AN APPROACH FOR RISK MITIGATION AND SAFETY DURING HUMAN-ROBOT COLLABORATION

MASTERS THESIS

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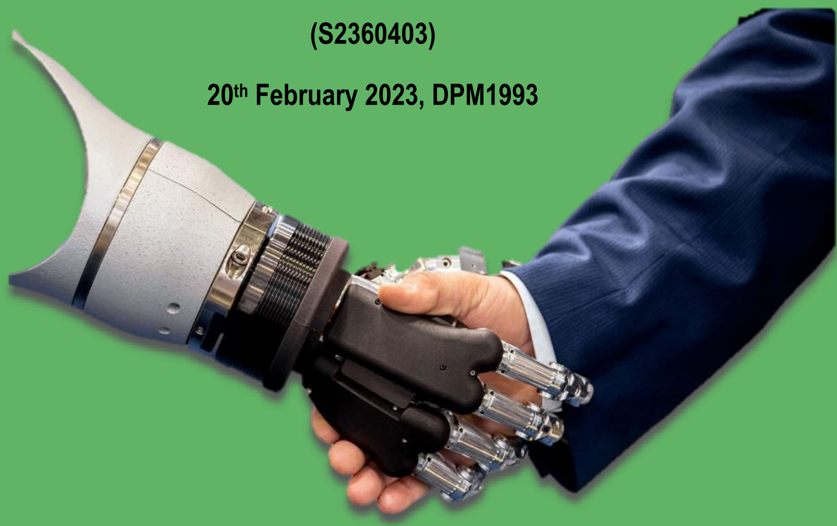
(S2360403)

20th February 2023, DPM1993



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ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my thesis advisor, Dr. Ir. S. Arastehfar, for his valuable guidance, support, and encouragement throughout my research and writing process. His expertise and patience have been instrumental in helping me to complete this thesis.

I would also like to thank Dr. Ir. P.K. Chemweno, for their valuable insights, constructive feedback on my research and patience. His guidance and support have been invaluable.

I would like to extend my gratitude to my family and friends for their unwavering support, motivation and encouragement throughout this journey. A special mention, to Mirjam IJmker who kept me motivated with her words of enthusiasm, care and support. Without their love and support, this thesis would not have been possible.

I would also like to acknowledge Sander Esselink for his insights on getting familiar with RobotStudio software and discussions during our meetings.

Finally, I would like to thank University of Twente for providing me with the resources and opportunities to have made this thesis possible.

I am deeply grateful to all of you and will always remember this experience with fondness.

ABSTRACT

With the advent of industry 4.0, collaborative robots(cobots) have emerged as the enabling technologies driving forward the smart factories. The advantages to combine human cognitive abilities with robot precision and accuracy has resulted in improved ergonomic working conditions for human worker, better quality and higher efficiency of the production process.

This thesis presents a safety approach for human-robot collaboration. The main objective of this research is to address the challenge of ensuring the safety of human operators while working alongside robots whilst also improving productivity and complying with one of the main existing safety standard in this regard, ISO/TS 15066.

The work employed in this research includes an overview of the general aspects in human robot collaboration and a thorough literature review of the existing safety standards and safety methods in human-robot collaboration. Concluding with the discussion on the gaps in the previously mentioned safety aspects, a new safety framework is proposed that combines the safety methods of speed and separation monitoring (SSM) and power and force limiting (PFL) from ISO/TS 15066 for a collaborative application. Following the case scenario description of the considered collaborative application and the initial hazard study, simulations and calculations are done based on the influencing parameters between human and robot at different hazardous positions to visualise and support the strategy of this framework. The results obtained are based on ISO/TS 15066 and describe a less stringent value pertaining to safe human-robot distance and safe impact force values, this shows that a safe and productive human robot collaboration can be achieved without placing the strict limiting values on the robot performance as per current standards.

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LIST OF ABBREVIATIONS

HRC	Human Robot Collaboration
SRMS	Safety Rated Monitored Stop
HG	Hang Guiding
SSM	Speed and Separation Monitoring
PFL	Power and Force Limiting
ISO	International Standards Organization
TS	Technical Specification
HAZOP	Hazard and Operability
UML	Universal Modelling Language.
PSD	Protective Separation Distance
2D	2 Dimensional
3D	3 Dimensional

1. INTRODUCTION

With the advent of Industry 4.0 it has brought forward a revolution in manufacturing that offers a new viewpoint on how production may work with cutting edge technologies [1], however the current market demands production of customized products with smaller lot sizes and reduced lead times [2]. Production and assembly systems therefore need to be flexible and adaptable to fluctuating demands. To achieve both flexibility and high degree of automation, a strong interaction between human and robot, also referred to as Human Robot Collaboration (HRC) is observed as one promising concept [2], [3]. In this concept, a human operates alongside a collaborative robot (cobot) in a shared workspace to combine and utilize the human's intelligence and flexibility with the robot's precision, repeatability and strength. An example of such a collaborative application in a production plant is shown in figure 1. In this example, the human and the YuMi robot are collaboratively assembling sockets, where the human is holding two parts/subassemblies and YuMi inserts the third part to complete the assembly. However, bringing together humans and robots is very challenging; one of the biggest hindrances in these combined interactions is ensuring the safety of operation [4],[5]. Any ineffectiveness of safety can result in complex and hazardous situations [6],[7], thereby hindering the potential use case applications of such a concept [8].

Figure 1 YuMi (a product of ABB) working together with a human for socket assembly [9]

In collaborative robotics, there is an absence of a physical barrier to allow interactions between cobots and humans. As a result, it is crucial that collaborative systems have design safeguards that reduce hazards which may cause injuries to the human. Safety is ensured through built in systems, sensors and monitoring devices and following the safety standards that prescribe safe guidelines for designing collaborative systems. The ISO/TS 15066 standard is defined as a technical specification document for collaborative operations. It introduces guidelines on safe collaborative operation primarily through stopping the kinetic motion of robots in the presence of human and defining force thresholds for different body areas [10]. Regardless, safety for HRC is still considered a challenge [6]. The challenge is twofold and lies in assuring safety of human whilst also ensuring the safety of operation, for example in a task involving the assembly of production boxes [11], shown in figure 2, the cobot folds the production box and holds it in place while the human is fastening the bolts to the edges box, in this situation, safety of human while holding the production boxes as well as the safety of operation by the robot while moving the item after human task needs to be ensured.

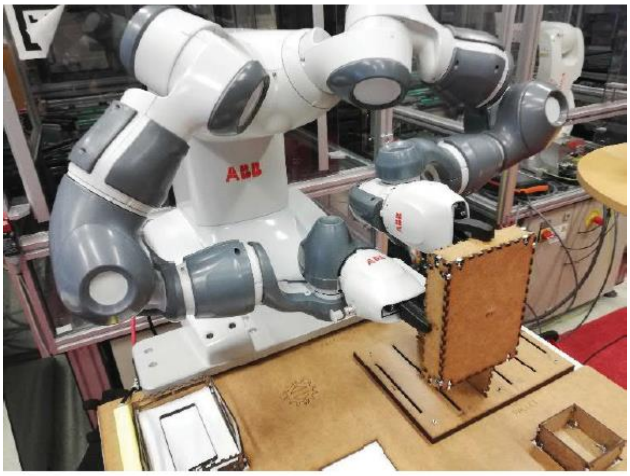


Figure 2 Cobot holding the production box [11]

Further, obstacles in the adoption of HRC are also due to ambiguity in the current standards and absence of clear procedures to prove the assurance of safety in these standards [4]. For this study, the work revolves around reducing risks during HRC by providing a safety framework to prove the assurance of safety of a collaborative pick and place application whilst also following the safety standard for collaborative robots and applications (ISO/TS 15066). The significance of the proposed approach is to demonstrate an approach for risk mitigation by utilizing the available concerned standard in a manner as to ensure safety whilst also maintaining productivity.

1.1 Background

1.1.1 Collaborative robots-Cobots

The term HRC applies to any situation where robots work directly alongside humans without safety barriers on the manufacturing floor. A prominent technology influencing human-robot interactions is collaborative robots, also referred to as cobots. Figure 3, shows some of the prominent manufacturers of such cobots for various sectors across the industry.

Universal robot, UR5 KUKA LBR iiwa ABB, YuMi

Figure 3 Prominent Cobot manufacturers [12]

Cobots are a new generation of robots that are born free and without any kind of fencing or enclosure, surpassing the limits and workplace constraints that prevent standard industrial robots from cohabitating and working side by side with their human counterparts. As stated in [10] the objective of collaborative robots is to combine the repetitive performance of robots with the individual skills and ability of people. Humans are able to apply their cognitive capabilities to react to influences, such as defective components or changing parameters of parts and processes and the robots have the advantage of accuracy during operation, repeatability, the handling of high loads and endurance [13].

1.1.2 Cobots vs Traditional industrial robots

Cobots have the capacity to stop their motion when they come across human employees or any obstruction in their path since they are equipped with sensors and are responsive to the detection of any unexpected force [14]. Compared to traditional industrial robots, this makes them very trustworthy partners when it comes to workplace safety.

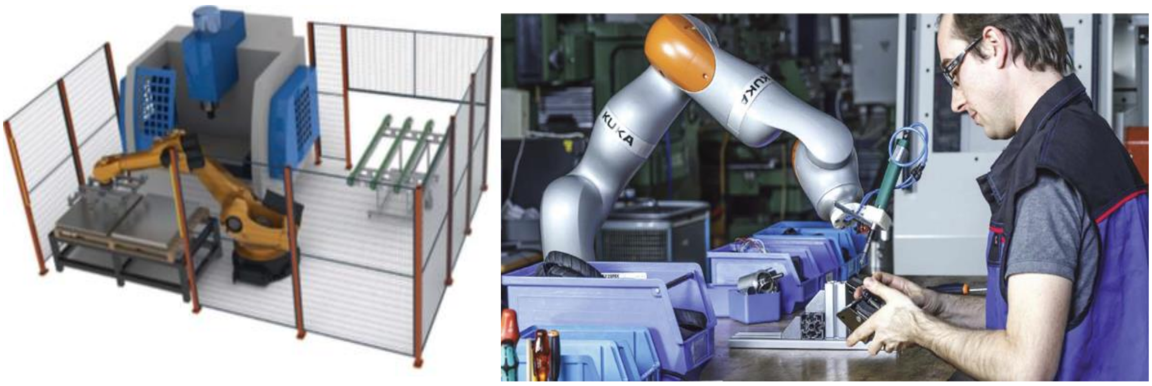


Figure 4 Traditional industrial robot and collaborative robot [6]

As shown in the left side of figure 4, the traditional robots have safety fences which are required to prevent harming the human operators, whereas the collaborative robots are without any fences thereby allowing the human worker to stand in its proximity and work together at the same task. The differences between traditional industrial robots and cobots are further extended in Table 1.

Table 1 Comparison between traditional industrial robots and collaborative robots [15]

Traditional industrial robots	Collaborative robots
Fixed installation	Flexibly relocated
Repeatable tasks, rarely changed	Frequent task changes
Online and off-line programming	On-line instructed and supported by off-line methods
Rarely interaction with the worker, only during programming	Frequent interaction with the worker, force/precision assistance
Worker and robot are separated through fence	Workspace sharing with worker
Cannot interact with people safely	Safe interaction with people
Profitable only with medium to large lot size	Profitable even at small lot size
Small or big and very fast	Small and slow
Not easy to teach	Easy to teach

A recent report from the International Federation of Robotics[16] indicates that the adoption of human-robot collaboration is on the rise. According to the report cobot installations grew by 11% from 2018 to 2019 as shown in below graph in figure 5. The graph also indicates that as more and more suppliers offer collaborative robots, the range of applications becomes bigger and the market share reached 4.8% of the total of 373,000 robots installed in 2019. It also states that even though this market is growing rapidly, it is still in its infancy, meaning that it is still a new technology and further growth and expansion in terms of research, development and implementation expected in this field.

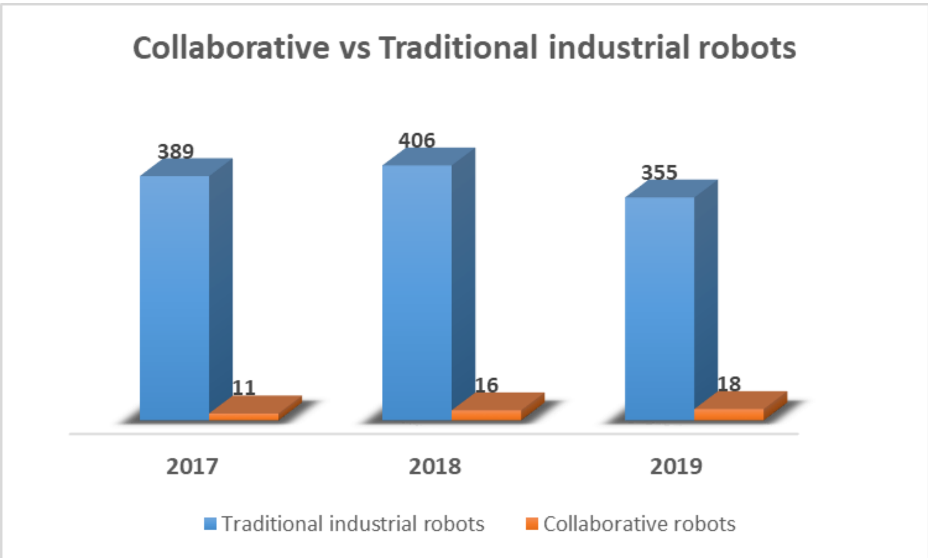


Figure 5 Collaborative and traditional industrial robots [16]

1.1.3 Benefits of cobots

Cobots tend to offer several benefits when implemented. They are easy to setup, as unlike industrial robots they are compact and simple to operate, hence they may be set up with low knowledge of programming and as a result, training human operators on how to use and program them will be simple

[17]. They can be managed and taught through intuitive systems, based on augmented reality, walk through programming or programming by demonstration [6]. Cobots can undertake a variety of tasks, making them versatile. They can be made mobile and can easily be transferred to help out another station. They operate much more straightforward than their industrial counterparts, which need extensive changes done to their software and hardware to be repurposed. Back injuries and discomfort were cited in almost 39% of work-related musculoskeletal disorders in the American workplaces in 2018, according to the Bureau of Labour Statistics [17] Cobots can easily take over repetitive manual work for employees and therefore allow them to take on other tasks and encounter fewer workplace injuries.

1.1.4 Industrial applications

Companies require a space-saving, cost-effective answer to problems such as worker retention and recruiting, talent shortages, productivity variations, and safety and health challenges[18], and one solution is utilizing cobots. Mass production companies, especially those in the automobile industry, are keen to implement HRC in order to increase their competitiveness and improve the degree of automation and manufacturing in their facilities. The Spartanburg plant of BMW Group succeeded in implementing cobots that work side by side with humans for equipping the inside of car doors with sound and moisture insulation, it allowed them to reduce improve ergonomics by taking over the repetitive and precision of the required task [19]. Audi is using human-robot cooperation (HRC) to apply adhesives in final assembly. Sensors in the robot arm recognize when a human is touched and automatically stop any movement in case of danger. Operators and robots work together without a protective fence to install large CFRP roofs [20]. Another application is The KUKA lbr iiwa for body-in-white production at Ford, the task deals with sealant seam application, the monotonous and strenuous application is made easy by the cobot taking over the repetitive task. The worker is required to program the motion sequence and the cobot executes it efficiently. Apart from automotive industry cobots can also be found in medical technology, with KUKA LBR med cobot tasks ranging from diagnostics and treatment to surgical procedures where precise work is essential can be assisted by these reliable machines [21].

1.2 Problem Statement

HRC is assuming a broader role in terms of having robot applications in close interaction with humans to improve ergonomic working conditions and productivity [3]. This collaboration has its benefits of alleviating human effort and improving productivity rates, most observed in assembly tasks as indicated by a survey found in [2]. In these tasks, pick and place is one of the most primary handling functions executed by cobots and humans in collaboration. Hence, having a safe collaborative scenario involving these pick and place actions is critical and one has to always consider the associated hazards and safety during its implementation in a combined work scenario.

Additionally a survey in [6] indicates one of the main challenges of HRC is to require a safe interaction. In the pick and place tasks, the absence of safety precautions, apart from unsafe interactions and operator injuries, can result in reduced productivity; for instance, workers may get close to a robot or collide with it, causing the robot to slow down or stop suddenly. This can reduce productivity and, in the worst-case scenario, have a negative impact on upstream and downstream workstations [22].

Obstacles in implementation of industrial work systems with cobots can arise due uncertainties as to how standards should be implemented, uncertainties about operational guidelines in a work environment, effect on the jobs of industrial workers [22]. One main concern of safety assurance is the alignment between the design safeguards (as in technical specification document ISO/TS 15066 for collaborative operations [10]) and potential hazards that may occur in collaborative tasks in a shared environment [23]. The solutions for safe HRC are therefore domain dependent and, hence research in this area is needed to mature with regard to considering different safety aspects, risk assessments and the development of appropriate simulation models and experiments for envisioning a safe collaboration [15]. Overall, for the pick and place task, it is important to come up with a safety strategy that ensures both the safety of human and productivity of operation while aligning the design safeguards with the potential hazards.

1.3 Research questions

The main objective of this study is to propose a safety strategy that aligns with the safeguards as in existing safety standard [10] and mitigates the anticipated operational hazards while performing a collaborative task in a shared work environment.

In order to achieve the above stated objective, research questions are framed as stated below,

Research question: How can a safety strategy be designed to comply well with the existing standard ISO/TS 15066 to ensure a safe collaborative pick and place operation between a human and a robot?

Sub Research question 1: What are the safety strategies for ensuring safe collaborative pick and place operation?

Sub Research question 2: How can safety methods in ISO/TS 15066 be applied in a shared collaborative work setting to enhance the safety of human operation?

Sub research question 3: What are the risk management steps needed to ensure a safe collaborative pick and place operation?

(Note: The statements are color coded to show relation of sub research questions with the main research question)

1.4 Scope of research and assumptions

The scope of research is on the safety aspects in a collaborative pick and place operation. Firstly, the safety strategy is implemented on the robot itself, denoting that the parameters arising out of robot motion namely, velocity of robot, force of impact, distance of robot from human and energy transferred during impact are the influencing parameters. The simulation is done on a simulation software RobotStudio (licensed by the university) for verifying the proposed safety strategy. The focus is not on having intentional contact during human robot collaboration (HRC) instead it is on reducing impact force during unintentional contact to avoid injury to the human. Lastly, the term ‘robot’ referred in multiple sections of this report primarily refer to collaborative robots (cobots).

Assumptions

No additional hardware or wearable for human detection, hence the measure of the distance, the intrusion distance(C) by which a body part of a human can intrude before being detected by sensors or scanners is considered as zero. Similarly, the uncertainty in positions of robot and operator positions are also not considered.

1.5 Outline of thesis

Chapter 1 presents the background of cobots, the problem statement, the research questions to guide the research and the scope and assumptions of research. Chapter 2 presents the literature review and provides information about the main aspects human robot collaboration scenario related to this thesis along with a detailed account of safety aspects, standards, risk assessment steps, safety systems in HRC and lastly the gaps on these discussed safety standards and safety systems. Post the findings in literature, a safety framework is proposed in chapter 3. In chapter 4 the proof of concept is elaborated along with its underlying steps. Chapter 5 presents the results and discussions and the final conclusions with the answers to the research question, limitation, challenges and future recommendations is given in chapter 6.

2. LITERATURE REVIEW

This section gives a description about existing knowledge of HRC, general safety aspects, concerned safety standards and safety systems in HRC. The chapter concludes with a discussion on the gaps in these standards and safety systems.

2.1 Human Robot Collaboration

2.1.1 Workspaces in HRC

The human and robot engage with each other in a shared environment known as the collaborative workspace and in standard document ISO/TS 15066 [10] it is defined as the space within the operating space (shared workspace) where the robot system (including the work piece) and a human can perform tasks concurrently during production operation

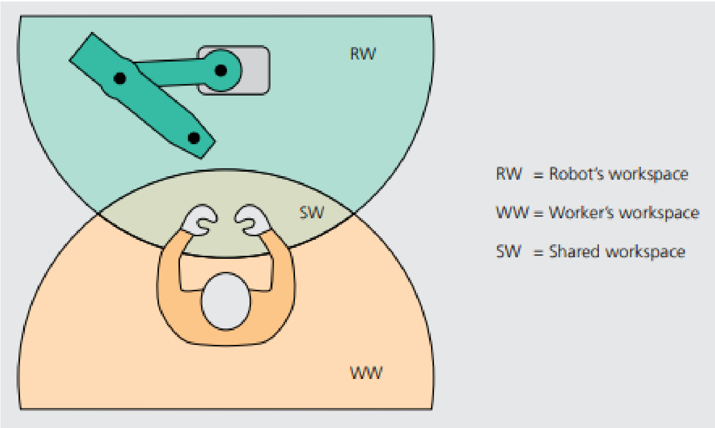


Figure 6 Robot’s and worker’s workspaces [22]

Figure 6, illustrates robot’s and human’s workspaces (RW, WW) which creates a shared workspace (SW) by overlapping each other.

2.1.2 Levels of interaction

It is worth noting that the levels of interaction in the shared workspace can be categorized in different categories. This study considers the categorization from [22], [24] which divides tasks according to the relation between a cobot, an operator, work pieces and the process being performed on the work piece(i.e. task specification). This categorization as indicated below in figure 7, distinguishes the various levels of interaction of a cobot in different industrial scenarios.

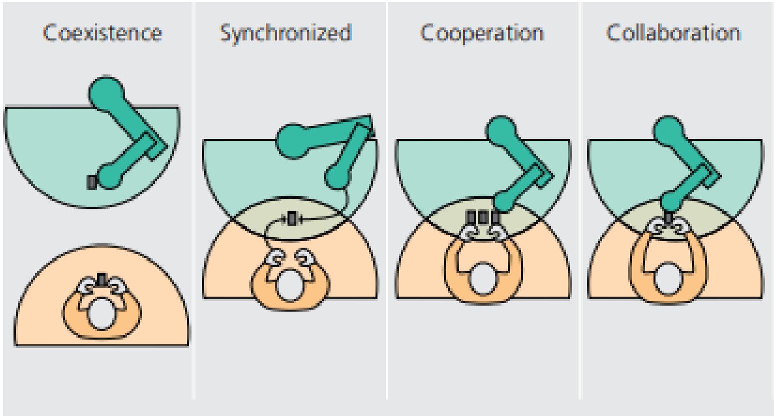


Figure 7 Levels of interaction between the robot and the human [22]

The categories are explained below:

- **Coexistence(Independent):** An operator and a cobot operate on separate work pieces independently for their individual manufacturing processes. The collaborative element is due to the co-presence of the operator and cobot in the same workspace without a fence or guard. That is, safety is achieved through the cobot's intrinsic safety and/or added hardware/software safety elements. Therefore, the cobot is aware of the operator's presence and acts safely.
- **Synchronization(Simultaneous):** An operator and a cobot operate on separate processes on the same work piece at the same time. There is no time or task dependency between them. However, the cobot needs to be spatially aware of the operator and his/her task requirements in order to respect the operator's space. Being able to concurrently operate on the work piece will minimize the transmit time of the work piece between the cobot and human, thereby improving productivity and space utilization.
- **Cooperation(Sequential):** An operator and a cobot perform sequential manufacturing processes on the same work piece. There are time dependencies between the cobot and operator for their processes as a result they work in a shared workspace at the same time but do not perform tasks simultaneously on the same product. In most cases, the cobot is arranged to handle tedious processes to improve the operator's working conditions.
- **Collaboration(Supportive):** An operator and a cobot work towards the same process on the same work piece simultaneously. There is dependency between the actions of the cobot and the operator. That is, without one, another cannot perform the task. The cobot needs to understand the operator's intent and the task requirements in order to provide appropriate assistance

Furthermore, it should be noted that neither this categorization nor the terminology used are unique, and others may be found in the literature[4], [25]–[28]

2.2 Safety in Human-Robot Collaboration(HRC)

2.2.1 General safety aspects

Robots play a significant role in manufacturing process and as briefed in previous section, there is a driving potential for them to grow in a collaborative scenario, however this integration still is limited and one of the major concerns is due to safety concerns. Safety is a fundamental prerequisite in the design of products, machines and systems especially for collaborative workplaces, where humans work alongside robots [6] and as the nature of manufacturing tasks are often hazardous in a shared workspace, safety assurance is critical when designing robotic systems for HRC [23]. Due to the varying nature of applications of cobot in HRC, the needs of safety are specific. Organizations deploying cobots must be aware of how to implement cobot in their dynamic workspace, this comprises of having knowledge of involved hazards, trust in automation both through psychological and technological factors and utilizing cobots in a manner that defines an acceptable margin between productivity and safety. incorporating their own safety strategy with the consideration from established safety standards [29]. The following paragraphs will look at understanding the standards for HRC, d discussion on these standards and the current safety technologies present in research and in industry.

2.2.2 Safety standards

As explained in [13] 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. ISO standardized multiple safety features into different documents, ISO10218 is a document describing the safe operations for robot and its environment and it is of two parts, the basic safety requirements on the robot and the robot system are described in the standards for the safety of the robot ISO 10218-1, and for the safety of the robot system ISO 10218-2. To provide additional details on the safety requirements and applications of collaborative document, ISO developed a technical specification document called the ISO/TS 15066. This document is aimed at offering guidance to both the manufacturers and system integrators in their various roles and responsibilities in bringing forth an HRC application. In particular, it includes information regarding collaborative robot system design, hazard identification, risk assessment and the requirements for the applications additionally, it provides a more detailed description of the safe collaborative modes of operation briefed in the paragraphs following this section. In all of the safety modes below, the protective principle applies in the shared, collaborative work space. It is worth noting that a combination of more than one of the basic protective principles is observed in practical applications of collaborative robots. Table 2, gives an overview of the relevant standards applicable in this regard.

Table 2 Relevant standards[30]

Title	Description
ISO 12100	Safety of machinery — General principles for design — Risk assessment and risk reduction
ISO 10218-1	Robots and robotic devices — Safety requirements for industrial robots — Part 1: Industrial Robots. This part is intended for those who develop and manufacture the robot itself and its controller.
ISO 10218-2	Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration. This part is aimed for those who integrate the robot system, including the robot, the endeffector and other equipment, devices products necessary to perform the required process.
ISO/TS 15066	Robots and robotic devices – Collaborative robots. This part supplements and builds upon the industrial robot safety standard ISO 10218. It provides additional guidance on design and risk assessment for collaborative robot application connected to the collaborative operation methods as well as defines biomechanical limits for power and speed limiting HRC applications.

Not all of the identified hazards apply to all robots, nor is the level of risk associated with a given hazardous situation the same for each robot. Regulations defined by standards are thus ambiguous and difficult to implement [31], therefore the standards specify a risk assessment to design safe working conditions.

2.2.3 Risk assessment

Risk assessment is a general methodology where the scope is to analyze and evaluate risks associated with complex system. It enhances understanding of risks, their causes, frequencies, consequences and probability. The basic steps in risk assessment are as shown in figure 8.

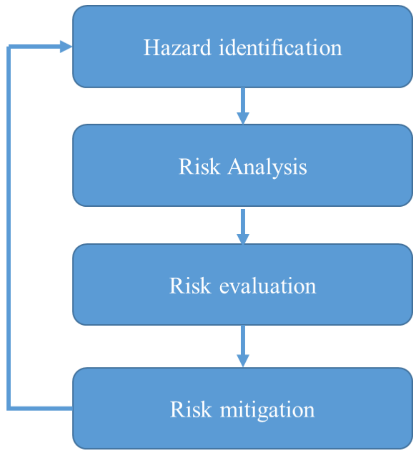


Figure 8 Risk assessment steps

Steps in risk assessment

- **Hazard identification-** The first phase of the risk assessment is the hazard identification, it is carried out manually by first identifying and then outlining each potential threat that could exist in the considered HRC scenario. The potential effects and harms to people and other things are also listed in a tabular manner. There are several methods to perform this phase such as the Hazard Analysis (PHA), Hazard Operability analysis (HAZOP), Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA). FTA and FMECA are more dedicated to advanced steps, focusing more on reliability aspects, whereas methods such as Hazop, PHA can be applied at early stages of development [32], additionally in PHA hazards for a specific scenario are identified from hazard checklists of a standard, however the ISO/TS 15066 standard does not include hazards for HRC scenario [33], hence we apply the Hazop method in this study. This method is further elaborated in appendix A.

- **Risk analysis-** In this step the risks associated with the identified hazards are estimated based on their severity of harm and probability of occurrence.
- **Risk evaluation-** a decision as to whether these risks are tolerable or not needs to made is performed in this step.
- **Risk mitigation-** In this step, safety measures either through design changes to the machine or through changes in the process of operation are suggested to reduce risks. Considering these above steps in risk assessment an iterative process from hazard identification to risk mitigation needs to be ensured until all hazards are brought down to an acceptable level.

To have continued safety of operation, the risk assessment also depends upon safe operation methods followed by the involved entities, in this case the robot and human. These collaborative operation methods are prescribed by a standard and should align with outcomes of risk assessment to have low risk operation [23]

2.2.4 Collaborative operation methods

A collaborative robot can solve a task in different ways hence the safety guidelines used can vary depending upon the amount of interaction required during the task and the application.

This section gives a brief description of the different collaborative operation methods present in HRC scenario as mentioned in safety standard ISO/TS 15066. ISO/TS 15066 specifies four different safety related guidelines where collaborative operations must include on or more of the following four modes [10]:

1. *Safety-Rated Monitored Stop(SRMS)*

In this method, the safety-rated monitored stop robot feature is used to stop robot motion in the collaborative workspace before an operator enters the collaborative workspace to interact with the robot system and complete a task (e.g. loading a part onto the end-effector). If there is no operator in the collaborative workspace, the robot may operate non-collaboratively. The operator is permitted to enter the collaborative workspace only when the safety-rated monitored stop is active and robot motion is stopped. Robot system motion can resume without any additional supervision only after the operator has exited the collaborative workspace. Safety rated devices (e.g. motion sensors, 3D cameras) are used to detect the presence of humans.

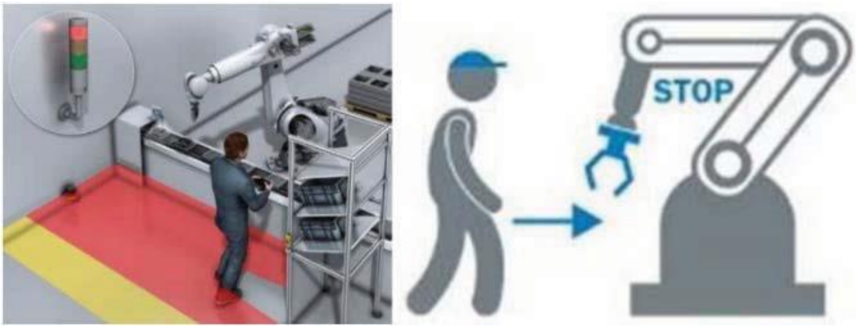


Figure 9 Operation in safety-rated monitored stop technique (SRMS) [34]

2. *Hand Guiding(HG)*

In this method of operation, an operator manually uses a hand-operated device to transmit motion commands to the robot system. The robot in this mode is enforced by a safety-rated monitored speed function and a safety rated monitored stop function.

Before the operator is permitted to enter the collaborative workspace and conduct the hand-guiding task, the robot achieves a safety-rated monitored stop. The robot's movements and program are interrupted when the operator enters the workspace. The robot performs the program automatically while it is inside the collaborative space. The robot state changes to safety-rated monitored speed functionality as soon as the user engages the hand guiding device, enabling direct robot movement. The robot returns in a safety-rated monitored stop when the user releases the hand guiding device and starts the previously interrupted program as soon as the user exits the collaborating area [6].

Figure 10 Operation in hand guiding technique (HG) [34]

3. *Speed and Separation Monitoring(SSM)*

In this method, the robot and the operator may move concurrently in the collaborative workspace. This type of operation allows the operator and robot system to move together in the shared workspace. By always keeping the appropriate separation space between the operator and the robot, risk is reduced. The robot system never moves so near to the operator that the protective separation distance is crossed. The robot system comes to an end when the separation distance falls to a level below the protective separation distance. The robot system can automatically restart motion once the protective separation distance is maintained again. The speed of the robot is adjusted according to the distance between the human and the robot itself and therefore speed reduction, later transition to safety-rated monitored stop is one possibility of keeping within the limits of protective separation distance. Another solution towards safe operation is through the execution of an alternate path which does not violate the safe distance thereby, continuing with active speed and separation monitoring.

Figure 11 Operation in speed and separation monitoring technique (SSM)[34]

4. *Power and Force Limiting(PFL)*

In this method of operation, physical contact between the robot system (including the work piece) and an operator can occur either intentionally or unintentionally. In power and force limiting (PFL), the contact force or power is restricted to avoid a potential injury to human. It is implemented by limiting the driving forces of joints at the design phase of cobot.

Figure 12 Operation in power and force limiting technique (PFL)[34]

The standard document ISO/TS 15066[10] provides the information for allowable biomechanical threshold limits, namely the permissible force and pressure values is defined based on contact scenarios that may occur during a collision. If the event of contact is detected, either the motor brakes of cobot are activated, or the torque control mode with gravity compensation is deployed to limit contact force or power[8]. Contacts occurring in this type are distinguished in two categories, quasi-static and transient. Transient contact is a dynamic impact where the body can freely move under the robot's force and quasi-static impact, where the robot crushes a human's body part against a fixed object. Under transient impact, the force can be two times higher than under quasi-static impact [10]. In transient contact head collision, i.e. contact between the robot and the operator's face, skull and forehead, is prohibited under any circumstances. With these maximum pressure and force thresholds, the transfer energy in a quasi-static collision between the robot and the human can be calculated. The transfer energy highly depends on the size of the contact area during the collision. The transfer energy determines the speed limit for the robot in the collaborative workspace which results in an acceptable transfer energy causing only minor injuries.

The biomechanical threshold limits are kept through active or passive risk reduction measures [10]. Active design measures focus on the control system of the robot, e.g. force and speed limiting functions, safety-rated monitored stop and safety-rated soft axis and space limiting function. Passive design measures, however, focus on the mechanical design of the robot system such as lightweight robots to reduce the consequences of a collision and round edges to increase the contact surface area.

Table 3 Summary of 4 types of collaborative modes

Type of collaborative operation	Main means of risk reduction
Safety-rated monitored stop (SRMS)	No robot motion when operator is in collaborative workspace
Hand guiding (HG)	Robot motion only through direct input of operator
Speed and Separation Monitoring (SSM)	Robot motion only when separation distance is above minimum separation distance
Power and Force Limiting (PFL)	In contact events, robot can only impart limited static and dynamic forces

A summary of the 4 types of collaborative modes as mentioned in the ISO/TS 15066 is as shown in table 3. It is observed that the amount of interaction between an operator and a robot increases from the first mode to the last, due to this increased integration the HRC scenario needs to be designed accordingly to meet the demands of safety and productivity as required. Therefore, for the different integration levels, the corresponding safety method used is different from each other.

2.2.5 Safety systems in HRC

In research as well as the industry, safety methods are defined considering different aspects and technologies depending on the application and task for developing safe HRC scenarios. In the following subsection an account of the applications of each safety methods (namely, the Safety stop, Hand guiding, Speed and Separation monitoring and the Power and Force limiting as mentioned in the ISO/TS 15066) through experimental studies to identify the affecting parameters that influence safety are discussed.

Some applications of safe collaborative methods in research follow:

a) **Safety rated monitored stop(SRMS)**

With the intention of promoting a fenceless cooperation between humans and robots, the robot should be able to achieve safety stop whenever the human enters the robot workspace, namely the safety rated monitored stop from ISO/TS15066 is to be followed. A new strategy for ensuring human safety during various levels of interaction is proposed in M. Bdiwi,et al [35]. In this paper the safety rated monitored stop is extended by considering the detection of events by a vision system and algorithm which describe human actions close to the robot. They specify the human features which should be detected by vision systems and the robot parameters which should later on be controlled. These parameters include the detection of human readiness, upper body and hands with a near field vision system and the monitoring of robot speed, position and torque. Therefore, for this mode (SRMS), the focus mainly lies on two aspects, one being the human detection directly through vision systems or indirectly through LIDAR sensors, stereo cameras and the other is having an estimation of braking distance of the robot.

These parameters are not significant for this study as human detection is not in the direction of research and hence this mode of operation will not be considered further in detail.

b) Hand guiding(HG)

In situations where the tasks involve the robot motion to be activated and manipulated by the human operator, Hand guiding is the relevant safety function considered. To demonstrate an this method Cacace et al [36], considers an industrial assembly scenario in which a human operator interacts with a lightweight robotic manipulator to accomplish insertion of accessories for car production. The main focus was on improvement of the operator's ergonomics while maintaining safety during task execution. To test their collaboration system, an experimental evaluation is performed on a mockup test bed as shown in figure 13, in this test bed the human can guide the end effector towards the desired target thereby combining the human movements with the robot motion. This combined hand guiding motion is studied with varying interaction modes (passive, guided and proactive) to determine the most suitable that reduce human effort.

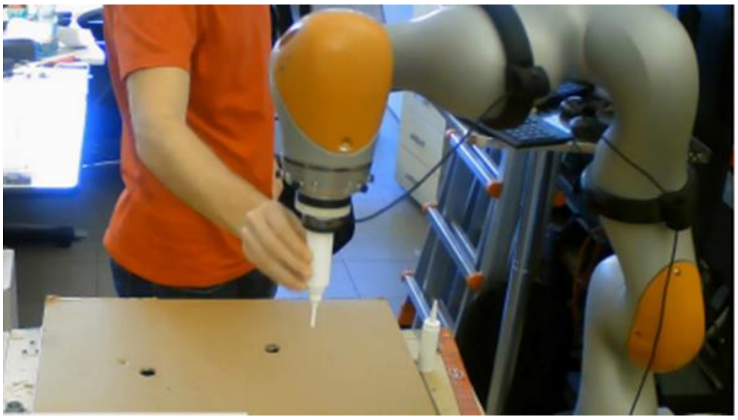


Figure 13 Experimental setup for hand guiding [36]

Compared to the passive (guidance along complete path) and proactive (no guidance), the guided (guidance only to reach target) offered best results as it offered more control. Other requirements of

Hand guiding mode are positioning accuracy, repeatability and supervision systems for the application of the correct item, if any of these requirements are compromised it can result in risks during operation. To this effect, a problem such as stick-slip (a sudden jerking motion that can occur when a robot is moving) which causes non smoothness during a hand guided operation is studied in Yun-Ju Chuang et al, [37]. In this study the moving force variations of the cobot during hand guiding along its distance, the experimental setup consisted of a dual parallelogram linkage mechanism to represent the robot arm for hand guided application as shown in appendix D. This arm is moved along different planes in the X-Y-Z workspace (appendix D) and the force is measured by a tension gage. The main contributions of this paper were investigating the hand guided force, the closer the cobot is to the origin point in space, the lower is the hand guided force and among the divided working planes, the cobot force increases as the working plane is lowered. Furthermore, the main parameters observed in Hand guiding is mainly the force (guided force and the contact forces) and direction of movement along the working plane. These parameters are not applied in this thesis and not useful for coming up with the required safety strategy as required for this study, hence this safety mode is not the main focus in this thesis.

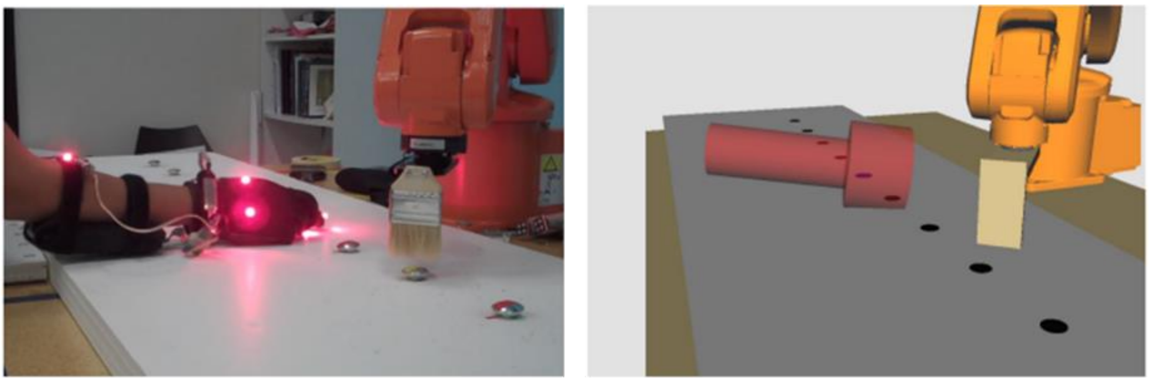
c) Speed and Separation monitoring(SSM)

Situations having continuous or intermittent interventions of human operator as in assembly and part handling operations cobot collision hazards are more likely to occur and in these moments speed of the robot and distance of operator need to be accurately monitored, the third type of safety guideline namely, speed and separation monitoring is a crucial safety parameter that can be applied. Research approaches implementing this strategy suggest varying solutions for collision avoidance and maintaining protective safe distances between active robot and the surrounding objects [6]. In an attempt to monitor the human-robot collaborative workspace and guarantee safety of humans a projection based sensor system is developed in C. Vogel et al, [38]. A visible area is projected around the robot to visualize the safe zone and later dynamic safety zones as shown in figure 14 are generated by linking the robot to the monitoring system to calculate the separation distance based on the current robot joint positions and the velocity of the robot.

Figure 14 Dynamic safety zone established around the cobot [38]

The projected safety zones are continuously monitored by a camera, which uses image processing to identify zone violations by comparing the camera's actual pixel locations to those predicted by the projector. Similarly in P. A. Lasota et al, [5] a real-time SSM system which is based on the measurement of the human–robot separation distance for accurate robot speed adjustment has been introduced. Although, in this approach a virtual representation of the workspace is constructed in a robot simulation environment that allows for the calculation of accurate separation distance data in real time. A sample workspace configuration and corresponding virtual representation are depicted in figure 15.

A similar idea of adapting a simulation environment to study parameters applicable for safety strategy in this thesis. The benefits of such an approach include visualization of a real environment virtually, implementation of different case scenarios, testing of different parameters and checking their influence, drawing reliable conclusions to further test in a real setup and in validation of the concept.



Real workspace Corresponding virtual representation

Figure 15 Real and virtual workspace for separation distance measurement [5]

The information on robot joint angles and the measure of the human positioning within robot workspace is derived from the robot controller and an external system for human motion capture respectively. Leveraging upon this real time information, the virtual workspace setup is updated and the separation distance between them is accurately calculated and relayed to the core program, which then transmits this information to the robot’s controller for speed adjustment. Another safety system for SSM consisting of tactile floor mat combined with projectors to display safety coloured zones is developed by R. Behrens et al, [39] .These safety zones are adjusted in relation with the robot speed and position (appendix E).

d) Power and Force limiting (PFL)

In order to fulfil safety conditions where robot can move freely in the collaborative workspace and allowing intentional contacts to occur during HRC scenario, the power and force limits (PFL) need to be applied on the robot to enable safety compliant operations. Rosenstrauch et al, in [40] an experiment was conducted using ISO/TS 15066, applying the PFL principle to a use case. A pick and place operation was analysed for a hazardous situation where there is a risk of the hand of a human operator being clamped, depicting a quasi-static contact condition. The allowed speed is calculated with equations and pressure and force limits given in ISO/TS 15066, interestingly it was shown that despite following the threshold limits in the standard document the application still can cause serious injury. To prove this Rosenstrauch et al, [40] simulate the scenario with a pork belly skin and the actual forces are measured by a force torque sensor. To demonstrate this the experimental setup is as shown in below figure 16.

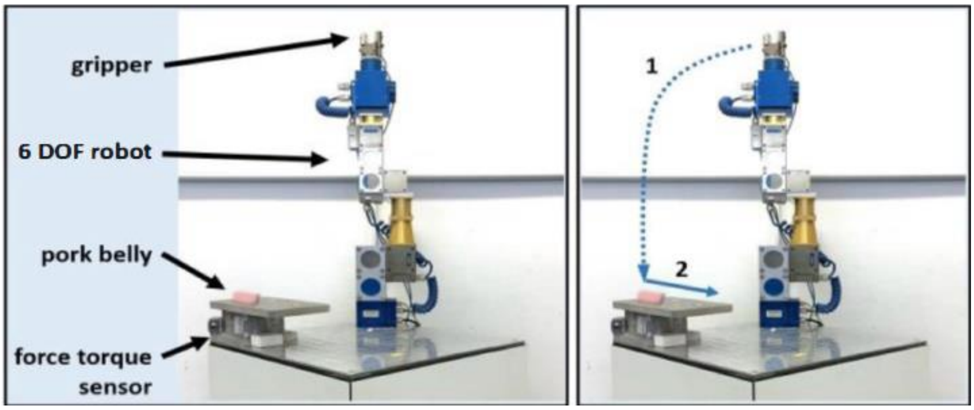


Figure 16 Experimental setup to analyse unsafe pick and place operation [40]

Severe damage to the skin could be seen despite applying 60% of the allowed clamping force. The results of this experiment depict the decreased but still existing gap between a feasible guideline for safety in human robot collaboration and the resulting real safety. The contributing factors for this gap are, too high threshold limits for the maximum permissible pressure during quasi-static contact which were derived only from one study, exclusion of sharp objects and unknown factors such as fast acceleration of human speed. Similarly, in this thesis to visualise unsafe contact situations and study the contributing factors for risk mitigation the same use case namely, the pick and place operation is adopted.

As opposed to the other three types of collaborative operation, PFL operation cannot be to prevent contact hence it is important to understand the risks involved and parameters affecting the same. For the purpose of studying the same, Björn Matthias et al,[41] considers an example application of a collaborative scenario where robots are operating according to PFL. A visual representation of typical workcells in cobots operating in PFL and the possible contact situations that may arise in this case is shown in figure 17 and figure 18 respectively.

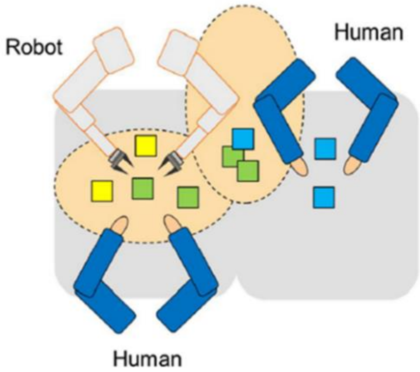


Figure 17 Typical workcell for cobots operating with PFL [41]

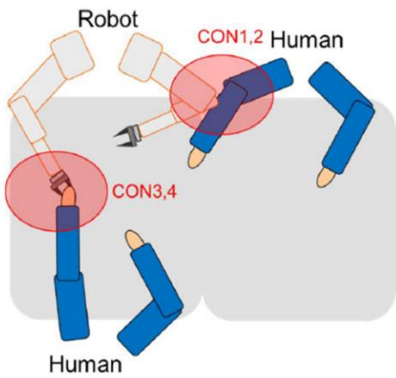


Figure 18 Representation of possible contact situations under PFL [41]

The risk assessment and study from the same research in [41] showed that limiting speed on the motion of parts of the robot manipulator can serve to mitigate the effects of transient impact by limiting the transfer of kinetic energy to the contacted body region, therefore it is worth noting that for transient events reducing the robot speed appropriately helps in managing their impacts. A similar principle is adopted in this thesis to formulate a safety strategy to reduce risks during HRC.

e) Combination of SSM and PFL

The SSM criterion needs additional hardware as it requires to monitor the worker position. In PFL, it does not necessarily need the adoption of additional hardware to monitor the workspace, as long as the velocity of the robot can be limited to safe values. The two safety criteria have different application scenarios however a meaningful combination of SSM and PFL would show substantial benefits in terms of productivity. To achieve high productivity whilst also maintaining safety of operation H. Shin et al, [42] combined the SSM and PFL method. They proposed a method of controlling the allowable maximum velocity even when the protective distance is violated. The allowable maximum velocity is calculated using a collision model that predicts the collision peak pressure and the peak force during a collision. The calculated pressure from the collision model is compared to the allowable pressure threshold from ISO/TS 15066 and current velocity of the robot to determine the safe velocity. This safe velocity is used to introduce a safety zone within the protective distance to increase robot operation efficiency. This idea to estimate the velocity at which the human is not injured in the event of the collision is used to propose a related safety strategy in this thesis to combine the benefits of safety with productivity.

In another research study by Lucci et al, [43] a safety algorithm based on the combination of SSM and PFL is proposed. This algorithm optimally scales the initial robot velocity whilst maintaining the consistency of the robot path. In order to check the benefits of such an approach, the authors apply and compare the methods of SSM and PFL both separately and in combination. The results show that in the combined approach productivity is higher (20% more than SSM, 460% more than PFL) as the robot is able to operate at higher speeds for a longer duration than when SSM, PFL are applied separately.

Another observation is that there is improved efficiency when the average distances between human and the robot is small (i.e tight collaboration) as for larger distances the robot reach its maximum safe velocity without being limited for safety by SSM or combined SSM-PFL. This is a key result favourable for this thesis as the study is based upon a pick and place operation that involves tight collaboration.

In Vysocky et al. [44] a motion planning approach that considers the safety limits as per ISO/TS 15066 and combines the safety modes of PFL and SSM is studied. In this study, Initially the relative velocity limit is calculated based on measurement of impact force of a co-working assistant (PaDY) against a tactile sensor and then motion planning is done in a manner that satisfies this relative velocity limit. In other words, if the relative velocity exceeds the safe velocity limits then the motion path is re-planned with a reduced value of relative velocity. For the motion planning the time of travel to the target and back to home position is modified and set based on calculated relative velocity to plan the new path. The experimental setup is as shown in figure 19.

Figure 19 Experimental setup for motion planning with PaDY[44]

The results of the experiment show an increase in the task completion time as per the proposed methods. The authors point towards the benefit of introducing safe velocity value in the motion planning phase of the robot as it helps in situations of object detection malfunction however suggest further research and experimentation in this area to reduce the task completion time for these proposed path methods.

2.2.6 Discussions on safety standards and safety in collaborative methods

From the literature discussed in the above sections several gaps are noted. In this subsection these gaps will be highlighted, first for the standards and next for the safety in collaborative methods.

A) Gaps in safety standards

The implementation of HRC solutions is limited by the current safety standards, even though guidelines as in as ISO/TS 15066 and standards for robotic devices exist, safety for HRC is still considered an important challenge[8], [29]. Some of the gaps pertaining to safety standards are highlighted as below.

- Risk analysis is usually not aligned with the standards

From the papers by several authors in [7], [23], [45] some important gaps are noted with normative standards, they do not specify particular safety assessment methods, consequently there is a gap to find an optimal combination between operator and robot's competences in various workstations therefore, it is still unclear how to bridge the criteria to satisfy hazard and risk analysis.[8]

- Varying Cobot application scenarios

In order to protect the physical safety of the operator, safety for collaborative applications and cobot regulation primarily focuses on the technological features of the cobot system. Further, the context in which cobots operate in an applied scenario is varying and that creates new risks[29].

- Parametric uncertainty with standards

The present guidelines are too general in this context and allows for multiple interpretation possibilities[40].Furthermore, the safety requirements in the existing ISO standards are not yet clear standards as it still has issues which are ambiguous and needs to be adjusted further. For example, in the case of safeguard mode 'Safety Rated Monitored Stop" (SRMS) which human parameters need to be detected by the vision systems and which robot parameter needs to be monitored during every level of interaction[35] is not defined clearly. As indicated in [39], the ISO/TS 15066 provides limit values which must be maintained by a collaborative robot in safeguard mode of "Power and Force Limiting" (PFL) however, these limits can only be applied for quasi-static contact type (clamping or squeezing) where speeds are low, the limits for dynamic contact or transient contact in the form collisions are still unaccounted. Additionally, in the same research paper, the limit values mentioned in PFL are only available for the intended use cases, limit values for the unintended contact due to foreseeable misuse is missing.

B) Gaps in safety of collaborative methods

Considering the use cases and examples of the four collaborative methods highlighted in the previous 2.2.4 section, it is observed that although these methods offer different measures of improving safety, they each have their own drawbacks.

- Safety rated monitored stop

Initially, in Safety rated monitored stop the robot needs to achieve a standstill while the person is in the robot's perimeter, if a software or hardware error occurs and human is not detected [35]then safety is compromised as collision is likely to occur. Also, in situations demanding close human-robot existence and interaction this mode of operation is not a suitable option.

- Hand guiding

Hand guiding mode has benefits of direct human interaction and can help in moving heavy objects however when it comes to operability and guarantee of safety during part handling or robot assisted motion, that still needs further research and development[46]. Improper hand guided forces, presence detection and speed limiting are important parameters.

- Speed and separation monitoring

In Speed and separation monitoring, protective safe distance, along with speed and position of operator are crucial parameters, the robot has to slow down or stop when the safety distance is breached, however there is still a chance of collision. In cases where the robot is carrying a work piece the safety can be an issue if the protective distance does not factor in the work piece dimensions as well, alternatively put it means that a collision can occur even if the robot is still within its limits and the work piece dimensions are not considered. Another consideration of SSM is that direction of travel is not considered in the equation, therefore it means that an operator can trigger a safety stop even if moving at a different direction of the robot's path in the safe zone, the disadvantage being it can lead to unnecessary stops in production cycle[47].

- Power and force limiting

Finally, in power and force limiting applications the downside is determining safe biomechanical values at different body points. At the moment the study conducted in ISO/TS 15066 is for an individual test case and considers lightweight robots and not heavy industrial robots[40], therefore an incorrect standard value could prove to be hazardous in real time applications. The limit values which appear in the ISO/TS 15066 are applicable only for the intentional contacts, the limit values for unintended contact due to foreseeable misuse is currently missing, as a result there is no safe value limits for all contact type situations [39].

Considering all the aforementioned drawbacks our research prompts to study the possibility of combining more than one safe collaborative mode to investigate possible benefits that can be derived in an HRC application. Additionally, drawing motivation from [42], the combination of speed and separation monitoring and power and force limiting is considered. To create a robot safety system capable of incorporating the mentioned safety modes in a commercially available robot, a safety framework is proposed and later on simulation study is conducted to validate the same.

3. PROPOSED SAFETY FRAMEWORK

In this chapter the safety strategy for risk mitigation is discussed. Initially the concept formulation consisting of various steps is explained, followed by an explanation of the proposed safety framework depicted by a flowchart. The chapter concludes with the explanation of different steps involved in concept implementation.

3.1 Concept formulation

The goal is to generate a concept that combines the SSM and PFL for a pick and place operation. The benefit lies in overcoming the disadvantages of these individual (SSM, PFL) methods, mainly the avoidance of unnecessary stops and control of velocity of the robot for enabling safe human robot interaction in close proximity situations. The idea is that with a safe value of velocity the limits of force on impact and energy transferred during impact can be controlled and the cobot need not frequently halt its operation. In this study the safety methods are applied in a unique safety framework, developed to achieve the advantages of safety and productivity in a pick and place HRC scenario. To achieve this the below steps are defined.

Step 1: Define the boundary of collaborative workspace

Even though there is a need for more intuitive and effective HRI methods to raise the usability and performance of HRC, these methods should be developed in accordance with safety standards [37] As long as the industrial robot operates in its allowed operating space, the general rules of safety are applied (robot stops immediately when someone enters the robot workspace). As robot enters into collaboration workspace, the standard ISO 15066 is applied. The research in this study concentrates mainly on collaboration workspace and the issues with safety that arises during operation in that pick and place HRC scenario.

Step 2: Defining the parameters

The necessary parameters to consider for developing the framework includes the contributing variables from safety method research examples as mentioned in the previous section of both the SSM([5] ,[39]) PFL([40],[41]) descriptions, these include the estimation of a safe distance between operator and the robot, safe speed of the robot, explained in below paragraphs. Additionally, the standard values of the energy transferred, bio-mechanical limits of the human at various points of collision from ISO/TS 15066 need to be considered.

Step 3: Calculation of the separation distance

A) Description of equation

As per Speed and Separation Monitoring (SSM), the protective separation distance between the robot and the human is crucial to avoid accidents that can occur during operation.

The protective separation distance, can be described by below formula as mentioned in ISO/TS 15066 [9]:

$$S_{safe}(to) = S_h + S_r + S_s + C + Z_d + Z_r \text{ ......(1)}$$

Where,

$S_{safe}(t_0)$ = protective separation distance at time t_0

S_h = operator's change in location, meaning the operator movement while the robot is stopping (mm)

S_r = the reaction time of the robot system, as the travelled distance of the robot before the braking is initiated (mm)

S_s = stopping distance of the robot while the robot is braking (mm)

C = intrusion distance based on the expected reach of a body part into the safety area before the laser scanner detects the human's leg. (mm)

Z_d = position uncertainty of the operator as the measurement tolerance of the sensing devices (mm)

Z_r = position uncertainty of the robot (mm)

This equation can be further simplified as below, from [47]

$$S_{safe} = (v_h T_r + v_h T_s) + (v_r T_r) + S_s + (C + Z_r + Z_d) \text{.........(2)}$$

Where,

T_r = the reaction time of the robot system, including the required time for detecting the operator's position with e.g. a laser scanner, signal processing and stop activation, but excluding the time until the robot stopped (s)

T_s = stopping time of the robot, from the activation time point of the stop signal until the standstill of the robot. It is a function of robot speed, load and motion path (s)

v_h = directed speed of the operator towards the robot, which can be either positive or negative depending on the direction of the movement (mm/s)

v_r = directed speed of the robot towards the operator, which can be either positive or negative depending on the direction of the movement (mm/s)

It is to be noted that the value of C, Z_r,Z_d depend upon sensor capability and performance which is outside the scope of this research and hence the intrusion and uncertainties of robot and human are considered zero. T_s, T_r are considered from product specification document of considered cobot [48].

B) Selecting the right velocity parameter for the velocity of the robot

It is observed from equation 2, the safety distance is directly dependent on the velocity of robot in the direction of the operator, velocity of human, braking distance and the robot travelling distance during reaction time. In this study the focus is on the velocity of the robot, parameters such as the braking distance, reaction time and velocity of human are already known from standard documents respectively[48],[46]. Furthermore, as the velocity of the robot increases, the minimum protective distance increases proportionally [47]. Therefore, the velocity of the robot is chosen based only on human-robot distance, however as we are progressing towards applications that involve more involvement of human and robot collaboration in a shared workspace, this velocity parameter is critical as it tends to affect the work productivity.

Step 4: Define safety zones considering velocity of the robot

To elaborate further, in situations where the human is stationary outside the path of the robot or when robot and human are moving away from each other, it is still possible that a safety stop is issued due to the value of the minimum safety distance and in such cases it leads to multiple unnecessary stops during the entire operation. As a result, the velocity estimation should be such that there is safety as well as productivity ensured during an operation. Hence, a plan to introduce a speed reduction zone where the operator and robot are both moving however the robot is moving at a reduced speed is formulated. This intermediate zone is established between the protective separation distance and the minimum distance to the robot. Figure 20 shows the different safety zones and the transition from the conventional strategy (figure 20. A) to the proposed strategy (figure 20. B).

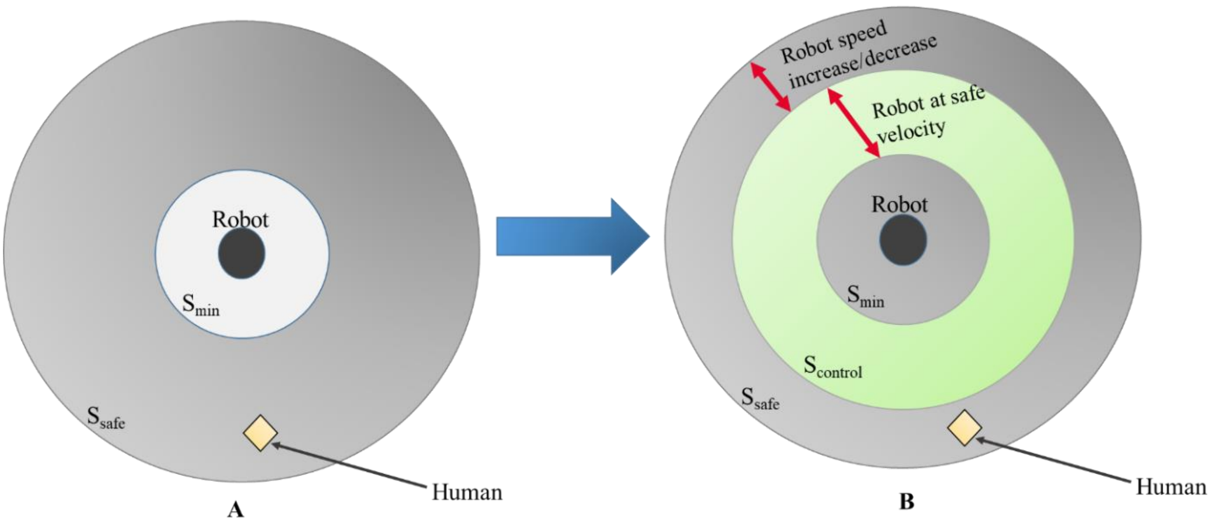


Figure 20 Explanation of different safety zones, conventional (A), proposed strategy (B)

In this figure there are three distances are observed namely, S_{min}, $S_{safe,}$ $S_{control}$.S_{min} is the minimum separation distance at which the robot should come to a standstill, breaching this distance would mean a guaranteed collision as the human would be in the robot workspace, S_{safe} this is the protective separation distance at which the robot is issued a safety stop when human enters the collaborative workspace, this is measured considering the distance between the robot arm and the human, $S_{control}$ is the distance calculated newly to introduce a speed reduced zone for avoiding unnecessary stops, the calculation for this is as explained in the next subsection. As per the conventional principle whenever the human enters the S_{safe} zone the robot is at standstill, whereas in the new proposed approach the robot velocity is reduced despite the human entering the S_{safe} zone and the robot operates at an estimated safe velocity in the $S_{control}$ zone. The commonality between both A and B is that the robot is at standstill when S_{min} is breached.

Step 5: Calculation of safe velocity for robot operation

In order to implement the above $S_{control}$ zone, the safe velocity that is allowed in this zone needs to be determined so that incase of any foreseeable contact it is not dangerous. For this, Power and Force Limiting (PFL) is referred, as per PFL intentional contact is allowed in its applications, however in this mode the safety is assured by ensuring that during an operation, the limits impact force or energy transferred of the robot particularly for the considered body region are not exceeded as per the values mentioned in ISO/TS 15066 [10], these limit values are shown in appendix F. The two governing equations for controlling the force and energy transferred dependent on speed are also mentioned in the same document.

A) Force-velocity

The relation between force and velocity is given as below from ISO/TS 15066 [10].

$$V_{rel,max} = (\mathrm{F_{max}})/\sqrt{\left(\frac{1}{m_h}+\frac{1}{m_r}\right)^{-1} * k} \quad \ldots..(3)$$

Where,

$V_{rel,max}$ = maximum permissible robot speed (mm/s)

m_h = the effective mass of the colliding body region (kg)

m_r = the effective mass of the robot (kg)

k = the effective spring constant to consider the deformation of the colliding body area and its energy absorption (N/mm), refer appendix F for values of spring constant as per different human body regions.

B) Energy transferred-velocity

The transferred energy is related to the robot speed as follows:

$$\mathrm{E} = \frac{1}{2} * \mu v_{rel} \ldots\ldots.(4)$$

Where,

v_{rel} = the relative speed between the robot and the human body region

μ = the reduced mass of the two-body system, which is expressed by below formula

$$\mu = \left(\frac{1}{m_H} + \frac{1}{m_R}\right)^{-1} \text{……..(5)}$$

mh = the effective mass of the colliding human body region (kg)

m_R = the effective mass of the robot (kg), which is the combination of total mass of moving parts of robot(M) and the effective payload(m_L)

$$m_R = \frac{M}{2} + m_L \text{……..(6)}$$

Hence from the above relations in (3) and (4), it is observed that the reduction of the impact force or the energy transferred during a contact scenario can be achieved by reducing the relative velocity between robot and human. At this point, this velocity as obtained from PFL is important because using the value of this velocity the safety distances in equation 2 can be calculated for the $S_{control}$ in SSM and in this way the combination of principles can be utilized.

3.2 Proposed Safety Framework

Using the above steps, a flowchart proposing this safety strategy is as shown in figure 21. The flowchart consists of different conditional checks and operations contained within the basic process start and a process end steps. The flow chart is mainly divided into two main regions, the SSM zone and the PFL zone as highlighted in red in the figure. The flowchart indicates an initial application SSM principle and then progresses towards the intended PFL application. The call-out bubbles are used to indicate information also mentioned in other sections of this report.

Elaboration of flowchart safety process

- Human detection

At the start, the human enters the workspace to perform the assigned task, as is the case for SSM, it requires safety sensors or vision technologies are used for detection of humans in safety zones. Human detection can be employed using varying commercially available technologies, such as Microsoft Kinect for motion detection, for this study research about sensor types and their technologies are out of scope and hence the human detection for this study is considered to perform at its best. After the detection signals are conveyed from these sensing technologies to the robotic controller to issue stop or resume motion of the robot arm.

- SSM block

The output from these sensors mainly consist the information of whether the human is in violation of the safety zone, in other words the distance between human and the robot is initially estimated and is checked to ascertain safety situation, this is indicated by the first conditional check of $S_{min}<S_{safe}$,

depending upon the situation the next step is performed. In case the distance is lesser than S_{min} the stop signal is issued as the human and robot are too close with each other and safety is compromised

If the distance is larger than the operation continues with the human moving inside the S_{safe} zone, a collision scenario could still persist and be hazardous for the human as the velocity of robot in this zone, configured initially is not decreased. Hence it is necessary to minimize the impact injury that could occur and the data resulting from a collision scenario, mainly the impact forces and the energy transferred are estimated considering this initial robot velocity, this is done to compare these values with the specification limits as described in the ISO/TS 15066 document and mainly to calculate the value of safe velocity and safe controlled distance that can be implemented in the reduced speed zone ($S_{control}$).

- PFL block

After the safe velocity and distance values are calculated the operation continues forward towards the intended PFL application. Therefore, it is to be noted that prior to performing the PFL application the velocity of approach of the robot is already at a reduced value than its initial value and this is important for PFL as the reduced velocity implies a lower value of impact force on the operator and in this way enabling lower chance of injury and risks.

During the PFL operation the collaborative task is continuously monitored for collisions and is executed till completion till safe conditions exist however, if an unsafe condition exists then it means that the robot is operating at an unsafe velocity and hence should come to a safety stop. The velocity for safe operation needs to be estimated further and the loop should be repeated such that the conditions are safe for task completion.

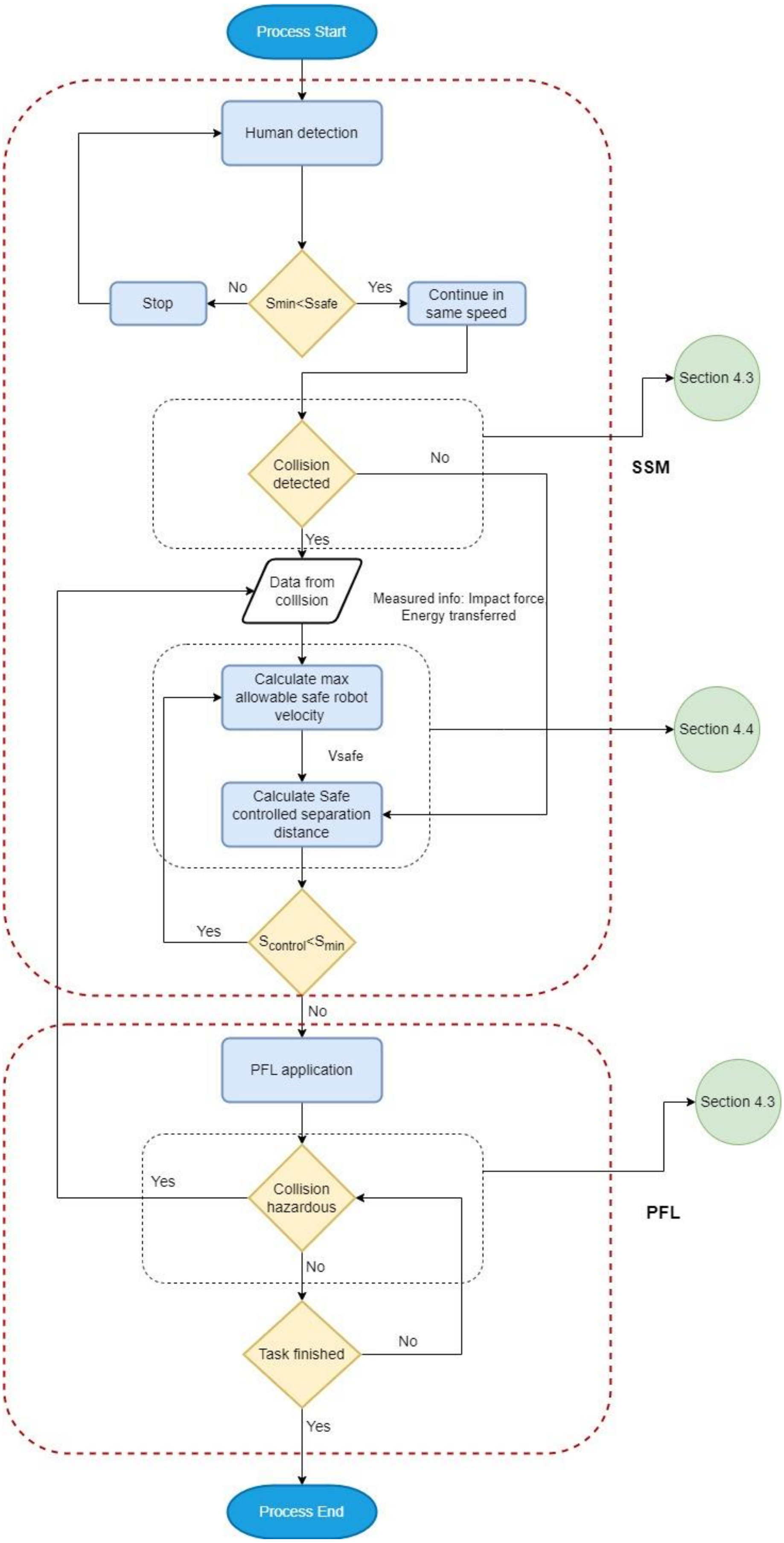


Figure 21 Proposed safety framework

3.3 Concept implementation

The implementation of the proposed concept is done in three steps, initially we consider the safety methods individually to estimate the first set of values and also to depict the distinction between applying the safety methods separately and in combination. Therefore, in the first step we estimate the safety zones as per SSM to estimate the minimum distance and the protective safe distance followed by the impact force and energy transferred values in PFL in the next step to compare with the standard values in the ISO/TS 15066 document and finally in the last step we combine both the principles by estimating the safe velocity from PFL and in turn the safe controlled distance for SSM.

1) Calculation of safety zones(SSM)

The protective safety distance (S_{safe}) and the minimum safe distance S_{min} are the two distances which are calculated for just applying the SSM. Figure 21 below illustrates the safety zones during just an SSM case.

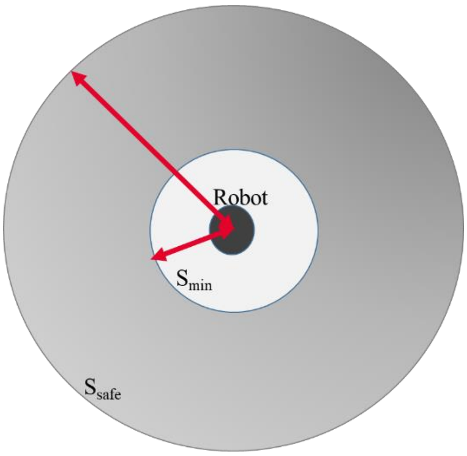


Figure 22 Safety zones during only SSM

Protective safe distance S_{safe} is given by equation 2 as mentioned previously.

$$S_{safe} = (v_h T_r + v_h T_s) + (v_r T_r) + S_s + (C + Z_r + Z_d) \text{ ....(2)}$$

Minimum separation distance S_{min} is the distance at which the robot has to be at standstill at all costs therefore the velocity of robot v_r is zero, reaction time of robot T_r and braking distance S_s are also zero, from [42]

$$S_{min} = v_h T_r + C + Z_r + Z_d \text{.......(7)}$$

Upon substituting the considered parameters, the two safe distances are calculated.

2) Calculation of impact force and energy transferred (PFL)

PFL deals with contact scenarios and hence in this safety method the information about impact force and energy transferred are required as per the body region considered and as per the contact type (Quasistatic or Transient), the maximum allowable limits are calculated for comparison with the limit values as in ISO/TS 15066 (see appendix F) document as below:

Impact force is given by,

$$F_{max} = v_{rel,max}\sqrt{\mu * k}\ldots\ldots(8), \text{ modified from equation (3)}$$

Energy transferred is given by equation (4) ,

$$E = \frac{1}{2} * \mu v_{rel}^2 \ldots\ldots(4)$$

Upon substituting the considered values, the resulting parameters are estimated and then compared with the specification limits in the ISO/TS 15066 document.

3) Calculation of safe velocity and safe controlled distance values (PFL-SSM)

The proposed framework consists of an approach to combine the PFL and SSM principles.

Initially the maximum safe allowable velocity is calculated from equations (3) and (4) of PFL. The values of other parameters in these equations are known beforehand, for the values of maximum permissible limits for force and energy transferred they are obtained from ISO/TS 15066 document as per the specific body region (see appendix X)

$$V_{rel,max} = (F_{max}) / \sqrt{\left(\frac{1}{m_h} + \frac{1}{m_r}\right)^{-1} * k} \ \ldots\ldots(3)$$

$$E = \frac{1}{2} * \mu v_{rel}^2 \ldots\ldots(4)$$

V_{safe} is the lower value resulted from above two velocities, as considered from[40]

Next the safe velocity value obtained from PFL is substituted in the equation (2) of SSM to achieve the safe velocity controlled zone, $S_{control}$

$$S_{control} = (v_h T_r + v_h T_s) + (v_r T_r) + S_s + (C + Z_r + Z_d) \ldots\ldots(9)$$

In this way there are three safety zones and a safe velocity, these zones are illustrated by the red, orange and green colored arrows in figure 23.

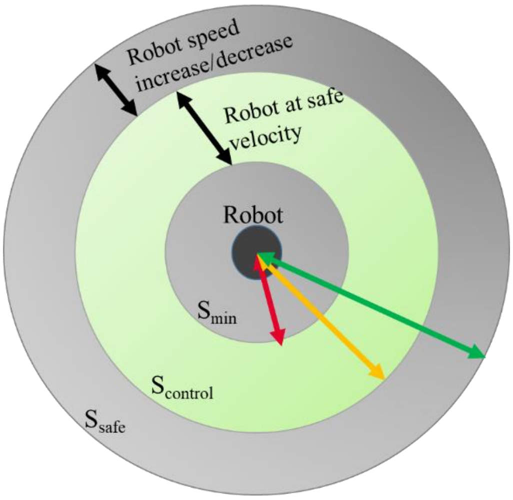


Figure 23 Safety zones during PFL-SSM

In this way the velocity of robot for PFL and SSM operations are applied together. Additionally, the values of impact force and energy transferred during a possible contact situation in this case is also compared with the standard values to observe the effectiveness of the safety strategy.

Summary

It is observed from the above steps that in the case of applying safety principles individually that the task is not yet optimal. To elaborate further, in SSM the safe protective distances for initiating protective stop and complete stop are calculated however in this mode of operation the cobot functions in a way that there are unnecessary multiple stops during the operation even when the operator has no involvement with interacting with the object or cobot just because of being present in the calculated safety zone. In the PFL situation, it allows scope for intentional contact and the ISO/TS 15066 states limits of force and energy transferred however the velocity at which the cobot can move safely in order to minimize dangerous injuries during unintentional contact situations still needs to be determined. Considering these disadvantages, the safety principles were combined to arrive at a safe allowable velocity (V_{safe}) in which the collaboration can occur for unintentional contact situations and further this safe velocity is used to calculate an intermediate safety zone ($S_{control}$) such that the cobot operates at a reduced speed zone and multiple stops can be avoided during the operation. The implementation of this concept is shown numerically and results are discussed in chapter 5

4. PROOF OF CONCEPT

In this chapter the different steps involved in developing the proposed strategy is explained. Initially a brief outline is given followed by the in depth explanation of each of the steps.

The proof of concept is done by testing the proposed framework in a suitable case scenario and further evaluating the results against the performance criteria. The success of the framework depends upon decreasing the impact force due to collisions in a collaborative operation such that they are within the limits as stated by ISO/TS 15066

The process of developing a safety concept for HRC can be divided into several steps:

- Step 1: Description of Case scenario
- Step 2: Hazard study
- Step 3: Simulation
- Step 4: Evaluation of framework

From the above steps, initially the considered case scenario for depicting HRC in this thesis is described, followed by a hazard study, here the different steps to identify and list potential hazards are explained. At the end of the hazard study one potential hazard is selected as a use case for simulation. In the simulation step, the description of creating a virtual environment along with the different steps involved in modelling and testing the selected hazard use case are explained. Lastly, considering the simulated use case, the framework is evaluated by calculations as per steps described in previous section (3.3 concept implementation) for results and discussions.

4.1 Step 1: Case scenario description

An example of an automotive case study from [3] is used as shown below in figure 24, which shows the overview of an HRC cell in 3D and the corresponding actual physical setup.

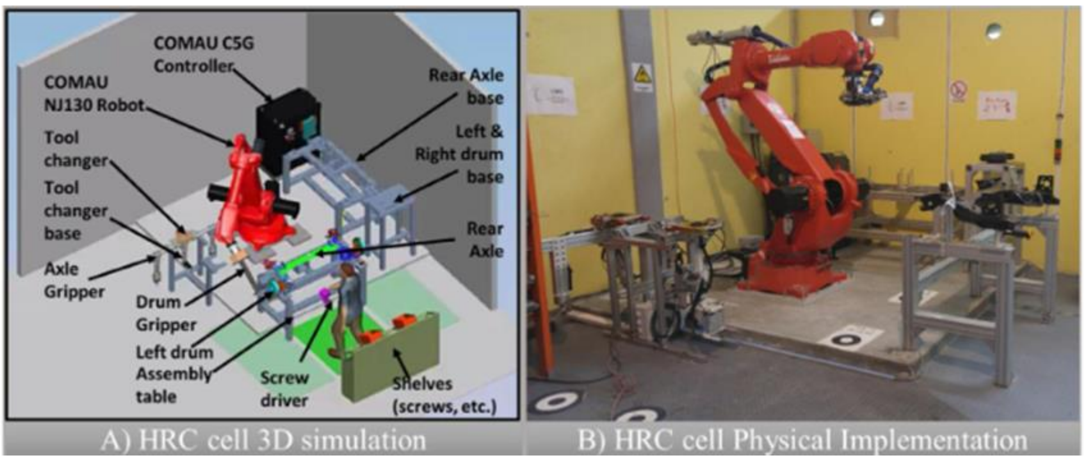


Figure 24 An automotive case study example for HRC [3]

The job performed is of a rear axle assembly in an automotive industry. The scenario involves two main tasks, loading of the rear axle on the test bed and the assembly of the wheels on the left and right side of the axle. The robot performs the handling of the heavy parts whereas the operator intervenes in between the operation to perform roles requiring dexterity (attaching cables and screws) as in below figure 25.

Figure 25 Manual tasks in the HRC test bed[3]

In order to construct a case scenario suitable for this thesis, the scenario from [3] is modified into a simple collaborative application namely the pick and place operation for further steps in simulation. The loading of the rear axle and wheels by the robot denotes the **picking operation** and the assembly of the wheel in the right place on the axle denotes the **place operation**.

Therefore, in the simulated scenario the cobot picks an object from a starting point and delivers it to its final destination along a predefined path as shown in example figure 26.

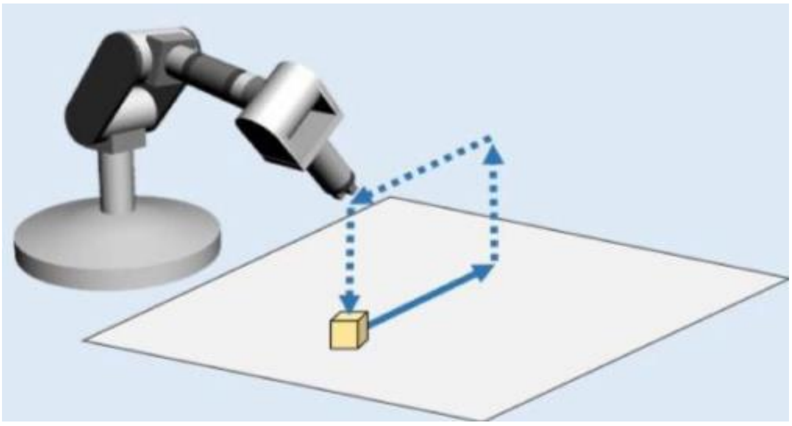


Figure 26 Example of pick and place task [40]

after the cobot has placed the object at its final location it returns to its original home position and resumes the operation for placing the next object. The operator intervenes in between to inspect and set the object in order before it is sent to its end destination as shown in figure 27.

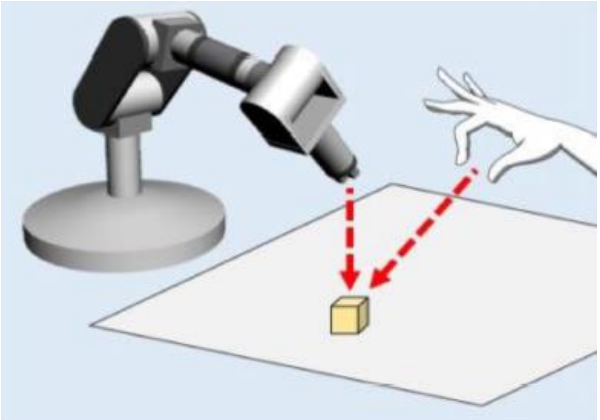


Figure 27 An example to show operator intervening in between task*[40]*

The task is successful if the correct object is picked and placed at its intended location without any safety issues during the entire operation, if the required object is incorrectly picked or the operator needs a different object to be transferred to end location, then the operator has to stop the motion of the cobot and interact in the collaborative workspace. Additionally, for a safe and successful operation, the cobot should consider the safety modes of operation, namely the speed and separation monitoring (SSM) and power and force limiting (PFL) as explained in the previous section 2.2.4, to implement in our proposed safety framework.

Next, potential hazardous situations are identified and listed followed by simulation of a selected use case for gathering information, for testing the proposed safety framework, these are explained in the further steps.

4.2 Step 2: Hazard study

4.2.1 Hazard study- Implementation of Hazop-UML

With the aim of testing the claims of the proposed safety approach, the next step in research is to conduct an experimental study. The objective of this step is to apply the Hazop-UML method to identify the hazards in operational phase as briefed in the previous section. The background and theoretical aspects related to this method are explained in appendix A.

It consists of following steps

A) Hazard use case definition
B) Creation of sequence diagram as per UML
C) Creation of Hazop table from sequence diagram

A) Hazard Use case definition

To achieve the experimental objective, as a first step, all relevant use cases descriptions involving the risk of physical contact between the operator and the robot is to be listed.

To develop the description of use case :-robot states, human role, nature of task need to be known[33].

The following robot states:

- Manipulation: Robot arm picks up or places a product
- Navigation: The robot's arm is moving towards to a target
- Idling: Robot is standing still because it is either waiting for the next task or had some technical problem

Next we define the roles of the human operator, these depend upon their expertise level and the type of collaborative interaction. The interaction types considered for the considered pick and place operation include collaboration, co-existence and co-operation as most of the actions arise from these three types of interaction levels.

For the pick and place case scenario considered previously, we describe different human roles in table 5 for having a broad perspective of the types of humans that could enter the workspace. A "skilled" person is one that has undertaken the necessary safety certification courses and "trained" denotes that a training to work collaboratively with robots have been attained. These include instructions of coming close-by the robot, understanding robot behavior (e.g. robot gradual speed reduction when the human gets closer) or even making physical interactions with it. For the pick and place case scenario only one human operator, skilled and trained is considered respectively. In summary, table 5 depicts the use case descriptions along with the human role and the robot stages.

Table 4 Hazard use case descriptions

		Human role			
Use case	Description	Type	Expertise	Nature of task	Robot state
UC01	The worker interacts with the robots in a collaborative way (working very closely to robot) while placing products on the shelf.	Co-existance worker	Skilled, trained and experienced	Collaboration	Navigational
UC02	**The worker takes different products from the storage and places them on the shelf, from where the robot will pick up the products and delivers them to the conveyor belt. The products should be carefully positioned so that the robot can easily pick it up. If it is placed at an unusual position or shifted, then the robot may have difficulties or may be unable to pick it up.**	**Collaborative worker**	**Skilled, trained and experienced**	**Collaboration**	**Manipulation**
UC03	A worker needs to remove items on the floor/to that the robot has dropped. When it happens, the worker enters the collaborative area and goes towards the dropped item. He/she is comfortable to come close to the robots in a safe way to perform its task, without interfering the robot's activities.	Co-existance worker	Skilled, trained	Co-existance	Navigational
UC04	If a robot breaks down during its operation or a deadlock occurs in the system, then the manager sends a technician. The worker enters in the collaborative area to replace or move out the robot in the presence of other working robots.	Co-existance worker	Skilled, trained	Co-operation	Idling/Maintenance
UC05	A visitor gets inside the warehouse and moving in the warehouse along with other mobile robots. He/she also observes the pick up operation around the shelf and may like to place the products for the robot or wishes to touch or come close to the robot.	External visitor	Untrained	Collaboration	Manipulation

B) Creation of sequence diagram as per UML

UCO2 from table 4 is taken from the table as we consider a pick and place scenario for our research study. A sequence diagram is constructed from the considered use case to determine the attributes necessary to identify the respective deviations. Here the different steps involved in the operation is identified and a functional description is given. Initially it is necessary to describe the interactions between the two actors, namely the operator and the robot to identify the different instances at which a potential hazard can occur Figure 27 as shown denotes the various interactions between human and robot and the order in which the collaboration takes place. The various attributes which contribute to the safety assessment are indicated in purple in the image.

C) Creation of Hazop table from sequence diagram

From the attributes in the sequence diagram, deviations are identified with the help of guidewords. These deviations denote the various hazards that can occur for a particular use case. There shall be many such attributes during a human-robot interaction, these are listed in a table in appendix B, however to narrow down the options for simulation one attribute is extracted from that table and is shown below in figure 28.

Attribute	Guide word	Deviation	Hazards
Pick object from user	No	No signal is received for operation	The robot does not pick up the object
	Other than	Robot recieves signal but picks object other than the one intented	human moves close to correct error, robot grips accidentally
	As well as	Message is sent as well as another message	The robot moves out of sync
	More than	More than one message is sent	human moves close to correct error, robot grips accidentally
	Less than	Message is sent less than intended	The robot moves out of sync
	Before	Message is sent before the completion of previous operation	The robot moves out of sync
	After	Message is sent after the completion of previous operation	The robot moves out of sync
	Part of	Only pick object is mentioned but from user is not specified	The robot fails to release product
	Reverse	To and from end locations for robot is reversed	The robot moves out of sync

Figure 28 List of identified hazards

The above attribute, “picking object from the user” is selected as it depicts collaboration in which there more frequency of interaction of the human hand with the cobot to perform a required action in the shared workspace. Additionally, since there is no crushing form of contact (quasi-static contact) that can occur during this considered hazard use case, the contact type considered for this hazardous use case is the transient contact type. Speeds will be higher for this contact type as compared to quasi-static and since in this mode cobot speeds are higher the back of the hands and fingers is the region of focus for safety during this interaction as this region is the closest part of the human interacting with the cobot for which the limit. Furthermore, the considered attribute is used to recreate the hazardous situation in the simulated environment briefed in the subsequent section to visualize and understand the breach of safety limits on the human operator.

4.3 Step 3: Simulation

As the identified hazard occurs during an operational phase, the simulation will also reflect the same. It is based on a collaborative scenario of an environment where a hazard occurs when the robot supports a person in a handling task. The section below gives an explanation of the setup of the simulated environment and the input parameters used. In the end the expected outcomes from the simulation is discussed.

4.3.1 Simulation environment

The simulation environment is built in RobotStudio, and will consist of an operator, the robot YuMi, placed on a platform and an object that needs to be displaced. Due to the fact that only collision scenarios need to be visualized, the operator is positioned stationary at the instant that collision occurs.

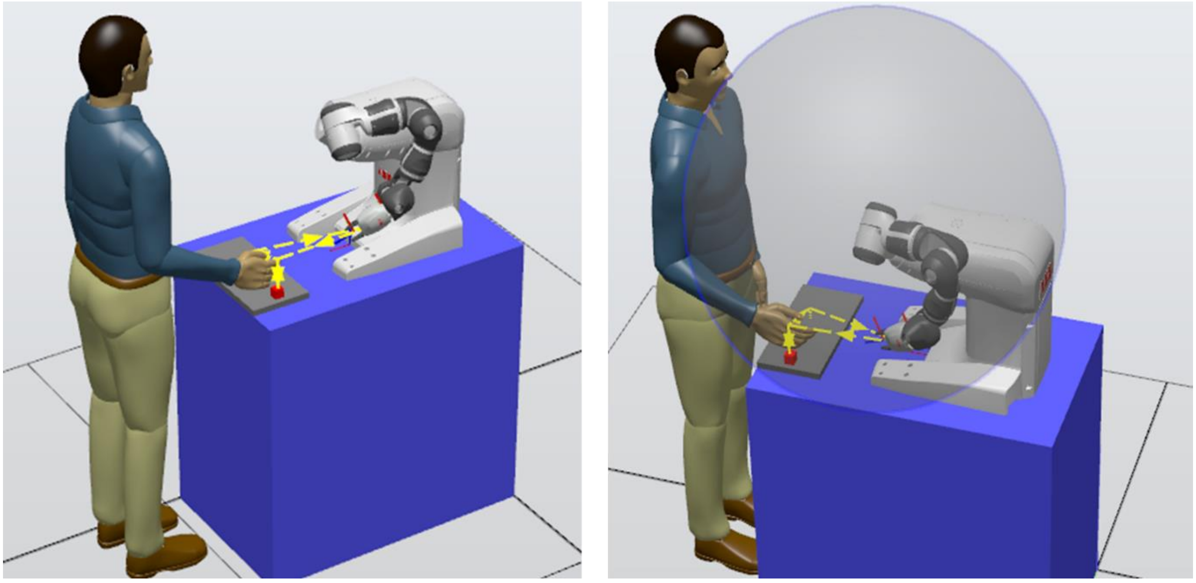


Figure 29 Hazard use case setup in RobotStudio

Figure 29, shows the hazard use case setup built in RobotStudio, the work piece is symbolized by a cube, shown in red and is picked from a starting point and delivered to its intended location. The yellow lines indicate these path lines.

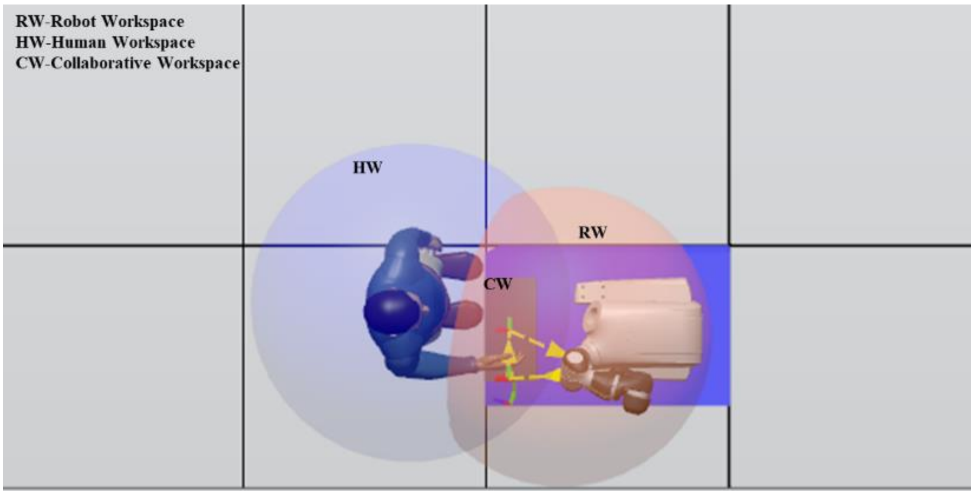


Figure 30 Different workspaces in the simulated environment

Figure 30 depicts the different workspace zones, collaborative workspace CW is the zone where both human and the cobot may interact, the robot workspace is the area which needs monitoring and requires additional safety measures and the human workspace is the region the human is allowed to roam around freely.

4.3.2 Parameter discussion

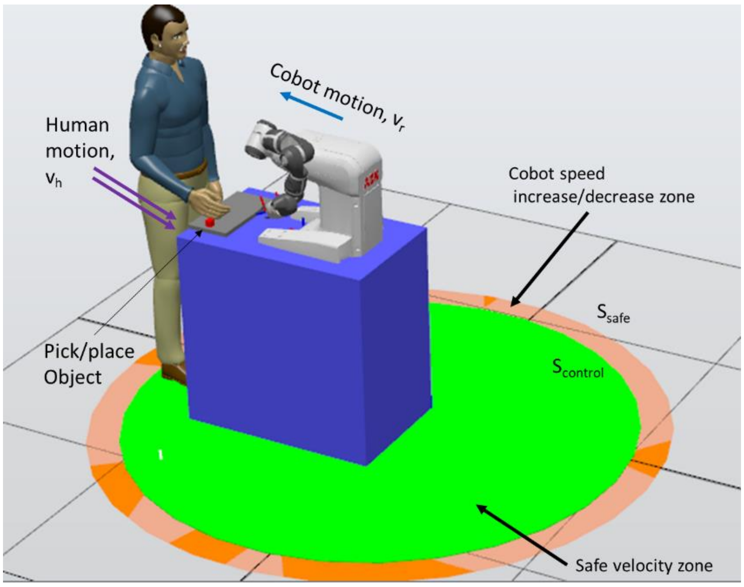


Figure 31 Pick and place collaboration

Figure 31 depicts the simulation environment for a pick/place use case scenario. The human and cobot are interacting in this situation to perform the task, this figure also depicts the variables influencing safety, i.e. the speed and distances. The human motion is shown by V_h (m/s) and is moving towards the cobot to pick up the object, V_r (m/s) is the cobot speed, the safety distances, namely the protective separation distance S_{safe} and control safety distance $S_{control}$ are shown accordingly in the colored zones. Another distance parameter not shown in the figure is the minimum distance S_{min}, this is the distance at which the robot motion should come to a standstill at any costs if breached by human.

The list of parameters concerned in this simulation are summarized in below table 5.

Table 5 Concerned parameters

	Parameter	Description
Velocity	V_r	Velocity of cobot
	V_h	Velocity of human
Distance	S_{safe}	Safe protective distance
	$S_{control}$	Safe control distance
	S_{min}	Minimum separation distance

4.3.2 Performing the simulation

The cobot is initially set at its home position and then it is made run along the predefined path created for the operation. The operator is positioned stationary such that it mimics the contact position at a particular instant of the robot's operation. The simulation is run with a fixed configuration, the one that allows the robot to reach the object and move along the path predefined. The most interactive parts during a collaboration the hands of a human as this part intrudes into the collaborative workspace repeatedly during tasks and therefore has higher risk of collision, specifically the back of the hands is considered and the standard values (spring constant k, permissible impact force and energy transferred) as applicable to this part is obtained accordingly from ISO/TS 15066 [10]. As a result, for simulation purposes only one region of human operator is considered and hence multiple configurations and different trajectories of the robot are not required.

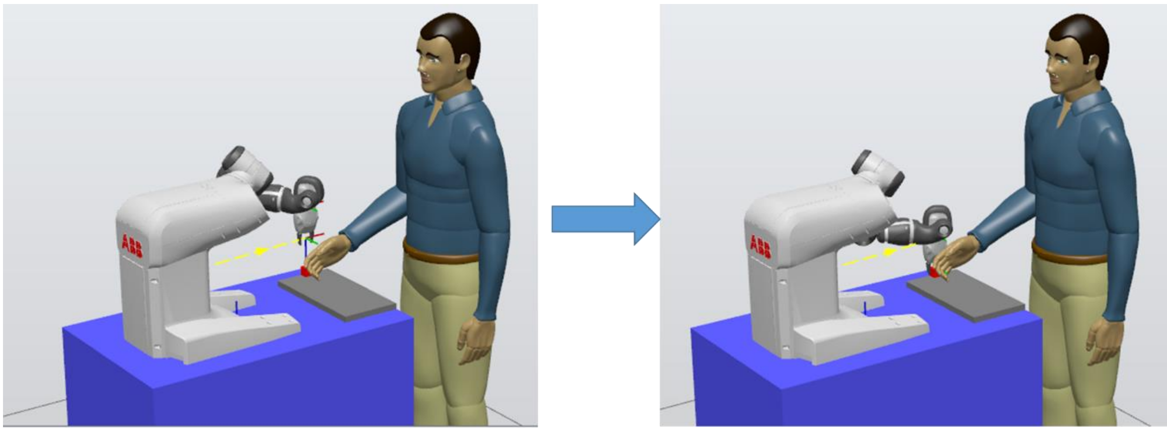


Figure 32 Hazardous interaction

Figure 32, visualizes a hazard situation during simulation when the cobot and human are interacting with each other, here the cobot reaches for the object and at the same time the human is also reaching for the object. The hazard that can occur in this case is the collision of the robot gripper with the back of the hand resulting in injury.

For generating different simulation under this scenario, three varying cases based on motion of human and cobot are considered as below

A) Human is stationary and cobot is in motion

The object has been placed and the human (specifically the hand) in this position is considered to be stationary whilst being in the path of the robot motion as shown in figure 33. Hence in this situation only speed of cobot v_r is considered.

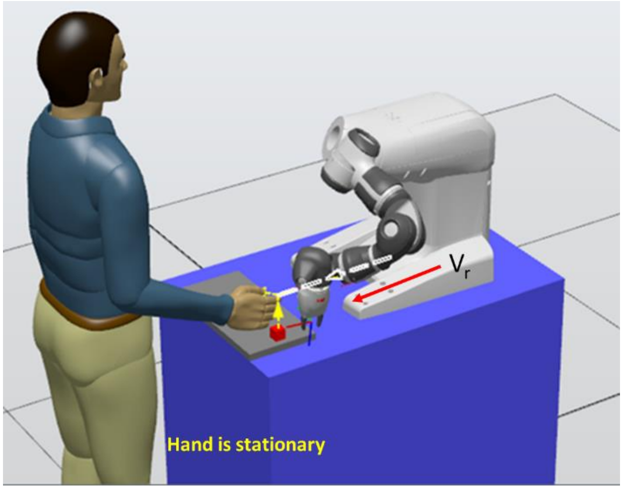


Figure 33 Only cobot motion

B) Human and cobot are in motion

In this situation both the human and cobot are in motion as depicted by the arrows in the below figure 34. Hence in this situation speed of human v_h and speed of cobot v_r is considered.

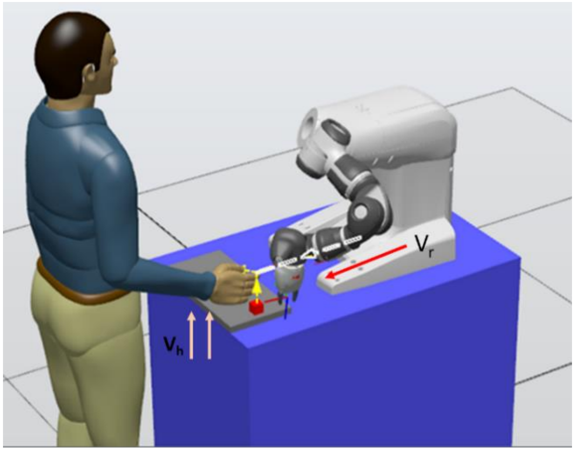


Figure 34 Both human and cobot are in motion

C) Human is in motion and the cobot is stationary

In this situation the gripper of cobot arm hovers over the target and is stationary, whilst the human is reaching for the object as in figure 35. Hence in this situation only speed of human v_h is considered.

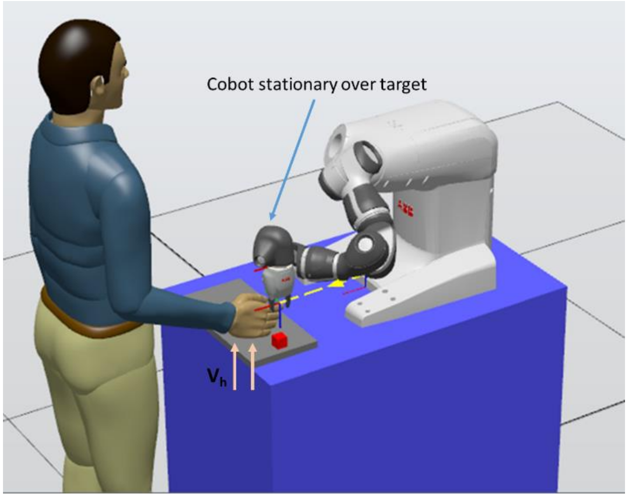


Figure 35 Only human is in motion

In summary, the above three cases are simulated as hazard cases in RobotStudio.

The inputs for the simulation in RobotStudio is velocity of the cobot, and the worst case value of human motion v_h (2 m/s, from as per ISO/TS 13855).

The outputs measured as a result of these collision scenarios is impact force and energy transferred as per respective equations (3),(4) from PFL, these are calculated and shown in the next chapter.

4.4 Step 4 Evaluation of Framework

In this step the main objective is to calculate the impact forces and the energy transferred by the robot during the hazard scenarios simulated in previous section. The calculations as per individual and combined safety principles is shown. Further a summary of the calculations and results and discussion of contact at different body regions is given.

A) Data preparation

Before the calculations are done, initial data considerations are required for calculating the required parameters. This data is accumulated from standard documents and from estimations. These are shown in below table 6 accordingly. The data shown in red are considered from ISO/TS 15066 document, the other values are estimated from calculations.

Table 6 Initial Data considerations

Body region	-	Hands & Fingers
Spring constant K	-	75 N/mm
Effective Mass of Human body region m_H	-	0.6 kg
Effective Mass of robot M_R $m_R = \frac{M}{2} + m_L$	-	2.829 kg where M=5.23 kg, from product specification manual ABB m_L= 0.214 kg, (Considering Stainless steel(ϱ=7930kg/m3), with 30x30x30 mm dimensions) m_L is the effective payload of the robot system, including tooling and workpiece
Effective mass μ $\mu = \left(\frac{1}{m_H} + \frac{1}{m_R}\right)^{-1}$	-	0.495
Max permissible force (Transient contact)	-	280N
Max transferred energy (Transient contact)	-	0.49J

B) Calculation of limit values

As explained in chapter 3, the calculations for the above data are done in a 3 step process, to understand and check the values obtained by applying the safety principles individually (SSM, PFL) and afterwards, apply them in a combined manner (PFL-SSM) as shown in below paragraphs.

1) Calculation of safety zones(SSM)

In this safety method the robot comes to a halt (protective stop) if the operator distance is less than permissible safe distance between them. Hence in this method of **only applying SSM,** the permissible safe distances for operation are computed, namely the protective safe distance (S_{safe}) and the minimum separation distance (S_{min}) and the parameters involved for these two distances are given in table 7. It is worth noting that the velocity of robot considered while calculating these safety distances is the velocity set by the human and is a fixed value in this collaborative mode of operation and for evaluating safety, the worst values will be considered (also shown in table 7). The equations along with the calculated values are given below, for step by step calculation refer appendix C.

The protective safe distance $S_{safe} = (v_h T_r + v_h T_s) + (v_r T_r) + S_s + (C + Z_r + Z_d)$ ....(2)

The parameters along with their considerations are given in table 7.

Table 7 Values of concerned parameters

Parameter		Value	Remarks
Description	Notation with units		
Velocity of human	V_h(mm/s)	2000	worst case as per ISO/TS 13855*
		0	When stationary
Velocity of robot	V_r(mm/s)	1500	Worst case as per IRB 14000 product specification document**
		0	When stationary
Reaction/sensing time of robot to issue stop signal	T_r(s)	0.1	Value considered from literature***
Stopping time of robot	T_s(s)	0.37	As per IRB 14000 product specification document**
Distance travelled by robot while stopping	S_s(mm)	253.67	See appendix C for calculations
Intrusion distance	C(mm)	0	Sensor dependent and is outside scope of research
Robot position uncertainty	Z_r(mm)	0	
Human position uncertainty	Z_s(mm)	0	

*from literature[47]
* from literature[50]
*** from standard document[48]

In order to estimate the protective separation distance for safety measures, the worst case condition is considered, when both the human and the robot are in motion and moving towards each other.

Substituting in equation (2),

$$\mathbf{S_{safe} = 1343.67mm}$$

The minimum separation distance S_{min}, is the point at which the operation must come to a safety rated stop at all costs i.e in this situation the velocity of robot V_r is zero. The stopping time of the robot is proportional to the velocity of robot [42], hence T_s is also zero.

Substituting in equation (7),

S_{min} is 200mm

2) Calculation of impact forces and energy transferred (PFL)

The limiting parameters to consider as per ISO/TS 15066 for this case are energy transferred and Impact forces (Peak forces) and the region considered is the back of hands for calculation as this is the most interactive part of the operator during a collaboration task. The speed of the robot is the same as initial conditions i.e 1.5m/s and continues to be the same during the entire path.

From concerned equations (4), (8) (see Appendix C for calculations).

Energy transferred during impact,

$$E = \frac{1}{2} * \mu v_{rel}^2 \ldots\ldots(4)$$

E= 0.557J

Maximum impact force

$$F_{max} = v_{rel,max}\sqrt{\mu * k}\ldots\ldots.(8)$$

F_{max}= 289.018N

However, note that the energy transferred during impact and the maximum impact force values are respectively greater than the allowable values of **0.49J** and **280N** as mentioned in ISO/TS 15066 [10], **hence operating under these circumstances is unsafe.**

From simulation in RobotStudio, calculation is done for various scenarios of robot and human motion for this case (PFL only) and the tabulated data of values is as shown in table 8.

Table 8 Energy transferred and Impact forces for varying cases

Case	Vrobot, mm/s	Vhuman, mm/s	Vrel, m/s	Energy transferred, J	Impact force, N
1	1500	0	1500	0.557	289.018
2	1500	2000	3500	3.032	674.375
3	0	2000	2000	0.99	385.357

Unsafe values indicated in red and the relative motion considered is between the operator and robot, when both are directed towards each other. It is worth noting that the for the current operating velocity conditions all three cases provide unsafe situations.

3) Calculation of Safe velocity and Safe controlled distance (PFL-SSM)

As mentioned in section 3.3 this calculation is done in two steps (see appendix C for detailed calculations)

A) Initially compute allowable safe velocity from PFL equations (3), (4)

$$v_{rel-max} = \frac{F_{max}}{\sqrt{\mu k}} \ldots\ldots(3)$$

$V_{rel-max}$ = 1453.179 mm/s……..(a)

$$E = \frac{1}{2} * \mu v_{rel}^{2} \ldots\ldots.(4)$$

V_{rel} = 1407.034mm/s….(b)

V_{safe} is the lower value resulted from above two velocities (a) and (b) (also referenced in[40])

Therefore, **V_{safe} =1407.034mm/s**

B) Calculation of safe control distance by using the estimated allowable safe velocity (V_{safe})

Substituting V_{safe} value as calculated in previous step in equation 2, the safe control distance $S_{control}$ is given below:

$S_{control}$=1334.373mm

It is to be noted that if the measured distance in the simulation is lesser than the safe distance calculated above the robot has to come to a halt as it would encroach the minimum separation zone.

5 RESULTS AND DISCUSSIONS

The previous section gave the description of evaluation of framework considering the three cases (SSM only, PFL only and PFL-SSM combined) along with their calculated limit values to ascertain the safety of the situation by comparison with the standard safe values in ISO/TS 15066. In this subsection the results obtained for these three modes of collaborative operation are presented and discussed together to arrive at a conclusion for this research study.

A) Results obtained for SSM only

In this principle of collaborative operation primarily the safe distance values between the human and the robot, S_{safe} and S_{min} are estimated. The values obtained for the considered hazard use case are as below

S_{safe} =1343.67mm

S_{min} is 200mm

These above values are used to define safety zones in this method and they indicate when the safety is breached. In other words, from ISO/TS 15066 [10] if the distance between the human and the robot (say $S_{present}$) falls below the protective safe distance S_{safe} the robot shall initiate a protective stop, meaning the velocity of the robot decreases and will come to a halt and shall resume motion only after their separation distance is exceeded. If the human continues to move towards the robot and the distance falls below the minimum separation distance S_{min}, the robot immediately comes to a standstill.

Therefore, the velocity of cobot varies with the safe distance values as indicated below

$V_r = V_{command}$ for $S_{safe} \leq S_{present}$ (where, $V_{command}$ is the initial velocity as set by the human)

$V_r = 0$ for $S_{min} < S_{present} \leq S_{safe}$

$V_r = 0$ for $S_{present} = S_{min}$

Conclusion: The cobot motion is interrupted every time the human enters this zone directly or indirectly and comes to a halt, as a result this has an impact on the productivity of operation leading to longer lead times while operating with only SSM principle.

B) Results obtained for PFL only

In this principle of collaborative operation primarily the contact values between the cobot and human for applications involving intentional contact, Energy transferred on impact (E) and maximum impact force (F_{max}) are estimated. As mentioned in The values obtained for the considered use case are as below

E= 0.557J

F_{max}= 289.018N

The motive in this mode of operation is to obtain the above values and specify limits on cobot velocity such that the contact situations are nonhazardous to the human working in the shared workspace. However, for the considered initial velocity, the above values indicate an unsafe situation. Table 8, also gives the values of energy transferred and maximum impact force for different velocity considerations as per relative motion between human and cobot and from the table it is observed that those velocities are also unsafe.

Conclusion: Despite having the safety measures (padding, sensors) in the design of the cobot, it can collide with the human and can result in injuries if operated at the considered velocities and hence needs to be changed for a safe value.

C) **Results obtained for PFL-SSM**

In this approach the principles of both the previously sated collaborative modes is combined so as to achieve an operation that has robot operating at reduced velocity with safe contact and avoidance of unnecessary stops while in operation. Therefore, safe velocity V_{safe} and subsequently the safe control distance $S_{control}$ are important parameters that are estimated.

$$\mathbf{V_{safe} = 1407.034 mm/s}$$

$$\mathbf{S_{control} = 1334.373 mm}$$

Therefore, adding the safe control distance the velocity of cobot operation changes as below:

$V_r = V_{command}$ for $S_{safe} \leq S_{present}$

$V_r = V_{safe}$ for $S_{control} < S_{present} \leq S_{safe}$

$V_r = V_{safe}$ for $S_{min} < S_{present} \leq S_{control}$

$V_r = 0$ for $S_{present} = S_{min}$

Conclusion: The cobot motion is regulated much better during the human's presence in the shared workspace with the introduction of safe control distance, hence unnecessary multiple stops as in the case of SSM only can be reduced, additionally with the reduced velocity there is a limitation on the PFL parameters (energy transferred during impact and the maximum force of impact) so contact situations are less hazardous than only PFL case. This is presented further in below paragraphs.

- Results of PFL-SSM across different body regions

From the steps in PFL-SSM, the calculations are extended to determine the values of transient contact with other body regions to ascertain whether the results yield in safe values, table 9 shows these values.

Table 9 PFL-SSM for contact across different body regions

Body region	From PFL							From SSM		
	F_{max}(transient)(N)	Effective spring constant K(N/mm)	Effective Mass of Human body region mH(kg)	Effective mass µ	Vrel (mm/s)	Vrel-max(mm/s)	Vsafe(mm/s)	Scontrol (mm)	Resulting Impact force, F_{res} N	Verdict
Skull and Forehead	-	150	4.4	1.721898	-	-	-	-		
Face	-	75	4.4	1.721898	-	-	-	-		
Neck	300	50	1.2	0.842591	1412.037	1461.59749	1412.037328	1334.8737	289.8275	Safe
Back and shoulders	420	35	40	2.642135	1375.649	1381.1402	1375.648566	1331.2349	418.33	Safe
Chest	280	25	40	2.642135	1100.519	1089.45808	1089.458081	1302.6158	280	Safe
Abdomen	22	10	40	2.642135	1347.855	135.345923	135.3459231	1207.2046	22	Safe
Pelvis	360	25	40	2.642135	1402.892	1400.73182	1400.731819	1333.7432	360	Safe
Upper arms and elbow joints	300	30	3	1.455996	1435.425	1435.42516	1435.425159	1337.2125	300	Safe
Lower arms and wrist joints	320	40	2	1.171671	1489.649	1478.14526	1478.145256	1341.4845	320	Safe
Hands and fingers	280	75	0.6	0.495013	1407.034	1453.17877	1407.03429	1334.3734	271.1088	Safe

The values of maximum energy transferred, F_{max} , effective spring constant K and effective mass of human body region m_h are taken from ISO/TS 15066 (see appendix E). The rest of the values in the table are calculated accordingly. They follow the same steps as per the PFL-SSM approach. Initially the safe velocity (V_{safe}) is calculated and then used to find the safe control distance ($S_{control}$). Later, the safe velocity is then substituted in the formula to estimate maximum impact force to compare with the standard allowable values mentioned in the ISO/TS 15066. It is observed that these values are either lesser or equal to the safe values mentioned in the document thereby indicating that safe values of contact can be obtained from the combined principle approach.

- Observations from simulation

Based on motion of human and cobot, simulation for hazardous contact is performed for three different cases as mentioned in chapter 4.3. The objective is to visualize these contact regions between the considered body part (back of the hands and fingers, as considered for this study in chapter 4.2) and the cobot. Figure 36, shows the specific region of contacts between the cobot and the human hand obtained while performing these simulations. It is observed that the cobot fingers or the base of the gripper are the regions of contact with the unsuspecting human fingers. This is interesting for this study as during a situation when only PFL principle is considered, where there is no reduction in the command velocity, such a type of contacts as in figure 36 is highly unsafe for the human. Therefore, by applying the PFL-SSM approach it is possible to reduce the initial velocity so that these contacts have lower impact forces as mentioned previously in table 9.

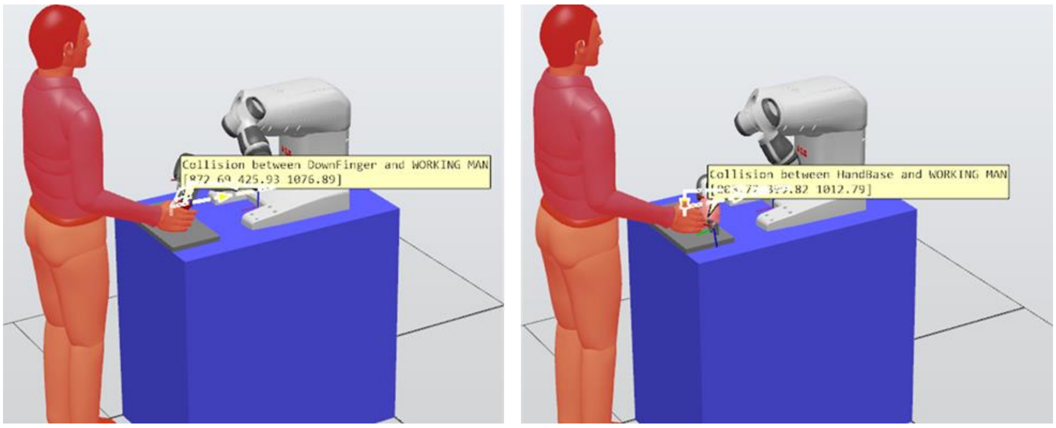


Figure 36 Situations of hazardous contact during task

- Graphical results from simulation

Graphs shown below for cobot velocity with respect to distance without (figure 37) and with (figure 38) safe intermediate safe zone (i.e for SSM only and PFL-SSM approach) is shown below. It is observed that when only SSM principle is applied there is a sharp decrease in the curve (figure 38), indicating the two functional states of the cobot in an operation that is either to move or come to a complete halt. Unlike this method when collaborative modes are combined (PFL-SSM) the velocity of the robot decreases with proportional to distance between the human and the cobot, the cobot moves with a safe-velocity within the intermediate safe control zone. It allows for continued operation of the involved task without the need to stop multiple times whilst keeping track of distance from human.

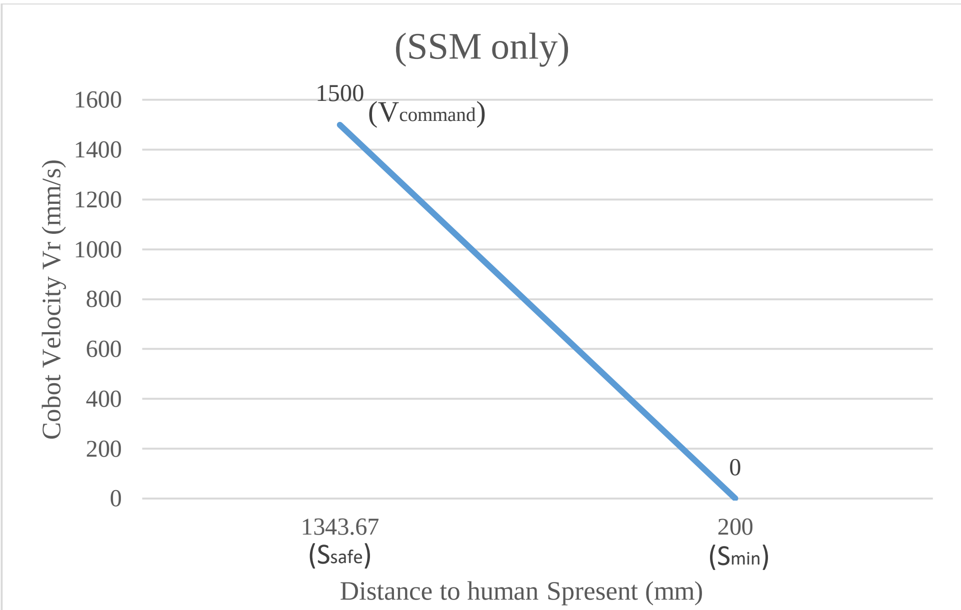


Figure 37 Robot velocity vs distance from operator (SSM), calculated by using Eq. (2).

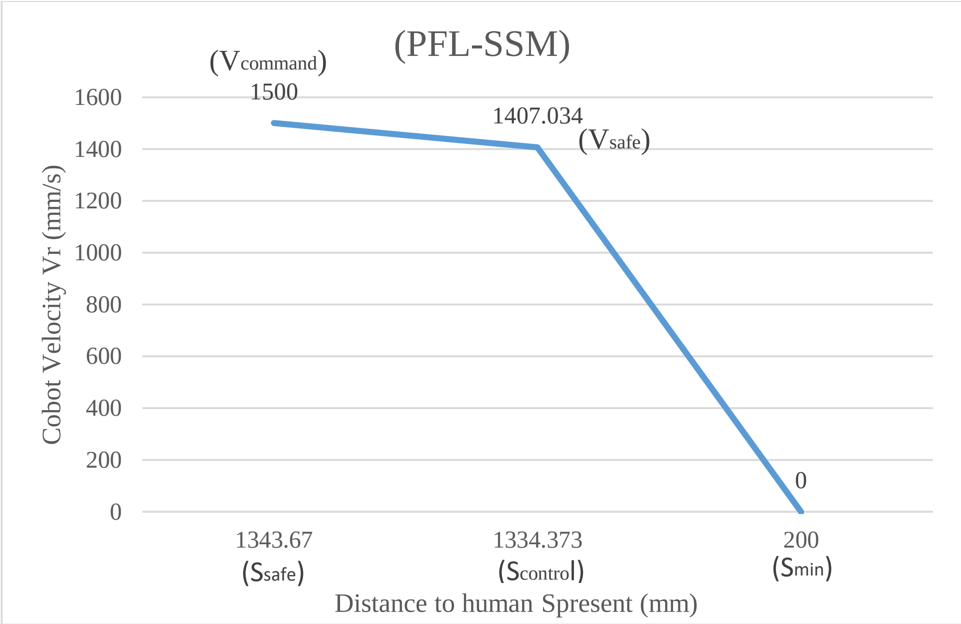


Figure 38 Robot velocity vs distance from operator (PFL-SSM), calculated by using Eq. (2),Eq. (3),Eq. (4)

6. CONCLUSION

In this chapter, the research questions framed at the beginning of the thesis are answered. The limitations and challenges of the implemented safety strategy are discussed and recommendations for future research are suggested.

6.1 Answers to research questions

This thesis proposed a safety strategy and its implementation in compliance with ISO/TS 15066 for a safe collaborative pick and place operation between a human and cobot. Below are the conclusions to the findings explained by answering the research questions.

- Sub Research question 1: What are the safety strategies for ensuring safe collaborative pick and place operation?

This research question is answered in sections 2.2.5 and 2.2.6. The main aim of safety in HRC is to avoid injury to the human from collisions and unintentional contacts. To achieve this several mechanical, sensory and control safety features can be merged such that if unsafe conditions do occur the robot can react better in a manner that reduces the forces at the impact [6]. Furthermore, due to the varying nature of applications of cobot in HRC, the safety strategy required for a particular HRC application will be different. However, existing standards offer guidelines that can be used to develop safety strategies. The technical specification document ISO/TS 15066 is an important standard in this regard for collaborative robots. It clearly specifies the four different types of safeguarding methods, these are safety-rated monitored stop, hand guiding, speed and separation monitoring and the power and force limiting. In safety-rated monitored stop, the cobot stops operating when the human is in close proximity to the cobots workspace, hand guiding is where the human guides the cobot's motion path along a particular trajectory. Next, in speed and separation monitoring a protective safe distance is calculated and is monitored such that the cobot initiates protective functions (safety stop or a reduction in speed) when these distances are breached. Lastly, in power and force limiting method different body regions describe limits on the impact force, energy transferred on impact for various intentional contact situations so that the cobot can be operated in a manner that does not violates these limits. Sensors, design modifications such as padding, limitations on force, velocity are adopted for safety through this method [6], [10].

- Sub Research question 2: How can safety methods in ISO/TS 15066 be applied in a shared collaborative work setting to enhance the safety of human operation?

The strategies proposed from the safety guidelines as mentioned above are not always free from risks [33], for example in power and force limiting, it allows close collaboration however, this poses higher threats to human is an inappropriate force on a distinct part of a human body can result in an injury [51]. Therefore, after examining the different safety methods proposed in ISO/TS 15066 a safety strategy was proposed with the main objective being to allow tight and continued collaboration between human and cobot with minimum loss of safety and higher productivity of operation. For this, particularly two principles PFL and SSM were considered. In PFL human spends significant amount of time in the workspace and in SSM the cobot is either commanded to stop or resume motion based on human position. Therefore, an approach for a meaningful combination of these two principles such that force on impact at close proximity is reduced whilst also avoiding unnecessary stops was suggested in chapter 3 to answer this research question.

- Sub research question 3: What are the risk management steps needed to ensure a safe collaborative pick and place operation?

In order to answer this question, the steps as defined by chapter 4, serves as a means to suggest one approach to a safe collaborative pick and place operation. This was initiated by adopting a safety assessment method, this has been elaborated in sections 2.2.3, where risk assessment along with its steps are explained. The method chosen for this thesis was the Hazop method, which describes deviations to process parameters by using guidewords, to identify risks in a particular scenario. Following the hazard identification, key entities, attributes of the entities and relationship among these attributes (as explained by the steps in section 4.2 Hazard study) [33], simulations was performed on RobotStudio to visualize these risks and their influencing parameters, namely velocity of robot and the safe distance between the cobot and the human (section 4.3). Lastly, the framework was evaluated by calculation of limit values and the results showed that with the combined PFL-SSM approach, the limits of maximum impact force was reduced to within the safety limits as per ISO/TS 15066 and from the graphs in chapter 4.4, the calculated safe control distance from the reduced velocity (V_{safe}) allows for a continued operation of the involved task without the need to stop multiple times whilst keeping track of distance from human.

6.2 Limitations and challenges

This research although presents an approach for risk mitigation, has some limitations. Firstly, the work in this thesis is primarily suited for a lightweight robot operating with a reduced payload, industrial scenarios have robots operating with heavier payloads and to be suited for collaboration would require them to operate under the PFL regime for which the certified technologies are not yet present [47].

Secondly, this work does not include emphasis of human detection, advances in safety rated cameras and sensing will be critical for monitoring the human position, human velocity, cobot and human uncertainties which are the additional parameters in equation (2), to calculate the protective safe distance in SSM.

Thirdly, for hazard identification the Hazop method is used, this method although beneficial in generating list of hazards, depends upon the expertise and background of the individual creating the hazard report hence this list of identified hazards may vary.

Lastly, this research proposes a safety framework for a collaborative pick and place operation, therefore for other applications involving HRC, it may require additional measures, such as implementing more test cases, adding additional conditional checks in the framework to make suitable decisions, while applying PFL-SSM together.

A main challenge of this thesis was to study the safe collaborative modes of operation in an HRC and develop an approach that complies with the standards and provides adds an additional layer of safety to the human while operating in a shared workspace with a collaborative robot.

6.3 Future recommendations

The use case considered for HRC was a collaborative pick and place operation, other collaborative scenarios involving human and cobot can be considered and studied with the PFL-SSM strategy. The method to identify risks was Hazop method, other safety assessment methods for example, ESHA (Environmental survey hazard analysis) could be explored to investigate hazards occurring in the surrounding of robots while executing an operation.

Another recommendation for future research is to develop simulation models in a dynamic setting where both the human and robot are in motion, instead of just the robot. This would allow to test and visualize a scenario closer to realistic conditions.

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8. APPENDIX

A. Hazard Study – Hazop and Hazop UML theory

A.1 The Method of Hazop

In this step the potential hazards for the considered pick and place collaborative application are identified and listed. The method used in this study is the HAZOP (Hazard Operability) technique. Hazop has two objectives, one is to identify hazards and the other is to propose recommendations aimed at reducing the associated risk. A given system is analyzed by listing the various deviations defined by the conjunction of parameters of the system (in this study the velocity of the robot, impact force on the operator) with specific guidewords. The guidewords are as shown in the table 10. The role of the guidewords is to stimulate ideas and initiate discussions that help in identifying potential hazards [32]

Table 10 Example of guidewords and their interpretation

Guidewords	Interpretation
No/None	Complete negation of what needed to happen/no part of the action is achieved
More	Quantitative increase
Less	Quantitative decrease
As well as	All the design intentions happened including extra additions
Part of	Only some of the design intentions happened
Reverse	The opposite of the design intentions happened
Other than	No part of the original intention happened, but is substituted by something else
Early	Something happened earlier that the desired clocktime
Late	Something happened later than the desired clocktime
Before	Something happened before it is expected
After	Something happened after it is expected

Therefore, utilizing the guidewords description of deviations can be listed, an example in this case could be: *velocity of robot* (parameter) when combined with *more* (guideword) the resulting deviation is "*velocity of robot is more than the required limits*". This could result in robot losing control and causing harm by collision with the operator or nearby structure in its environment. After identifying the hazard scenario using guidewords with the process parameters, the next step would be to identify the cause and effects of the deviation. At the end is a document which describes: item (which part of the system), parameter, deviation, possible causes, consequences, safeguards, comments, and actions required and so on.

An example of a Hazop table is as shown in table 11, for a use case considering a robot grabbing a part from the hands of a human operator. With the guideword other than the robot is still moving as it tries to grab the hand rather than the part, resulting in a severe injury to the human.

Table 11 Example of Hazop table entries

Element	Guideword	Deviation	Use case effect	Severity	Possible cause	Integrity level requirements	New safety requirements	Remarks
Robot grabs part from human	Other than	Robot grabs the human hand other than the part as intended	Collision can take place with human and robot can cause severe injury	High	Robot did not detect human		Robot to be equipped with sensors for detecting human features	situational awareness of robot needs to be upgraded

The Hazop method therefore has advantages of identifying hazards and has been adapted to different domains. The modification of this method lies in adapting the list of parameters and the list of guidewords to the specific viewpoint as applied to a considered system [52]. The main downside of performing only a HAZOP is that it is difficult to use the right parameters. Additionally, by using HAZOP, it is difficult to implement with the human robot collaboration. Therefore, the safety assessment method is extended by using the method explained by Guiochet [32] which uses a Universal Modelling Language to implement the human robot interaction into the HAZOP method.

A.2 The method of Hazop-UML

The Universal Modelling Language(UML) uses diagrams to describe a system. These diagrams are called sequence diagrams. Sequence diagrams are used to define the interaction between humans and robots, as seen in figure 39.

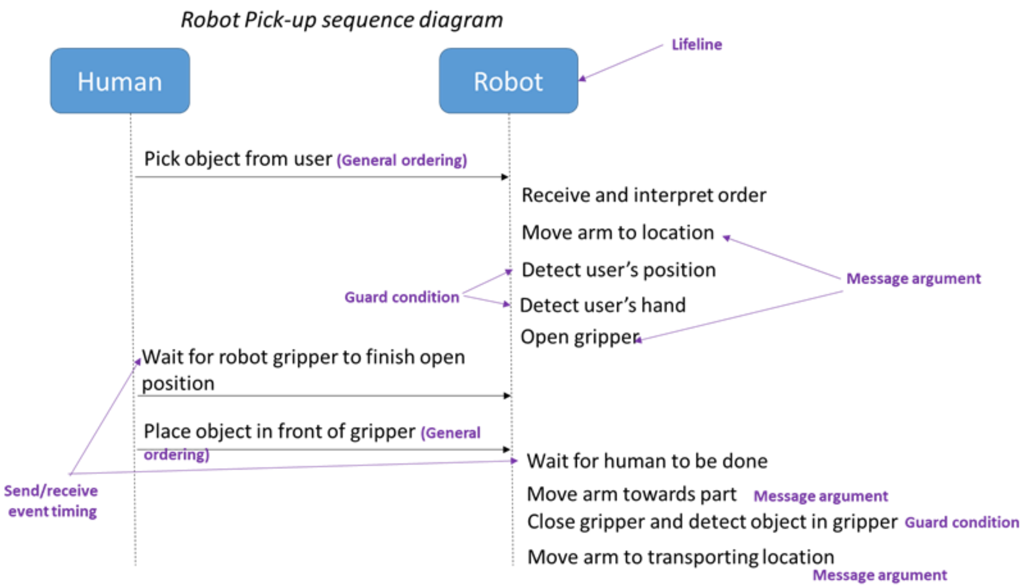

Figure 39 Sequence diagram of robot picking up a part and placing in human's hand

Sequence diagrams identify in which order the human-robot collaboration takes place. This already results in adding the human part to the safety assessment compared to a normal HAZOP. This can be accomplished by describing 5 attributes. The first ones are the general ordering, these make up the predecessors and successors of the interaction. An example of predecessors/successors are that the robot receives an order to take an object from a human's hand. Other attributes are message timing, send and receive objects, message guard condition and lastly, message arguments. Message timing can be that the robot receives the message to pick an object from a human's hand in a certain time. Send and receive objects is when the message is received by the right robot. Message guard condition, for example, is that the action is fulfilled, for example to detect the human hand. Lastly, the message arguments state where the robot needs to be for example.

In conclusion

UML also uses the same guidewords as Hazop in table 10, to identify deviations within the diagrams. The difference is that they are used for operational phase rather than the design phase as in Hazop. Guidewords are used to identify deviations from the attributes in the diagram and the similar table as in Hazop is constructed to document the list of hazards. The advantages of this combined approach is that it can show interaction is HRC and can be adapted quite well by those using it. It is important to note that Hazop-UML does not identify all hazards. The limitations are firstly, because no single technique is capable of identifying all the hazards, secondly as guidewords are either too numerous or limited for the analysis and this depends upon the initiator of the method, thirdly Hazop-UML does not consider the hazards due to the layout of the environment (external factors such as objects in vicinity, obstructions at the entrance)[32]

B. Hazop table from sequence diagram

Attribute	Guide word	Deviation
Pick object from user	No	No signal is received for operation
	Other than	Robot recieves signal but picks object other than the one intented
	As well as	Message is sent as well as another message
	More than	More than one message is sent
	Less than	Message is sent less than intended
	Before	Message is sent before the completion of previous operation
	After	Message is sent after the completion of previous operation
	Part of	Only pick object is mentioned but from user is not specified
	Reverse	To and from end locations for robot is reversed
Wait for robot to finish gripping	As well as	This message as well as additional operation(robot movement command) is executed
	Early	Message sent earlier than the robot has reached intented location
	Later	Message sent later than the robot has reached intented location
Robot	No	Message sent but never received
	Other than	Message sent to wrong object
	As well as	Message sent to movment arm as well as stationary arm
	Reverse	To and from end locations for robot is reversed
	More	Message sent to more than one movement arm
	Less	Message sent with less instructions for performing operation
Close gripper and detection during operation	No/none	The required operation is not performed
	Other than	The gripper is closed but object is not grabbed
	As well as	The gripper is closed as well as at incorrect location
	Part of	Only part of the arm has reached location for gripping
	Late	The operation is performed at incorrect timing
Movement of robot arms/Gripper motion	No/None	Expected movement is never achieved
	More	The robot arms move more than the set/prescribed parameters(force, velocity)
	Less	The robot arms move less than the set/prescribed parameters(force, velocity)
	As well as	There is robot arm movement as well as gripper is activated
Gripper motion	Part of	Only a part of the gripper is open during pick up
	Other than	The gripper open and close position is different than intended

C. Calculation of limit values

- **Calculation of safety zones in SSM**

$$S_{safe} = (v_h Tr + v_h T_s) + (v_r T_r) + S_s + (C + Zr + Zd)$$

Additionally,

S_s= distance travelled by robot while stopping (mm)

= 2*π*r (stopping distance in category 0 stop°/360°) as per [51]

(Where r =specified radius)

=2*π*559mm*(26°/360°)(Yumi has reach of 559mm)

=253.67mm

From above values we calculate Safe distance as per highlighted equation

S_{safe} = (2000*0.1+2000*0.37) + (1500*0.1) + 253.67 + 0 + 0

S_{safe} = 1343.67mm

The minimum distance S_{min}, the point at which the operation must come to a safety rated stop at all costs i.e when velocity of robot is zero is given below

S_{min} when v_r=0

Also, T_s=0 as dependent on v_r

$$S_{min} = v_h Tr + C + Zr + Zd$$

= 2000*0.1 + 0 + 0

= 200mm

- **Calculation of Energy transferred and maximum force on impact as per PFL**

Energy transferred from equation (7)

$$E = \frac{1}{2} * \mu v_{rel}^2$$

E = 0.5*0.495*$(1.5)^2$ (v=worst case, 1.5m/s)

0.557J , which is greater than 0.49J, mentioned in ISO/TS 15066 standard document hence the contact is unsafe.

Impact force,

$$F_{max} = v_{rel,max}\sqrt{\mu * k}$$

F_{max} =1.5*√(0.495*75000)

=**289.0177N**,

- **Calculation of Safe velocity and Safe controlled distance (PFL-SSM)**

$$v_{rel-max} = \frac{F_{max}}{\sqrt{\mu k}} \ldots\ldots (3)$$

Where,

F_{max} =280 N (for Back of hand as per ISO/TS 15066)

μ=0.495

k =75 N/mm

$V_{rel-max}$ = 1453.179 mm/s

$$E = \frac{1}{2} * \mu v_{rel}^2$$

Where,

E = 0.49 J (for hands and fingers as per ISO/TS15066)

μ = 0.495

V_{rel} = 1407.034mm/s

V_{safe} is the lower value resulted from above two velocities[40]

V_{safe} =**1407.034mm/s**

A) Calculation of safe control distance using the allowable safe velocity

Substitute this value in below equation for safe control distance at reduced speeds

$S_{control} = (v_h T_r + v_h T_s) + (v_r T_r) + S_s + (C + Z_r + Z_d)$

$= (2000*0.1+2000*0.37) + (1407.034*0.1) + 253.67 + 0 + 0$

$S_{control}$= **1334.373mm**

D. Dual parallelogram link setup for studying hand guiding[37]

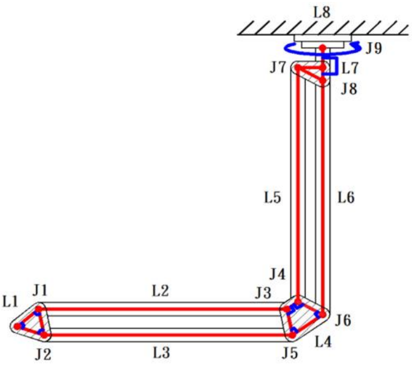

Figure 40 Skeleton of the palletizing robot arm

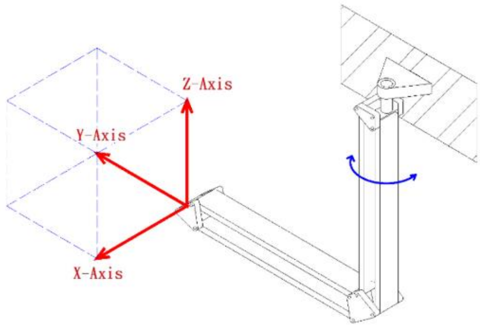

Figure 41 Representation of the X-Y-Z coordinate system for defining the working space of cobot's motion

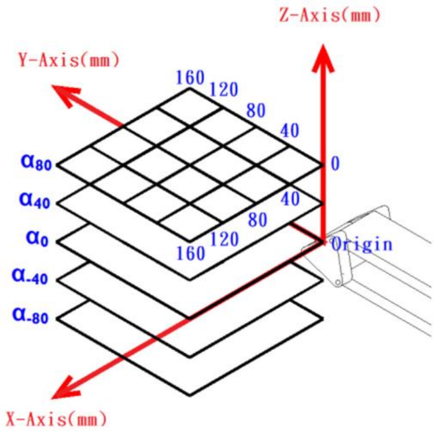

Figure 42 Decomposition of the 3D working space to measure the hand guiding force in each of these planes

The cobot arm is moved horizontally along different planes in the X-Y-Z workspace, as shown in figure 42 and the force is measured by a tension gage. This is done by fixing Z to a given plane and sweeping the position along the X and Y axes, by starting from the origin point (0), in the plane a0, the arm is displaced in the X direction (i.e. X= 40, 80, 120, 160) for Y =0. This is repeated for each plane's different positions in the Y direction and the force values are noted.

E. Safety zones monitoring a technique for SSM[39]

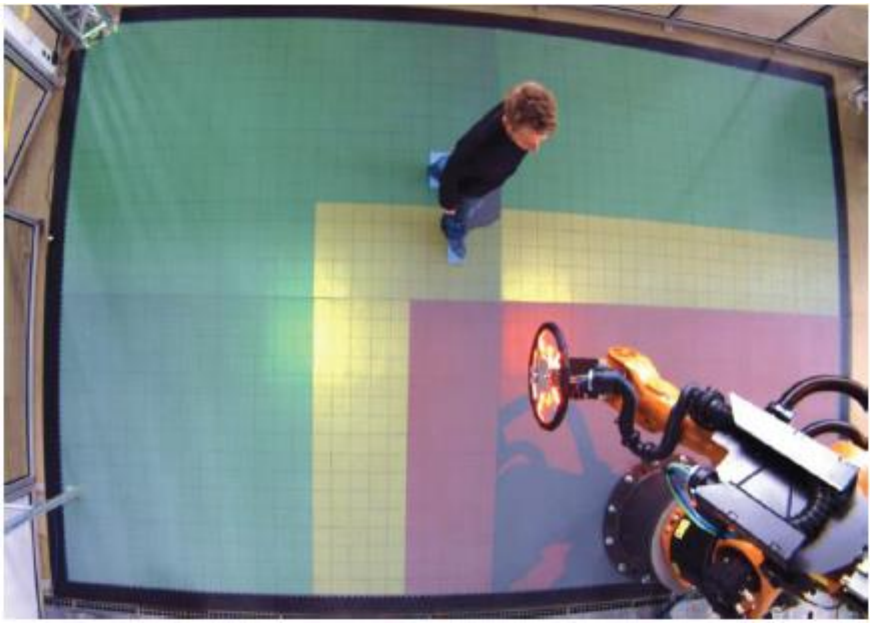

Figure 43 Tactile floor with spatial resolution combined with projectors to display safety zones (top view) [39]

Figure 43 shows and industrial floor mats which are provided with a sensitive sub-layer made of tactile cells. To establish safety zones around a robot, the tactile floor monitors the movement of any person on it, it also has the capability to monitor multiple people. Some features of this approach are that the colored safety zones can be easily adjusted in correlation with the robot position and speed according to the distance equation of ISO/TS 15066.Also, the tactile floor can be combined with a projection system to make the safety zones visible [39].

F. Effective masses and spring constants for the body model, from ISO/TS 15066[10]

The effective masses and the spring constants used to represent the human body regions is shown in below table 12.

Table 12 Effective masses and spring constants for the body model

Body region	Effective spring constant K (N/mm)	Effective mass m_h (kg)
Skull and forehead	150	4.4
Face	75	4.4
Neck	50	1.2
Back and shoulders	35	40
Chest	25	40
Abdomen	10	40
Pelvis	25	40
Upper arms and elbow joints	30	3
Lower arms and wrist joints	40	2
Hands and fingers	75	0.6
Thighs and knees	50	75
Lower legs	60	75

G. Limit values from ISO/TS 15066[10]

Table 13 shows the limit values for contact between a robot and human are needed for calculation during the PFL collaborative mode of operation.

Table 13 Biomechanical limits

Body region	Specific body area	Quasi-static contact		Transient contact	
		Maximum permissible pressure [a] p_s N/cm^2	Maximum permissible force [b] N	Maximum permissible pressure multiplier [c] P_T	Maximum permissible force multiplier [c] F_T
Skull and forehead [d]	*Middle of forehead*	*130*	*130*	*not applicable*	*not applicable*
	Temple	*110*		*not applicable*	
Face [d]	*Masticatory muscle*	*110*	*65*	*not applicable*	*not applicable*
Neck	Neck muscle	140	150	2	2
	Seventh neck muscle	210		2	
Back and shoulders	Shoulder joint	160	210	2	2
	Fifth lumbar vertebra	210		2	2
Chest	Sternum	120	140	2	2
	Pectoral muscle	170		2	
Abdomen	Abdominal muscle	140	110	2	2
Pelvis	Pelvic bone	210	180	2	2
Upper arms and elbow joints	Deltoid muscle	190	150	2	2
	Humerus	220		2	
Lower arms and wrist joints	Radial bone	190	160	2	2
	Forearm muscle	180		2	
	Arm nerve	180		2	
Hands and fingers	Forefinger pad D	300	140	2	2
	Forefinger pad ND	270		2	
	Forefinger end joint D	280		2	
	Forefinger end joint ND	220		2	
	Thenar eminence	200		2	
	Palm D	260		2	
	Palm ND	260		2	
	Back of the hand D	200		2	
	Back of the hand ND	190		2	
Thighs and knees	Thigh muscle	250	220	2	2
	Kneecap	220		2	
Lower legs	Middle of shin	220	130	2	2
	Calf muscle	210		2	