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Safety requirements for collaborative robots

Assessing legal, technical, and human factors in human-robot collaboration

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Bachelor's thesis

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Abstract

The demand for flexible human-robot collaboration in manufacturing is increasing constantly, and collaborative robots offer a viable one solution for this. With various methods and features, these robots can work safely in shared workspace with human, even without physical safeguards. This capability enhances automation's productivity by combining the robot's mass production and precision with the flexibility of humans. However, deploying robotic cells without safeguards is not risk free and necessitates strict regulation to ensure safety of human workers. Machinery Directive and ISO safety standards provide guidelines for integrators and manufacturers to ensure the safety of machinery. Despite these measures, robotic systems and their applications may still present legal challenges. Fortunately, constantly updating standards and the introduction of new Machinery Regulation are trying to keep pace with rapidly evolving industry. The availability of these safety mechanisms, coupled with their regular updates, ensures the advancement of human-robot collaboration, enabling more flexible and efficient production processes.

This thesis focuses on assessing the safety requirements for collaborative robots and systems. In an attempt to assess this topic, first the difference between conventional industrial robot and collaborative robot is defined. The key functions essential for collaborative robots are discussed, along with some alternative concepts for achieving these functions. The structure of regulation is detailed, explaining the hierarchy and the contribution of various regulatory laws and standards to collaborative robot safety. Risk assessment, a crucial aspect of safety for all machinery, is explored specifically for collaborative systems. This includes presenting different methods aimed at ensuring a successful risk assessment process. The wide range of risk factors in human-robot collaboration are examined. Additionally, a small study was conducted as a part of this thesis to evaluate the effectiveness of collaborative robot's safety functions. This involved measuring the force excreted to a robot from collision to a rigid body, with both power and force limitation activated and deactivated. The results of this comparison are intended to provide insight into the effectiveness of the safety methods for collaborative robots.

Key words: robot standards, collaborative robots, human-robot collaboration, robotic safety

Generative AI was used in this thesis to correct grammatical errors and to enhance clarity.

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Abstract

Ihmisen ja robotin välisen yhteistyön kysyntä valmistusteollisuudessa kasvaa jatkuvasti, ja yhteistyörobotit tarjoavat yhden mahdollisen ratkaisun tähän. Erilaisilla menetelmillä ja ominaisuuksilla nämä robotit voivat työskennellä turvallisesti jaetussa työtilassa ihmisen kanssa, jopa ilman fyysisiä turvajärjestelyjä. Tämä kyky parantaa automaation tuottavuutta yhdistämällä robotin massatuotannon ja tarkkuuden ihmisen joustavuuden kanssa. Kuitenkin robottisolujen käyttöönottaminen ilman fyysisiä turvajärjestelyjä ei ole riskitöntä ja vaatii tiukkaa sääntelyä työntekijöiden turvallisuuden takaamiseksi. Konedirektiivi ja ISO-turvastandardit tarjoavat ohjeita integraattoreille ja valmistajille koneiden turvallisuuden varmistamiseksi. Näistä huolimatta, robottijärjestelmiin ja niiden sovelluksiin voi silti liittyä haasteita lakien soveltamisen kanssa. Onneksi jatkuvasti päivittyvät standardit ja uuden koneasetuksen käyttöönotto pyrkivät pysymään nopeasti kehittyvän teollisuuden mukana. Nämä turvallisuusvaatimukset ja niiden säännöllinen päivitys varmistaa ihmisen ja robotin välisen yhteistyön edistymisen, joka edesauttaa joustavampaa ja tehokkaampaa tuotantoa.

Tämä tutkielma keskittyy arvioimaan yhteistyörobottien ja -järjestelmien turvallisuusvaatimuksia. Pyrkimyksenä arvioida tätä aihetta, määritetään ensin perinteisen teollisuusrobotin ja yhteistyörobotin välinen ero. Esitetään yhteistyörobottien kannalta olennaisimmat toimintafunktiot, mukaan lukien muutamia vaihtoehtoisia konsepteja näiden toimintojen saavuttamiseksi. Turvallisuuteen liittyvien lainsäädännön rakenne selitetään yksityiskohtaisesti, tarkentaen eri lakien ja standardien suhteita, ja vaikutusta yhteistyörobottien turvallisuuteen liittyen. Riskinarviointia tarkastellaan erityisesti yhteistyöjärjestelmien näkökulmasta. Tämä sisältää muutamien menetelmien esittelyn, joiden tavoitteena on varmistaa onnistunut riskinarviointiprosessi. Tutkielmassa tarkastellaan ihmisen ja robotin välisen yhteistyön laajaa riskitekijöiden kirjoa. Lisäksi osana tutkielmaa suoritettiin pienimuotoinen tutkimus arvioimaan yhteistyörobotin turvatoimintojen tehokkuutta. Tämä sisälsi robottiin kohdistuvien voimien mittaamisen törmäyksessä “power and force limitation” (PFL) toiminnon ollessa aktivoituna ja deaktivoituna. Tämän tutkimuksen tulokset havainnollistavat yhtä yhteistyörobottien turvamenetelmän tehokkuutta.

Avainsanat: robotti standardit, yhteistyörobotit, robotin ja ihmisen yhteistyö, robottien turvallisuus

Tässä tutkielmassa generatiivista tekoälyä hyödynnettiin kieliopin ja selkeyden parantamiseksi.

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1 Introduction

Robots have long been integral to the industrial sector, offering efficient and profitable solutions for performing repetitive tasks. Unlike human workers, they are not prone to fatigue, enabling them to perform repetitive tasks with consistent precision and without decline of performance over extended periods. However, a significant drawback of these industrial robots is their safety concerns when operating in proximity to humans. Because of this they are usually behind barriers or with other measures unreachable to human workers. As better solutions are needed in industry every day, the next step to increase manufacturing was to make human-robot collaboration possible, providing even more efficient and flexible manufacturing [1]. These systems, known as collaborative robots, are specifically designed to safely interact with human operators, marking a significant step forward in the evolution of industrial robotics.

As mentioned before, safety concerns with industrial robots were often solved through the use of safeguards. Now when humans and collaborative robots need to work together, this approach is no longer viable [2]. This shift brought up a new problem to be solved for the safety of workers [1]. Multiple new ways of preventing collision with human and cobot and ensuring safety of workers were introduced [2]. As it is with everything related to the safety of humans, regulations needed to be able to ensure the safety of the workers. Significant advancements in the safety of human-robot collaboration in the industry can be traced back to the year 2006, when the first regulatory tools specifically designed for collaborative robots were introduced [2]. The regulatory tools for collaborative robots and human-robot collaboration are evolving constantly when more and more entities are adapting collaborative robots to their processes. A common challenge encountered with regulations in this matter is that while they provide general guidance on ensuring safety [1]. Issues arise due to the unique nature of many human-robot collaboration applications, this uniqueness introduces numerous challenges that are not easily addressed by broad regulations [1]. Furthermore, the “articulated regulation” as described by the referenced paper, can be seen as the main limiting factor for validating the safety of a specific human-robot collaboration solutions [3].

The objective of this thesis is to clarify the structure of the current regulatory framework governing human-robot collaboration and collaborative robots. This exploration begins by defining what constitutes a collaborative robot and outlining its key functionalities. The current forms of regulations and their relations are introduced. Also, the challenges regarding current regulation, as previously mentioned, are analyzed. An important part of overall safety is the process of risk assessment and the application’s risk factors which both will be covered in the aspect of human-robot collaboration. Lastly, this thesis includes a small study aimed at assessing the effectiveness of a specific safety method employed by collaborative robots, known as power and force limitation.

2 Robotic manipulators

When discussing robotics in the industrial sector, the focus is typically on industrial robotics. Industrial robots have been used in various tasks for over 50 years now [2]. One of their purposes since the beginning have been to aid humans with dangerous or repetitive tasks [2]. This can be observed from the fact that the first thought of building a remotely controlled robotic manipulator came from the need to handle radioactive material after World War II [4].

Throughout history there has been different visions of what is an industrial robot. One of the true pioneers of industrial robots J.F.Engelberger had his own simple way of defining an industrial robot in one phrase “I know one when I see one” [5]. Since then, the definition of industrial robot has luckily changed to something that is more informative. Today probably the most considerable definition is made by the International Standards Organization (ISO). It defines that industrial robot is an “automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” [5], [6]**.** This definition offers a more precise description of what is an industrial robot and what functions it has.

2.1 Defining collaborative robot

The ISO 10218-1 standard states under the definition of industrial robot that for the standards purpose, collaborating robots are considered as industrial robots [6]. This indicates that the collaborative robots are just a specific type of industrial robot [7]. It is even further confirmed by the ISO’s definition of collaborative robot which states being a robot which is in collaborative workspace with human [8].

There are also some clear differences which are present for collaborative robots. These differences helps to define the collaborative robot and distinguish it from conventional industrial robot. The ISO 10218-1 standard requires for a robot to be defined as collaborative robot or commonly abbreviated as cobot to have at least one of four safety modes that ISO standards provide [6], [7]. These safety modes are examined more thoroughly in chapter 4. Other distinguishable factors to determine cobots are that they are easier to program, they are designed to share a collaborative workspace with human, and they are made safe enough for humans to work concurrently on a same task or object with them [7]. These things are rather less significant in defining the cobot because they can be observed in different ways and can be in many cases true with just a regular industrial robot. It is also important to note that the definition of cobot is changing all the time or more specifically broadening as their user base is increasing [7].

2.2 The need for collaborative solutions

In latest years when the Industry 4.0 era has increased the demand of manufacturing, making it more versatile than ever before [9]. Customers demanding products with even smaller batch sizes, leading to companies especially small and medium-sized enterprises, struggling to find skilled workers to manufacture these products [7]. This has led the companies in need to create even more tailored manufacturing solutions with improved sustainability and better quality with still maintaining efficiency for mass production [9]. Before, capabilities provided by regular industrial robots in industrial automation are not enough anymore. Where the industrial robot can maintain high efficiency and high quality it lacks the flexibility to adapt with fast changes in production [9]. On the other hand, humans can handle quick changes in production and deal with unexpected factors that increase uncertainties, they are less efficient compared to industrial robots [9].

One solution provided for this problem are collaborative solutions. Limiting factors like fences needed to be removed to achieve the desired flexibility of collaborative solution [2]. This had to be done without sacrificing the safety of the automation solution, so the need for other types of safety functions was inevitable [2]. From this need, the new concept of collaborative robot was introduced [2]. Cobots in Human-Robot Collaboration (HRC) offers the combination of mass production from automation and flexibility of a human [9]. Cobots are usually easier to program which helps with the problem previously encountered to find a skilled worker to program the industrial robot [7]. Also, the cobots are required to be safe to interact with human meaning that there is no need for similar safeguards as there was with industrial robots [7]. This makes the cobot an attractive option not only in terms of productivity but also in the financial aspect of an investment.

2.3 Alternative ways to increase collaborativeness

While safety standards specify certain criteria for collaborative systems, achieving collaborativeness in a system does not always mean that there should be a cobot utilized. Nor are the safety requirements that safety standards define easy to achieve even with a cobot. Safety standards that ISO defines makes the collaborative systems standardized and safer, but they also increase the need for active stress and force measurements, and risk assessment [10]. This is why different entities have come up with out-of-the-box ideas to offer solutions which achieve the needed safety and are not strictly dependent on the safety setting of a robot.

One of these solutions focuses on implementing a non-embedded solution for speed and separation monitoring in a system as a safety control mode. This solution utilizes time of flight sensing method [11]. The idea is to monitor human worker with visual sensing system, with this monitoring it is possible to conduct artificial skeletal model of the human worker, which can then be tracked [11].

When human position is known constantly with the help of skeletal model, the distance between the worker and the robot joints can be found [11]. The concept for the solution is to monitor if the skeletal model of a human worker gets too close to the robot joints [11]. If this happens, the robot will set its velocity and acceleration based on that distance [11]. The working principle of the whole system is visualized in Figure 1. Solution was completed so that it fits the requirements of the ISO's technical specification ISO/TS 15066 [11].

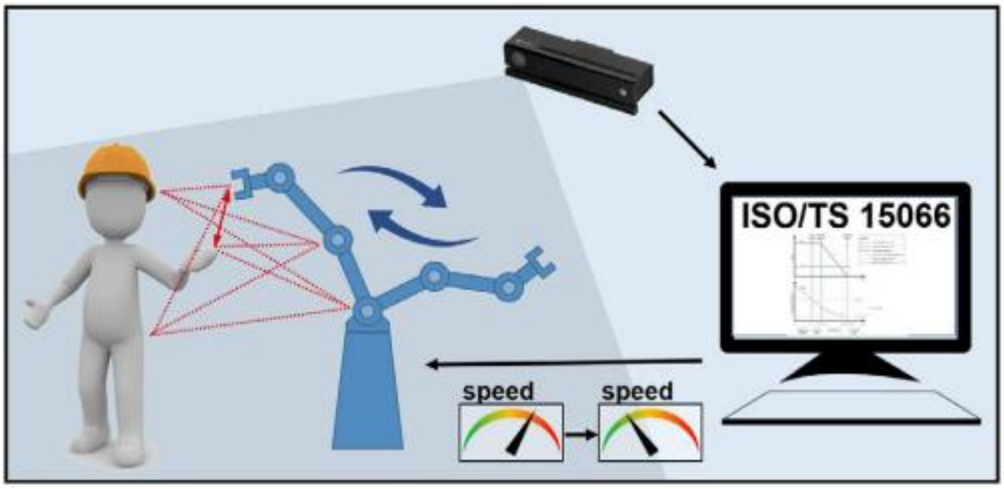

Figure 1: Overview of the entire system setup [11].

Other solution takes a totally different approach. Instead of speed and separation monitoring it introduces an external soft skin solution presented in Figure 2. The soft skin makes industrial robots collaborative, or cobots even safer [12]. The solution falls under implementing an optional way for power and force limiting method that ISO/TS 15066 specifies [12]. Not only does this soft skin provides a passive shock absorption thanks to the padding, but also with sensors integrated it can work as active collision detection [12]. The research for this soft skin solution was conducted with both an industrial robot and a cobot [12]. The results showed that for the velocities used, even the industrial robot did not exceed the force limits set by the ISO/TS 15066 [12]. This result indicates that the method could be used to make human-robot collaboration possible even when using industrial robot [12].

Figure 2: External soft skin safety covers on robotic manipulators and the experimental setup [12]. The soft skin can be recognized as the white cushioning on the cobots.

3 Collaborative robot’s safety regulation

When robots and humans work in collaborative environment, the risk of injury is clearly evident. From this reason, regulation is needed to ensure safety of human workers. In Europe there is a hierarchy for the regulation of robot safety. On top of this hierarchy sits the Machinery Directive 2006/42/EC which is the bottom line for regulation [3]. To complement Machinery Directive each member state of EU has to transpose the directive into their own laws, and these are mandatory to comply with [13]. Defining the lower levels in this hierarchy there are standards which specify the safety aspects in compliance with Machinery Directive [3]. At even lower levels of the hierarchy there are technical specifications (TS) and technical reports (TR) to detail standards even further [3]. Visualization of the whole hierarchy presented in Figure 3.

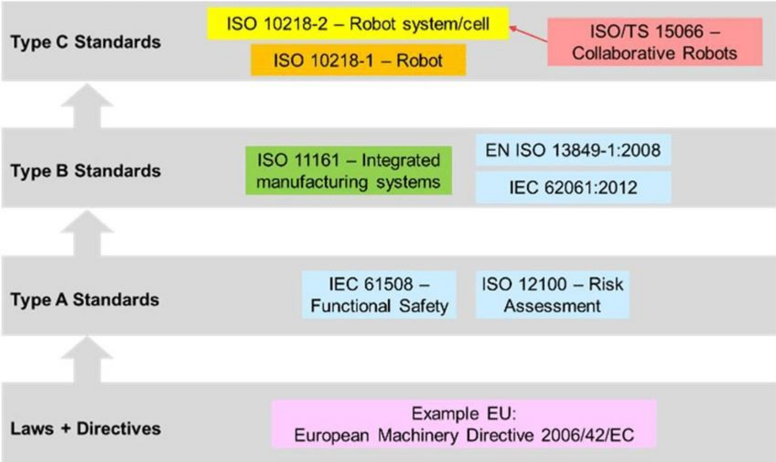

Figure 3: Hierarchy of Directives, Laws, and Standards for safety of machinery [26].

3.1 Machinery Directive

Machinery Directive 2006/42/EC is directive that the European Union has set to define health and safety requirements for general applications. The particular directive also specifies some requirements for specific types of machinery [14]. Machinery Directive is converted into all the different languages spoken in the member countries and is incorporated into the national law of each member state [3]. A robot falls under the scope of the Machinery Directive because based on the specification by the directive it has “linked parts or components, at least one of which moves” [3]. It is important to note that even when Machinery Directive concerns robots, industrial robots are not actually considered as machinery, instead they are considered as “partly completed machinery” [3]. The most significant difference which this creates is that robot itself can’t get CE marking for Machinery Directive [3]. To get a CE marking for a robot it must be considered as “completed machinery”, meaning that the robot must be part of a specific application [3].

While the industry goes forward with such a high phase the laws and directives become less relevant when new technologies are made. To this end the European Union has acted by updating the current Machinery Directive to ensure the safety and compliance of new machines in future. Machinery Regulation 2023/1230/EU will replace the current Machinery directive [13]. The regulation is set to be implemented in early 2027 but there are some parts of it that are going to apply already in 2024 [13]. The big difference of the upcoming regulation is that from 2027 and on it is not directive anymore but rather regulation as the name suggests. This means that the requirements are directly applicable in EU member states and there will no longer be need for transposing them into legislation of the member states [13]. This also means that with the regulation manufacturer has to make sure that their product is in line with its requirements [13]. Another aim for the new regulation is to simplify issues, for example in incomplete machinery such as cobots, and make sure that all the machines in the market are safe for humans [13].

3.2 ISO Standards

International Organization for Standardization (ISO) is an international organization whose goal is to provide structure for creating standards [15]. These standards are made for customers to guarantee quality, safety, and efficiency [15]. The standards are made by field professionals such as buyers, sellers, manufacturers, customers, or regulators [16]. This thesis focuses mainly on the subbranch of ISO standards called safety standards. These safety standards include the requirements for safe human-robot collaboration (HRC).

ISO has multiple committees to create and update the standards. ISO Technical committee 229 is in main charge of providing the standards for industrial and service robotics [3]. Their working principle for creating solutions concerning safety is to have a common understanding with the community so that the standards would be best suited for them [3]. It is important to know that even the standards are only technical references meaning that their compliance is not mandatory [3]. However, if the solution does not adhere to standards, it means that the integrator may need to prove that the equivalent level of safety is achieved in other manners [17]. There are standards labeled as “harmonized” which are recognized by the European standard organization as being in full conformity with the relevant directive or regulation [3]. This recognition provides presumption of conformity for applications following harmonized standards [3]. ISO standard 10218 is a harmonized standard, whereas TS 15066 is a technical specification and not a standard, meaning it is not applicable for that categorization.

Safety standards made by ISO are categorized into A, B or C types of standards [3]. The hierarchy of these types is shown in Figure 3. First, type A standards provide basic safety information for design, and they are valid for all machines [3]. Second, type B standards states some generic rules for particular safety features or protective equipment [3]. Lastly, type C standards define machine-specific regulation [3]. This includes industrial robots and cobots, which are the main focus in this thesis. Type C standards take priority over type A and B, meaning that compliance with a type C standard negates the need to separately consider same regulation form type A and B standards [3].

ISO 10218-1

ISO 10218-1 is the first part of ISO 10218 type C standard [6]. This part focuses on specifying all the things that need to be considered for the safety of industrial robot [6]. This includes guidelines for design, safeguards, and manuals to make the robot safe [6]. Standard states common hazards known with robots and provides solutions to minimize or eliminate these [6]. One hazard which is excluded from this standard intentionally is noise emission [6]. ISO 10218-1 considers robots as partly completed machinery [3]. The first part was updated later based on experience gathered on developing the ISO 10218-2 standard, this included for example the definition of singularity and power loss requirements [6]. Standard is only applicable to a robots manufactured after its release date [6].

ISO 10218-2

The second part of ISO 10218 standard focuses on the hazards present in robot systems, cells, and lines [8]. These can be considered in general as integrated applications [3]. Standard states that the entities responsible to provide safe working environment of robot system are stakeholders [8]. Stakeholders in this context encompass groups like manufacturers, suppliers, integrators, and end-users [8]. The standard additionally includes specifications for industrial robot systems, which form a component of a larger integrated manufacturing system [8]. The second part introduces more concepts of HRC, such as definitions of terms and regulation for systems in collaboration with human. It is essential to observe that robotic system might include other machines which are in the influence of different standards [8]. These machines should be referenced according to their respective standards [8].

ISO/TS 15066

ISO/TS 15066 is a technical specification from ISO. To emphasize, it is a technical specification not a standard. This means that it is not harmonized, and it is not in scope of A, B or C type. Its objective is to provide more detailed information about the HRC systems with actual measures [3]. The specification includes details for topics such as cobot system design, hazard identification, risk assessment and requirements for applications [3]. The risk assessment does not only include the cobot system itself but also considers the surroundings it is placed [18]. This is important because the risk for safety might not be only caused by the system itself but rather when it interacts with the environment. TS 15066 is a supplement for ISO 10218 standard and is dependent for the robot and the system to comply with the 10218 standard [18]. The Technical Specification takes a deeper look into the collaborative modes from which fulfilling one of their requirements is minimal for cobots [3]. The Technical Specification provides more detailed values for each of these collaborative modes and what are the precise criteria for these modes to make HRC possible and most importantly safe for humans. The HRC is fast developing field which means that the values overall and especially in power force limiting are expected to change as new editions of the Technical Specification comes out [18].

3.3 Legal challenges associated with collaborative robots

HRC and cobots themselves are relatively new sight in industry. Since the implementation of HRC solutions there have been discussion of how to regulate these solutions in order to make them safe for humans. Previously discussed directives, standards and technical specifications try to come up with an answer for this. Unfortunately, the problem is not that simple to just put some limitations and requirements so we could call the HRC solution safe and start using it. The first problem we run into is already in the risk assessment part of the HRC system. Even when the standards states the method for risk assessment, it is noted by the industry that it is very similar to the risk assessment for any other machine or technology [1]. This is not seen as a good thing because the fact is that cobots usually work with close contact to humans and should be treated with required manner [1]. Also, for the safety validation of a HRC solution the regulation is said to be clunky and lacking instructions for clear and understandable testing procedures to validate the safety [3].

Manufacturers usually market the cobots as flexible and possible to use the same cobot in many different tasks due to the lack of safeguards and ease of moving it [1]. In theory this is true and would be a great benefit for a customer, but a problem arises with the legislation. As previously mentioned, cobot is considered as partly completed machinery, meaning that cobot itself can’t get CE marking, but rather the system can. So, when moving the cobot to another task the whole CE marking, and risk assessment process have to be done all again [1]. This is not only time consuming but costly and makes the cobot less appealing solution [1]. Another factor which may diminish the appeal of HRC is that ensuring safety often results in decreased automation efficiency [1]. Considering that HRC solutions are usually more expensive, it might be a dealbreaker for many entities to invest in cobots [1]. Fortunately, there might be light at the end of tunnel since the new Machinery Regulation is coming and updates for the standards are regularly introduced.

4 Safety functions of collaborative robot system

In marketing and common discourse, the word “collaboration” is usually associated with robotic systems without prominent safeguards [1]. For most HRC situations the term collaboration is not that unambiguous. It is imperative to review what type of collaboration is in case. When the degree and characteristics of collaboration is known, not only is the work of programmers easier when the limitations of the collaboration are present, but it is essential for doing risk assessment to recognize which regulations need to be followed [1], [9]. Research has shown that there are multiple different ways to determine the degree of collaboration between human and robot [1], [9]. Even when the levels of collaboration might be named differently, they still follow the same principles in most cases. For this thesis levels of collaboration are divided the in four different categories as presented in Figure 4 [9].

The first level of collaboration is named as independent. In this, operator and a cobot work on their own work pieces in a same workspace [9]. The collaboration dependency here is that the operator and cobot share the workspace so that the cobot is aware of the human when working [9]. The second level is called simultaneous. This refers to a situation where cobot and operator work simultaneously on a same work piece but on separate task or processes in Figure 4 [9]. There is no process or time dependencies so the main focus for the cobot is to give operator needed space to complete the process without the risk of collision [9]. The third level is sequential. In sequential collaboration cobot and operator work on a same work piece sequentially as the name refers [9]. Time is the dependency in this situation between the operator and the cobot, managing it to take turns working on their own processes [9]. Then the collaboration takes a leap forward and the cobot cannot only rely on ensuring the safe space for the operator. The fourth and most collaborative level of collaboration is called supportive. The operator and cobot works interactively on a same process with the same workpiece [9]. The robot needs to have a good awareness of the operator’s intent and task requirements in order to guarantee safe collaboration [9]. The dependency in supportive level is the same working process illustrated in Figure 4. Cobot has to make sure that it does not cause safety concerns while working on the same process simultaneously. This can be achieved with safety control modes.

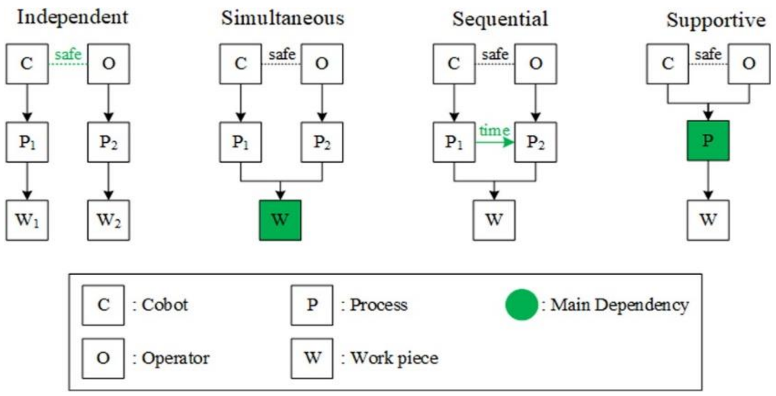

Figure 4: Different levels of collaboration in industrial setting [9].

Previously mentioned ISO standards all discuss the topic of safety control modes when operating in collaborative workspace. When HRC system is designed and made in compliance with the ISO 10218 standards it should fulfill at least one or more of the safety control modes [8]. Any malfunction of these safety features should result in “protective stop” as describes in standards, and the operation should not continue until restart is done from outside of the collaborative workspace [8]. ISO/TS 15066 provides more detailed specifications for these safety control modes [19]. Safety control modes are illustrated in Figure 5. Next the main points of the four safety control modes will be introduced.

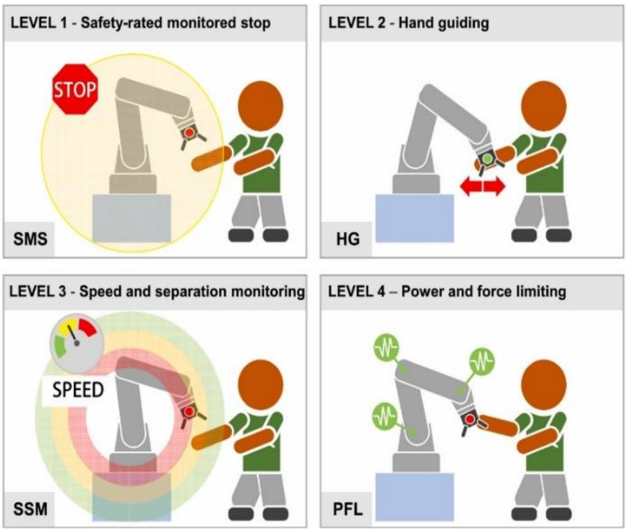

Figure 5: Collaborative safety control modes [1].

Safety-Rated Monitored Stop (SMS): A robot can work in an open workspace but when human enters it the robot shall stop and wait until the human has left the collaborative workspace [19], [18]. This enables the robot to continue its action without the need for any separate confirmation which makes the working more productive and collaborative. This can be achieved with a conventional robot or a cobot.

Hand-Guiding (HG): A robot can be operated directly from the manipulator itself [18]. Standards specify safety requirements for this method in situations like unintentional or mismatched commands [19]. This method can be used for instance to reposition a robot as an aid to lift heavy objects for the human worker efficiently. Hand-Guiding can also be utilized for conventional robots.

Speed Separation Monitoring (SSM): It is one of two safety modes where robot can move independently in a workspace with human. In SSM robot keeps track of the distance to human worker and adapts its speed according to it [19]. If the robot reaches too close to a human, it shall stop [18]. Distances between a robot and a human should be set in risk assessment for the system complying with ISO/TS 15066. SSM can also be applied to conventional robots if the safety criteria is met.

Power Force Limiting (PFL): The only mode where the robot is primarily designed specifically for certain type of operation [18]. This specific design is what is commonly called cobot. Here the cobot is equipped with safety system that monitors forces on the axis so that they do not violate the force limits set [1]. To aid the forces to maintain the under the limits, cobot should have a safe design with smooth surfaces [1]. This mode enables the cobot and the operator to have physical contact [1]. To help risk assessment, ISO/TS 15066 specifies detailed information about the values of force-, speed-, separation distance-, bio-mechanical-, and contact limits [1].

5 Risk assessment

Risk assessment is vital for the safe operation of robotic systems. It is an iterative process which can be categorized into different parts [1], [20]. Risk assessment begins with risk analysis and continues with risk evaluation [20]. Risk analysis includes following parts, “determination of the limits of the machinery”, “hazard identification” and “risk estimation” [20]. With risk analysis, information is gathered to help determine if actions to suppress risks are required [17].

Firstly, the initial step in risk analysis is to determine the limits of the machinery [17]. The intention in this part is to establish when and how the robotic system is used or when it should not be used [17]. This considers all the steps of the system’s life cycle [17]. Secondly, hazard identification should be conducted. This part is relatively self-explanatory, in order to assess or mitigate any risks you first need to identify them [17]. Hazard identification also considers the possible changes of misuse of the system [17]. Lastly, the estimation of the risks can be conducted. ISO 12100 Safety of Machinery standard offers valid approach for estimation of the risks [20]. This includes following a three-step formula which analyzes the severity of harm and the probability of occurrence [20].

Once the risk analysis is completed, the risk evaluation can be carried out. Risk evaluation defines if actions for risk reduction are needed [20]. In the event that risk reduction is necessary, iterative process should be continued until all the identified risks are in acceptable level [17]. ISO 12100 suggest using another three-step method [20]. This iterative method begins with mitigating risk with design measures [17]. If this is not possible step two should be followed. In step two the risk mitigation is executed with safeguards and other protective measures [17]. If these steps still don’t eliminate the risk, step three should be taken. Third step is applicable only if steps one and two were appropriately done and the risk still remains [17]. The third and last step is to minimize the risk with information in systems manual, different announcements or various warning signs [17]. Risk assessment is considered complete when all the identified risks are either mitigated or reduced to an acceptable level, and the assessment has been documented properly [20].

5.1 Risk factors

When considering HRC solutions, several safety concerns are present as observed in this thesis. This is why risk identification is important and always a part of the risk assessment process. A paper was conducted by Nicole Berx et al. gathering risk factors in HRC and classifying them into set of classes [21]. They identified 254 individual risk factors from 32 different references analyzed [21]. The classification resulted in five main classes of risk factors presented in Figure 6 with the number of risk factors in each class [21]. The subsequent sections, 5.1.(1-4), provide a comprehensive overview of the findings presented in this paper [21].

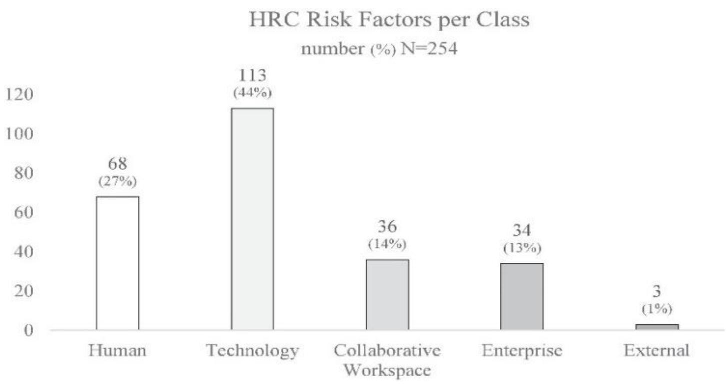

Figure 6: Five main classes of risk factors in HRC [21].

5.1.1 Technology

The largest class with the most risk factors identified was labeled as technology. This class contained 44% of all identified risk factors. Technology class included both the more traditional information technology and the digital technology often referred as Industry 4.0. This concept included mostly risk factors related to the cobot itself (88%), along with some risk factors associated with the operating system which extends over the cobot system. Factors within the cobot system were mostly related to the software and hardware aspects of a cobot, for example bugs and programming issues. Additionally, there were end effector related concerns such as tooling and workpieces. While programming accounts for half of all related risk factors related to cobot systems, representing the largest subclass identified in this research. It is notable that minimizing programming errors determines on a large scale if the cobot is safe to use in collaboration with human. [21]

5.1.2 Human

The second class, which represents little less than a third of all risk factors is related to human operators or any other humans in the cobot’s proximity. From this class three different subclasses were created which were psychosocial, cognitive ergonomics and physical ergonomics with percentages of 54%, 28% and 18% respectively. These subclasses draw inspiration from the International Ergonomics Association’s (IEA) definitions. IEA defines these three classes under human factors in organizational ergonomics. Human factors by IEA also includes psychosocial factors. Human factors in HRC consists of risk factors associated with trust, human error, stress, load due to increased knowledge demands and risks with physical workload which might cause physical disorders and problems. ISO safety standards mention human related factors in their risk assessment processes but it is important to note that these risk factors are mostly considered with physical aspect and the psychosocial aspect is not well mentioned. This might be due to the complexity of assessing the psychosocial hazards. [21]

5.1.3 Collaborative Workspace

This class represents the risk factors associated with collaborative workspaces where the human and cobot interacts with each other. It can be differed from human factors since the collaborative workspace may contain risks which are not directly related to humans nor the cobots. The aforementioned class included subtopics like access-, layout-, obstacles of the workspace. Also, risk factors identified in maintenance were included in this class. The maintenance factor were categorized as a distinct risk with the intention to embrace its importance for safety and attention towards maintenance workers. [21]

5.1.4 Enterprise and External

Class enterprise in this context may also be interpreted using the more common term “organization”. Accordingly, the enterprise refers to various legal entities and economic purposes of the HRC system. Within the enterprise class’s ethical consideration several risk factors are identified such as social acceptance of cobots, privacy concerns regarding data collection by the cobot systems and autonomous decision making of cobots based on algorithms without human intervention. The other side considered is organizational ergonomics which covers topics such as employees’ lack of training and aspects of work design. This includes factors like working hours, which contribute to an increased number of risk factors. The ethics of technology acceptance is a topic which is considered as an impactful part of this research, and it is becoming more popular over time. While new technologies like AI is integrating with the HRC solutions in terms of safety, it is still seen as a double-edged sword. On the other hand, AI can help to reduce the risk in HRC, but it can also affect the safety in the physical, social, and cognitive perspectives for the workers. [21]

The last and most insignificant of these five classes identified was external. This class had two main risk factors which were related to regulations and environmental conditions. These risk factors refer to difficultness to interpret legislation and the risk of weather conditions such as direct sunlight to a HRC system impairing vision and making it difficult to see clearly. Overall, only three risk factors were identified which marks the less significant nature of this class. [21]

5.2 Navigating risks in human-robot collaboration

There are many things to consider when implementing the HRC solution and assessing its risks. Regulations provide a thorough framework for risk assessment in robotics and nowadays information for assessing risks in HRC solutions is well available. It is important to recognize, from the outset of the HRC solutions risk assessment understanding that situations may arise where even with actions to minimize risks hazards could still remain present and pose risks in safety [22]. In this situation, the conventional safeguarding method of fences and other measures are the only option [22]. Also, while small cobots with limited speed can be understood as a safe option for HRC, even the ISO/TS 15066 states that if the cobot is handling sharp objects it causes remarkable risk [18], [23]. For this reason, it is understood that it is the application of the cobot which needs to be considered in risk assessment whether the solution is safe for collaboration [23].

Additional factors to be evaluated in risk assessment of HRC solutions are related to safety modes which allow the collaboration to happen. Standards introduce formulas to calculate the PFL permissible threshold for the force of contact force in collaboration situations [24]. ISO/TS 15066 also specifies a certain levels for these forces in different human body parts [24]. It also details time for the physical contact between the cobot and the human [24]. For reference, in cases were the cobot clamps a human increase the hazard risk significantly [24]. This relation to time is illustrated in Figure 7. In addition, the relative motion of human to the cobot can increase the forces [24]. These are also topics to consider in HRC solutions risk assessment [24].

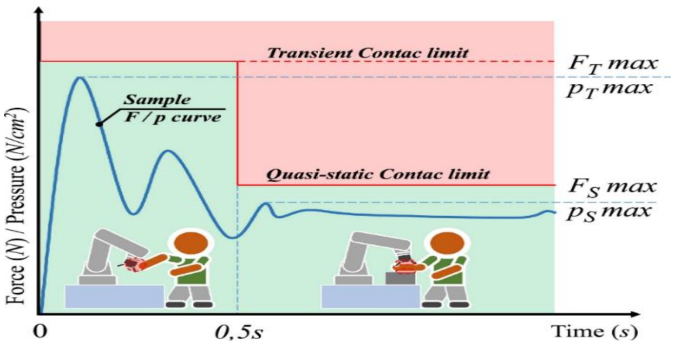

Figure 7: Acceptance of force related to time in PFL contact [24].

As previously stated, the HRC solutions' risks depends largely on the application. This brings the need for re-assessing risks every time even a smallest change is made to HRC application [23]. With significantly more complex process of risk assessment in HRC solutions the process is more likely to have errors and needs a skilled personnel to do the assessment of risks, compared to conventional solutions [23]. All this considered and given the iterative nature of risk assessment in HRC solutions, it is essential to adopt digitalized and more automated methods for risk identification [23]. This approach is necessary to enhance cost-effectiveness and minimize errors [23].

6 Dynamics of collaborative robot collision study

6.1 Introduction

As a part of this thesis, a study was conducted on the forces exerted on a cobot during collisions and compared them to forces experienced by conventional industrial robot without power force limitation in same setting. Data was gathered from ten different collision situations, varying in speed and power force limitation control methods. The objective was to highlight the differences between a cobot and a conventional industrial robot in collision situations, illustrating why power force limitation is justified for ensuring safe collaboration between humans and cobots.

6.2 Setup

The study was carried out using Yaskawa's Motoman HC10 robot. "HC" stands for "human collaborative" illustrating cobot. The "10" in the name suggests that the maximum payload for the cobot is 10 kilograms. The setup for the study utilized Yaskawa's TeachMe Cell, which is a robotic product specially designed for teaching and it is suitable for office spaces and classrooms. The cell was modified by adding aluminum structure, as illustrated in Figure 8. This structure served to connect a plastic plate with a soft foam topping, which was used as a surface for the cobot to collide with. The structure itself was relatively rigid and well within the cobot's reach. The cobot had no additional equipment and was equipped with comparatively small tool. More information about the robot functions and commands used in this study can be found from the Yaskawa's manuals [25].

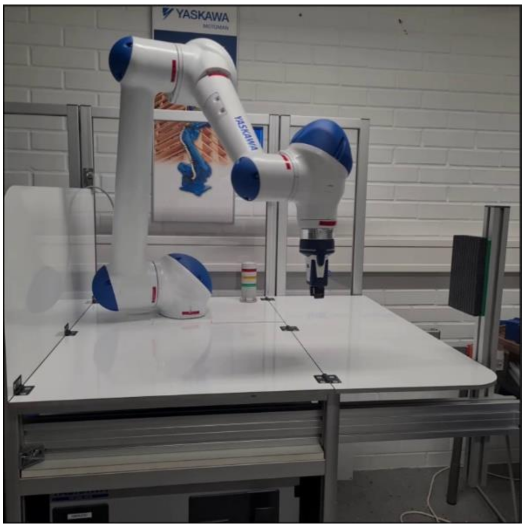

Figure 8: TeachMe Cell with added aluminum structure.

6.3 Data collection

The cobot is equipped with built-in sensors on each axis which measure torque affecting on them. Based on these values the force affecting robot's tool center point (TCP) can be calculated. The data required for this study, was the amount of force affecting the TCP per unit of time. The application for monitoring these forces is called External Force Limit (EFL). This force measuring system is used to achieve the needed PFL qualification for the cobot. Gathered data was then utilized to determine the force in x-direction on the TCP. To measure this force during a collision, two different jobs had to be created for the cobot. Job refers to a program that is run by the cobot. These jobs were then run simultaneously using a function in Yaskawa's programming language Inform called PSTART. This command is used to run multiple jobs simultaneously. The two jobs were named as "törmäystesti" (collision test), as shown in Figure 9 and "voimalasku1" (force calculation 1), as illustrated in Figure 13.

```
1  /JOB
2  //NAME TORMAYSTESTI
3  //POS
4  ///NPOS 2,0,0,1,0,0
5  ///TOOL 0
6  ///POSTYPE PULSE
7  ///PULSE
8  C00000=214215,29823,139033,-2847,-74441,-79950
9  C00001=319434,65149,188505,719,-86607,-146081
10 ///POSTYPE BASE
11 ///RECTAN
12 ///RCONF 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
13 P00030=-400.000,0.000,0.000,0.0000,0.0000,0.0000
14 //INST
15 ///DATE 2023/10/13 13:23
16 ///ATTR SC,RW
17 ///GROUP1 RB1
18 NOP
19 SET D002 0
20 MOVL C00000 V=250.0
21 MOVL C00001 V=250.0
22 PSTART JOB:VOIMALASKU1 SUB1
23 SHCKRST
24 SHCKSET SSL#(1)
25 IMOV P030 V=50.0
26 END
```

Figure 9: Törmäystesti job.

The "Törmäystesti" job was used as the main job including all move points and other necessary features to achieve the desired results. The actual executing part of the job starts from line 18 in Figure 13 which reads "NOP". The lines before this merely to setup the required settings to run the job as intended.

Firstly, the job sets double variable to zero, tracking to which variable the measured force is stored. The cobot's starting position is set, as seen in Figure 10. Then, the cobot is programmed to approach the collision plate linearly, as shown in Figure 11, at a speed of 250 mm/s to align itself perpendicularly with the plate.

Following this the force measuring is initiated with substitute job “voimalasku1”. A shock reset is performed on the cobot to calibrate the shock sensors. Finally, the cobot moves linearly toward the plate with desired speed for each test, illustrated in Figure 12. The movement is achieved with Yaskawa Inform’s “IMOVE” movement type, allowing the cobot to move towards the plate until stopped by either EFL or shock sensor.

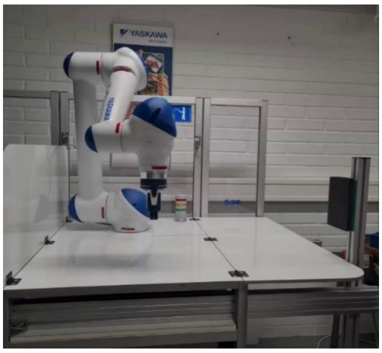

Figure 10: Starting position.

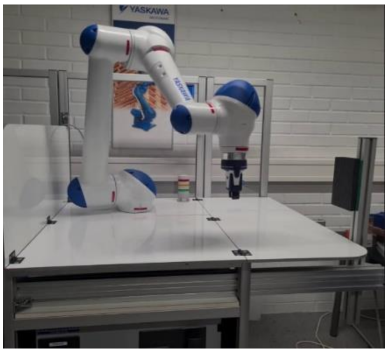

Figure 11: Approaching point.

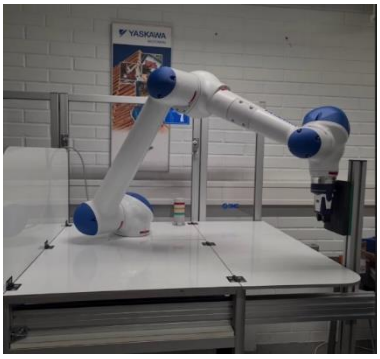

Figure 12: Collision.

The substitute job for force calculation runs on the background after being initiated from the main job. This substitute job captures the “Current (N)” value of “Fx”, as seen in Figure 14. This value is obtained from cobot’s register and stored in an I-variable assigned by the double variable. The stored value represents the force in newtons that is affecting the TCP horizontally in this case. Subsequently, the value of the double variable is incremented by one, ensuring that each subsequent value is stored in a different variable. This process repeats until the cobot is stopped.

A specific time has been set at the end of each cycle in the substitute job to determine the time between each measured force. In this study, the time was set to 0.03 seconds. The value was chosen through experimentation because there was a constraint on the number of variables that could be stored. 0.03 seconds provided the most measurements without exceeding the limit of stored variables.

```
/JOB
//NAME VOIMALASKU1
//POS
///NPOS 0,0,0,0,0,0
//INST
///DATE 2023/10/13 13:26
///ATTR SC,RW
NOP
*A1
GETREG I[D002] MREG#(320)
ADD D002 1
TIMER T=0.03
JUMP *A1
END
```

Figure 13: Voimalasku1 substitute job.

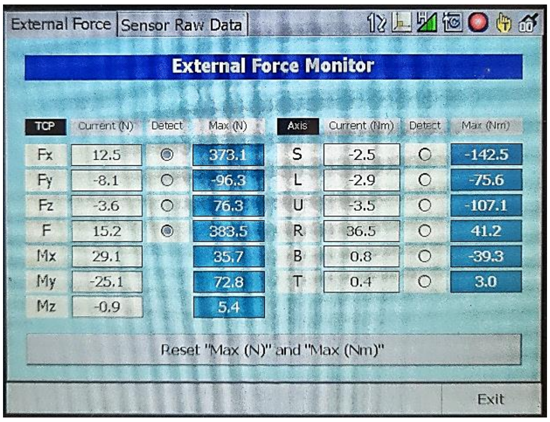

Figure 14: External Force Monitoring interface.

6.4 Data analysis

The data was gathered from ten different collision scenarios. These scenarios were tested with both the EFL on and off, and at five varying speeds ranging from 50 mm/s to 250 mm/s. The selection of the speeds was based on typical velocities used in human-robot collaborative situations.

Graphs made from collected data were modified slightly from the original data obtained using the “voimalasku1” job. As illustrated in Figure 13, an integrated application named External Force Monitor captures the maximum force value it can detect. This value is reset each time the reset button is pressed. In this study, for each new collision, this value was reset, and the maximum force during that collision saved manually from the application. Then this maximum force was added into the graphs to better demonstrate the forces exerted on the robot during collisions.

Without including the maximum force value, the total forces would have been notably lower resulting in less comparable data. The reason for this error is because the job measures force at 0.03-second intervals, limited by the capacity of variable storage. If the maximum force occurs between these intervals, it is not captured. External Force Monitor application on the other hand samples data more frequently which enables collection of more precise data.

Figures 15, 16 and 17 illustrate the graphical expression of force exerted on the robot’s TCP during collisions with speeds of 50 mm/s, 100 mm/s and 150 mm/s respectively. These speeds are comparatively lower than the others tested in this study. As observed in Figures 15, 16 and 17 when the EFL is activated during a collision with the robot, the force measurements continue beyond the peak force. In contrast when EFL is deactivated, the plots terminate at the force peak. This difference is because in the HC10 robot, activation of the shock sensor will halt all ongoing jobs and issue an alert saying that shock sensors have turned on. This indicates that the robot has most likely hit something and should not resume its current job before manually continued. Instead at slower speeds the EFL can stop the robot before the shock sensor is triggered allowing continuation of force data collection until manually stopped, as was the case in this study.

The reason EFL can stop the robot before the shock sensor activates is that it is more sensitive than the shock sensor. In Yaskawa robots, there is an option to adjust the sensitivity of the shock sensor which might raise questions about the necessity of EFL. However, the need for an additional force-limiting method, in this case EFL, is that the shock sensor lacks precision and is not in scope of the safety standards. Setting the shock sensor’s force limit very low can cause frequent activations when the robot’s direction changes rapidly even at slow speeds. This makes the functioning of a robot rather difficult.

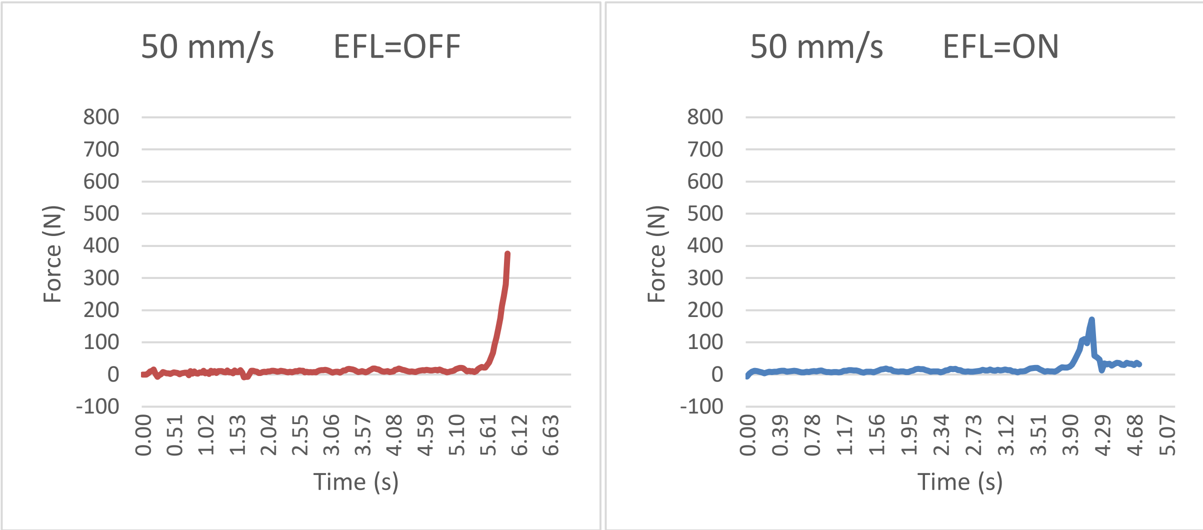

Figure 15

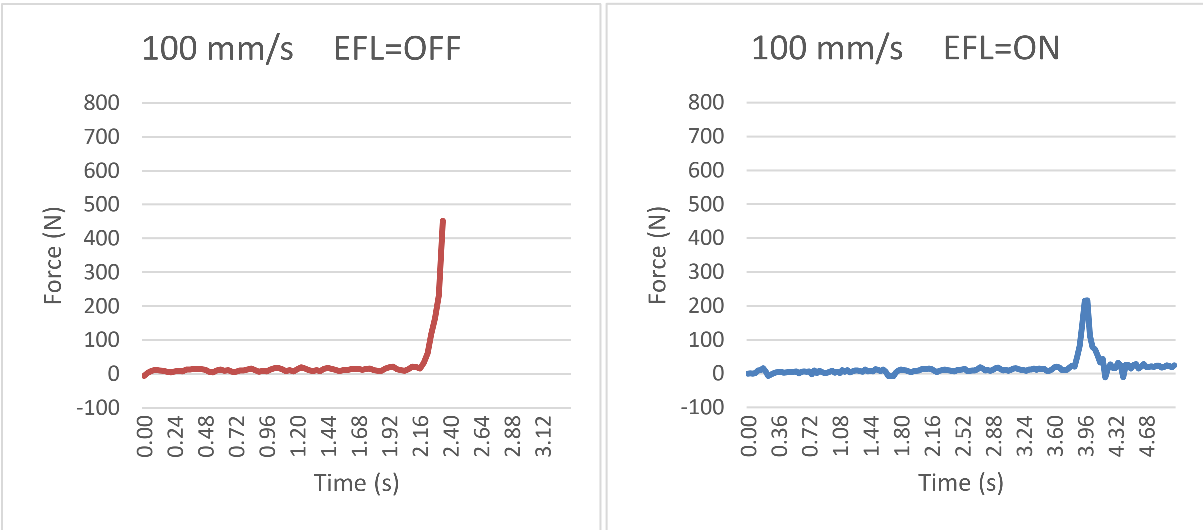

Figure 16

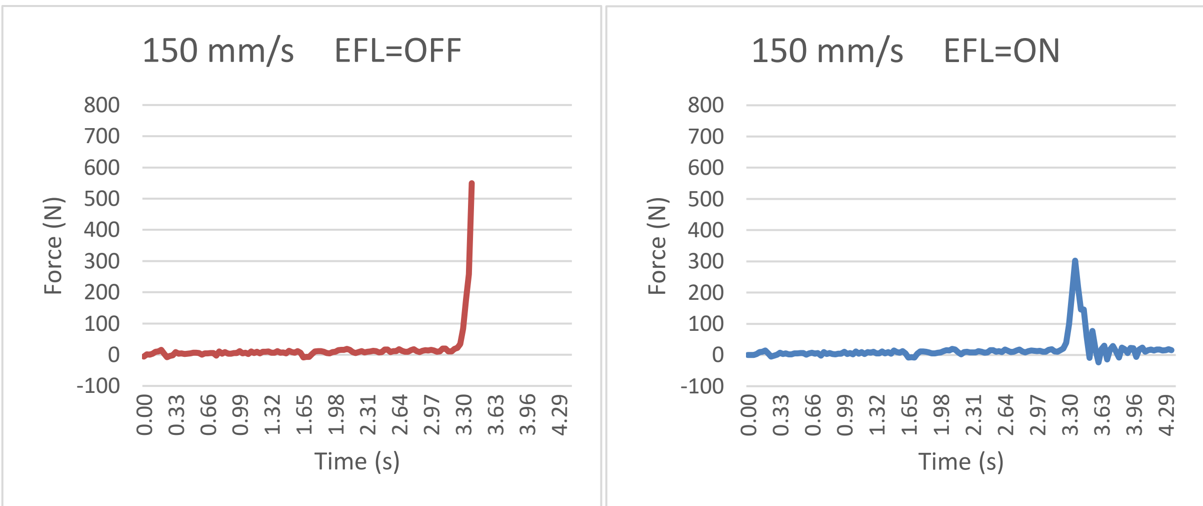

Figure 17

Figures 18 and 19 represent the collision forces at speeds of 200 mm/s and 250 mm/s respectively. These can be considered as higher speeds in this study. As observed in Figures 18 and 19 the measuring of the force stops at the peak force even when the EFL is activated. This occurs because despite the EFL's activation and stopping the robot the forces are still high enough to trigger the shock sensor also. This results in the previously mentioned error and stops the job program. High-speed scenarios like this highlights the significance of the EFL. Even when shock sensor is triggered in both scenarios the force without EFL activated is significantly higher.

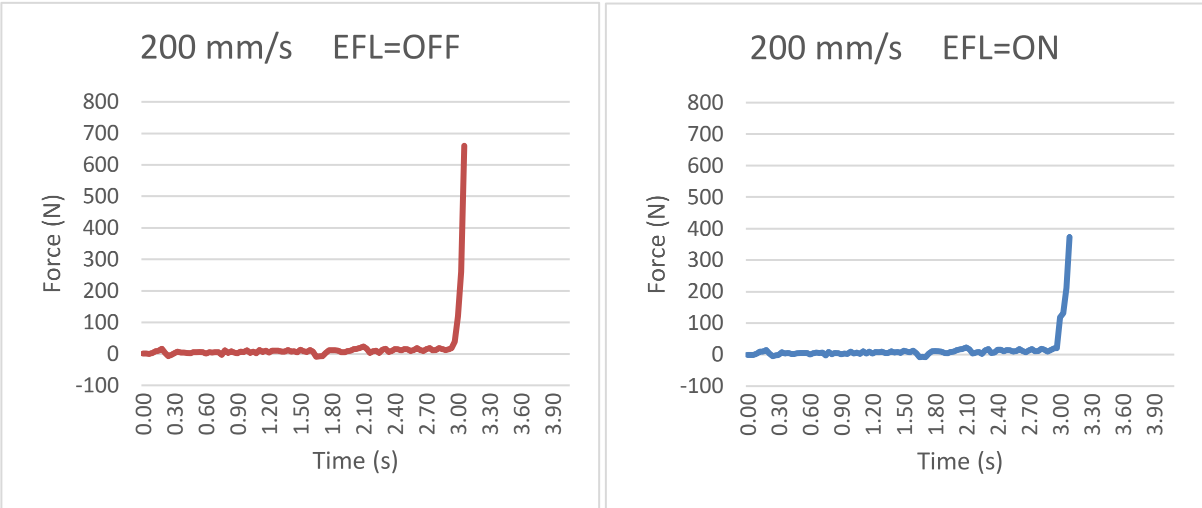

Figure 18

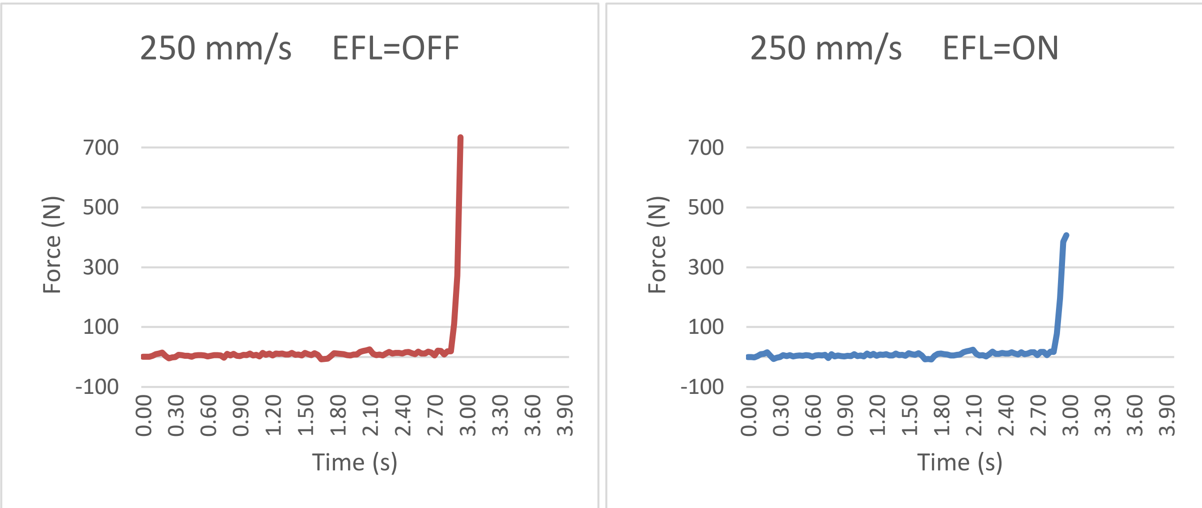

Figure 19

Based on measurements taken at five different velocities a graph is constructed that illustrates the maximum force exerted to the robot at each speed with the EFL both activated and deactivated. This graph is presented in Figure 20. An interesting finding is that the increase in maximum forces for both conventional and collaborative robot scenarios remains relatively linear. This linearity is evident from the linear fit applied to Figure 20. Gathered information suggests that the sensors detecting the forces are constant and well calibrated. The graph also reveals that as the speed increases, the difference in each maximum force values slightly increases. Assumption can be made that at higher velocities the force reduction capability of the EFL also increases to some extent. However, due to a lack of data this assumption cannot be confirmed.

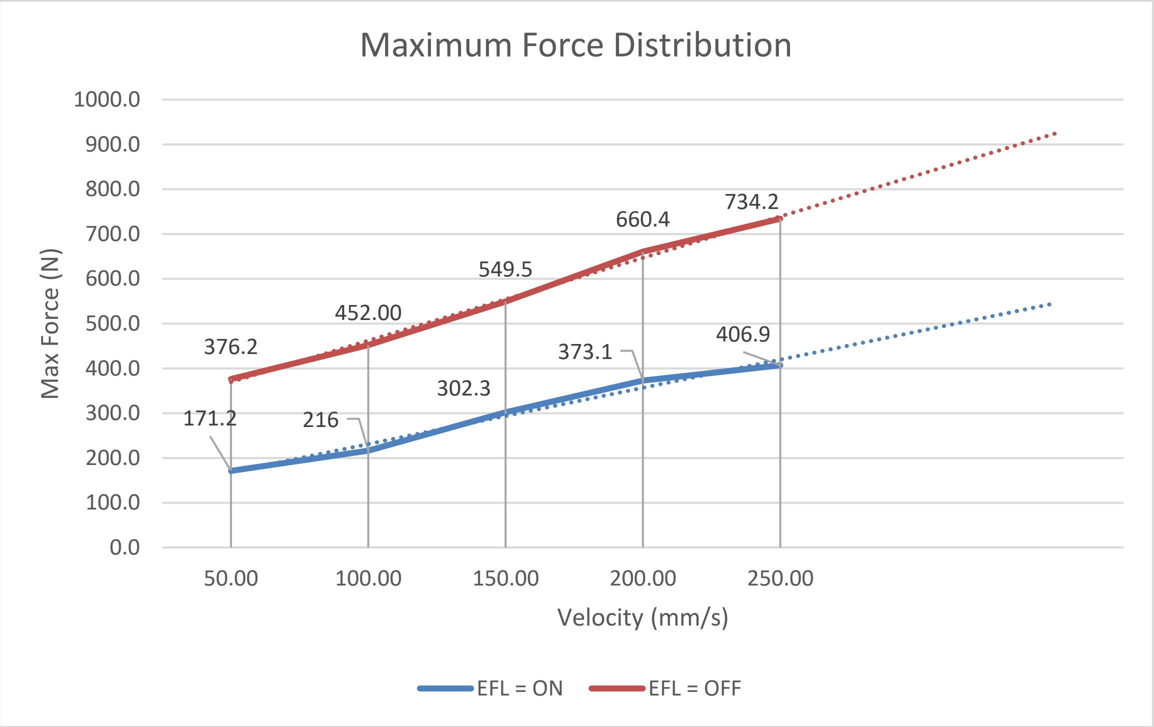

Figure 20: Maximum force distribution of each velocity.

6.5 Results

Overall, this study demonstrates that the EFL activated significantly reduces the forces exerted on the robot. As observed in the force graphs, The absence of EFL can result in forces nearly doubled to those when it is activated. This finding marks the importance of precise and accurate force measurement in achieving collaborativeness.

Even though the graphs show relatively linear trend of increasing force with velocity it is important to note the inaccuracies in the force measurement methods used in this study. First, the force measured is the force exerted on the robot, not on the object. This can lead to significant differences in measurements. For example, if the robot moves slowly but the object or human approaches it, the forces are much higher than if the human was standing still. Second, the values are recorded at least 0.03-second intervals. This leaves a somewhat remarkable gap between measurements, as observed from the highest values recorded by the External Force Monitor application. Lastly, the force exerted on the TCP is a calculated value and not an actual measured value. On TCP the force in x-direction is calculated based on data from the sensors in each joint’s axis. Considering these factors the results indicate a trend but cannot be directly compared to a collision involving a human.

Concluding discussion

The prevalence of human-robot collaboration is on the rise as businesses strive for greater efficiency and more adaptable production methods. Although current regulations offer guidelines for the safe interaction between humans and robots, there is considerable scope for enhancement. This necessity for improvement is largely due to the sluggish pace at which laws and standards are updated. It is widely recognized that legal frameworks often lag behind technological advancements, a trend that also applies to human-robot collaboration. As discussed in this thesis, many aspects of the risk assessment process for collaborative robots remain largely unchanged from those applied to conventional industrial robots. This similarity leads to challenges and risks when trying to develop safe collaborative robot systems. However, there is optimism as regulations continue to evolve and improve. The forthcoming Machinery Regulation, as highlighted in this thesis, aims to address the complexities of safety regulation concerning collaborative robots. Additionally, the increasing dialogue around robotic safety is likely to accelerate the advancement of regulations and enhance the overall safety of robotics.

This thesis underscores the key elements of safety regulation that should be considered when deploying collaborative robot solution. It also provides fundamental understanding of the functions which are present in collaborative robots. The study included in this thesis highlights the quality of one particular safety method utilized in collaborative robots. According to the findings of this study, the implementation of power and force limitations significantly enhances robotic safety However, due to the limited data, the results do not support definitive conclusions but rather suggest a general trend.

The author claims that the preliminary and crucial step in adopting a collaborative solution is to assess the actual need for a collaborative robot. As discussed in this thesis, there are various ways to achieve collaborative solutions without resorting to what is traditionally recognized as a collaborative robot. This approach not only reduces costs but may also increase efficiency. In the author's view, not every robotic system needs to facilitate human-robot collaboration in the future. Rather, it should be regarded more as an optional tool for certain applications than a wholesale replacement for existing robotic solutions.

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