMODULE
D. Appendix : RAPID program Test 4

118. PROC main()
119.   CONNECT intno1 WITH Routine1;
120.   CONNECT intno2 WITH Routine2;
121.   CONNECT intno3 WITH Routine3;
122.   CONNECT intno4 WITH Routine4;
123.   CONNECT intno5 WITH Routine5;
124.   CONNECT intno6 WITH Routine6;
125.   ISignalDI di_Stop_Moving,1,intno1;
126.   ISignalDI di__Resume_Robot,1,intno2;
127.   ISignalDI di_Stop_Moving_Red,1,intno3;
128.   ISignalDI di_Resume_Robot_Red,1,intno4;
129.   ISignalDI di_Stop_Moving_Green,0,intno5;
130.   ISignalDI di_Resume_Robot_Green,1,intno6;
131.   reset di_Execute1;
132.   reset di_Exe_Green;
133.   reset di_Exe_Red;
134.   Path_10;
135.   Path_80;
136. ENDPROC
137. TRAP Routine1
138.   StopMove;
139.   reset di_Execute1;
140. ENDTRAP
141. TRAP Routine3
142.   StopMove;
143.   reset di_Exe_Red;
144. ENDTRAP
145. TRAP Routine5
146.   MoveJ Target_140,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
147.   MoveJ Target_150,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
148.   MoveJ Target_140,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
149.   MoveJ Target_150,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
150.   MoveJ Target_140,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
151.   MoveJ Target_150,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
152.   MoveJ Target_140,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
153.   MoveJ Target_150,v2000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
154.   reset di_Exe_Green;
155. ENDTRAP
156. TRAP Routine2
157.   STARTMOVE;
158. ENDTRAP
159. TRAP Routine4
160.   STARTMOVE;
ENDTRAP
TRAP Routine6
STARTMOVE;

ENDTRAP
PROC Path_10()
SetDO di_Exe_Green,1;
SetDO di_Exe_Red,1;
SetDo di_Execute1,1;
MoveJ Target_210,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_220,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_230,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_240,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_250,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_260,v1000,z1,gripTCP\WObj:=Workobject_Manikins;
MoveJ Target_270,v1000,z1,tcpSpindelmotor\WObj:=Wobj_Perform;
MoveJ Target_280,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_290,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_300,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
ENDPROC
PROC Path_80()
SetDO di_Exe_Green,1;
SetDO di_Exe_Red,1;
SetDo di_Execute1,1;
MoveJ Target_140,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_150,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_160,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_170,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
MoveJ Target_180,v1000,z1,tcpSpindelmotor\WObj:=wobj_Perform;
CloseWObj;
ENDPROC
## E. Appendix: Experimental Test Plan in a Manual Mode

### Experimental Test Plan in Manual mode of Robotic cell at PTC

<table>
<thead>
<tr>
<th>Predefined Entry Points</th>
<th>Description</th>
<th>Speed of Robot in Rapid program</th>
<th>Actual Robot Speed</th>
<th>Robotic cell field Detection by device</th>
<th>Robotic cell field Detection by zone</th>
<th>Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterance point 1</td>
<td>Enter the person in robotic cell</td>
<td></td>
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</tr>
<tr>
<td>Enterance point 1</td>
<td>Enter the person in collaborative work space</td>
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</tr>
<tr>
<td>Enterance point 1</td>
<td>Going back from collaborative work space</td>
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<td></td>
</tr>
<tr>
<td>Enterance point 1</td>
<td>Going back from robotic cell</td>
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<td>Enterance point 2</td>
<td>Enter the person in robotic cell</td>
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<td>Enterance point 2</td>
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<td>Enterance point 2</td>
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<td>Enter the person in robotic cell</td>
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<td>Enter the person in collaborative work space</td>
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<td>Enterance point 3</td>
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<tr>
<td>Enterance point 3</td>
<td>Going back from robotic cell</td>
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</tbody>
</table>
# F. Appendix: Experimental Test Plan in Auto Mode

## Experimental Test Plan in Auto mode of Robotic cell at PTC

<table>
<thead>
<tr>
<th>Predefined Entry Points</th>
<th>Description</th>
<th>Speed of Robot in Rapid program</th>
<th>Actual Robot Speed</th>
<th>Robotic cell field Detection by device</th>
<th>Robotic cell field Detection by zone</th>
<th>Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance point 1</td>
<td>Enter the person in robotic cell</td>
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<tr>
<td>Entrance point 1</td>
<td>Going back from collaborative work space</td>
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<tr>
<td>Entrance point 1</td>
<td>Going back from robotic cell</td>
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</tr>
<tr>
<td>Entrance point 2</td>
<td>Enter the person in robotic cell</td>
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<tr>
<td>Entrance point 2</td>
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<tr>
<td>Entrance point 2</td>
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<tr>
<td>Entrance point 3</td>
<td>Going back from collaborative work space</td>
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<td></td>
</tr>
<tr>
<td>Entrance point 3</td>
<td>Going back from robotic cell</td>
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</tbody>
</table>