Multi-axis industrial robot braking distance measurements
- For risk assessments with virtual safety zones on industrial robots

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Summary

Industrial robots are increasingly used within the manufacturing industry, especially in collaborative applications, where robots and operators are intended to work together in certain tasks. This collaboration needs to be safe, to ensure that an operator does not get injured in any way. One of several solutions to this is to use virtual safety zones, which limits the robots working range and area to operate within, and may be more flexible than physical fences. When the robot exceeds the allowed limit of the virtual safety zone, a control system that monitors the robot position, forces to robot to stop. Depending on the current speed and payload of the robot, the initialized stop has a braking distance until the robot has completely stopped. How far the separation distance between human and robot must be, is calculated using ISO-standard guidelines when doing risk assessments. To support affected personnel in their work, an investigation and experimentation of braking distances among several robots has been conducted. These testing experiments have been designed to simulate a collaborative operation which is an excessive risk in a robot cell. The tests have been performed with various speeds and payloads, for comparison between the robot models and for validation against already existing data. The difference with this study compared to existing ones is that several robot axis’ are used simultaneously in the testing movements, which is a benefit since a robot rarely operates with only one axis at a time.

Main results of the performed tests are that the robot doesn’t obtain speeds over 2000 mm/s when axis 1 is not involved, before the virtual safety zone is reached. Axis 1 can generate the highest speeds overall, and is therefore a significant factor of the braking distance. The results and conclusions from this thesis states that these kinds of tests give useful information to the industry when it comes to safety separation distance and risk assessments. When applying the information in a correct way, the benefits are that a shorter safety separation distance can be used without compromising on safety. This leads to great advantages in robot cell design, because space is limited on the factory floor.
Affirmation

This master degree report, *Multi-axis industrial robot braking distance measurements*, was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree. The contents that are presented in this report should not be solely used when designing virtual safety zones. Safety personnel should always do their own risk assessments with current conditions. The author cannot be held responsible for any damage or injury that might occur as a result by the information in this paper.

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Björn Lindqvist

Signature by the author

Date

Björn Lindqvist

11/6–2017
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Symbols and glossary

FlexPendant  A handheld device for controlling the ABB robot, which is connected to the controller.
TCP  Tool Center Point. Reference point of a tool in the robot system.
Linear Movement  A robot TCP motion of the trajectory path between two points which is linear. The robot calculates small intermediate steps along the trajectory to make the movement linear.
Joint Movement  A robot TCP motion where the robot axis moves freely between two points.
Jog  Moving the robot manually with the FlexPendant joystick in a coordinate plane or by robot axis.
RAPID  Programming language in ABB robots
1 Introduction

Industrial robots are rapidly increasing in numbers in manufacturing and production today, and are giving benefits like increased efficiency, productivity and repeatability. Collaborative robots, which are intended to work together with humans in a shared workspace, are especially increasing due to the applications that utilizes the advantages of both humans and robots. This collaboration between human and robot obviously needs to be safe, with a minimal risk of injury or harm to the human. One of the many safety solutions to this, is to limit the robot’s work area with virtual safety zones, that makes the robot stop if it moves outside a predefined safety zone. This is something that not only applies to collaborative robots, but to industrial robots in general. The idea of this kind of safety solution is, when the robot operates outside its premises, the safety system forces the robot to stop. By using this type of safety solution, among others, enables more flexibility than using physical fences, even if fences have their benefits as well. An example of a safety zone is illustrated in Figure 1, where a virtual box is surrounding the robot and limits its movements and reachability.

This feature of safety zones is something automation companies almost inevitably include in their products of automation solutions for the manufacturing industry. The solutions that is meant here are machinery or robot cells developed for increasing productivity, efficiency, repeatability or to perform heavy or dangerous tasks that humans can’t. The safety zone feature is something several leading robotics manufactureres has in their robot product lines, and at ABB robotics, this feature is called SafeMove. As mentioned above, virtual walls are build up in the software and limits the robot’s reachability and movements in certain chosen areas with help of zone monitoring and supervision.

One issue with this safety zones that might occur is, that the robot does not stop right where the safety zone is set, because of the robots braking distance. A higher speed of the robot arm when initializing the stop should result in a longer braking distance, as a hypothesis. This is something that must be taken into consideration when designing a safety system and when doing risk assessments, and it is not obvious how far distance the robot need, to do a complete stop after initializing the stop. The concept

![Figure 1. Example of a virtual safety zone seen from above](image-url)
of braking distance is illustrated in Figure 2. The restricted space is where the braking distance is supposed to occur.

Today, assumptions are made together with tables of braking distance measurements provided by robot manufacturers when doing risk assessments on robot cells. One identified problem with these measurements is, that only one axis is tested at a time. An industrial robot rarely operates with only one axis at a time, even if the data is useful as guideline. The desired safety distance from the robot and operator or object is called safety separation distance, and it is crucial to have it sufficient to ensure operator safety. It would be easy to just make a physical fence outside the robot’s maximum reachability to ensure that no one comes near the robot, but that luxury of space on the factory floor is something that is rare in the industry, and not practical at some cases nor flexible. So how can robot cell designers know where to place the safety zones and fences? To help affected personnel in the work, a study of braking distances has been conducted and executed.

1.1 Problem description

The braking distance is only one part of the safety separation distance, and it is the factor that is given attention in this study. This work will be about studying how far the robot reaches before it does a complete stop, beyond a virtual safety zone, from various positions, and with various speed and payload. This will be tested on three types of robots (small, medium and large). One goal is to analyse which axis of the robot is weaker and need a longer braking distance. Several axis’ will be used simultaneously, and one test will be influenced by previous test done by a robot manufacturer, with one-axis braking distances for verification. The robot movement will be tested in both linear and joint movements. Same movements will be tested on all three types of robots, to see if there are any correlations. The measured distance will be from the edge of the
virtual safety zone, to the Tool Center Point (TCP) of the robot arm when stopped. These measurements will be logged and put together into tables and will be shown in graphs. The tests may be repeated several times to obtain a mean value of the braking distance. Category STOP1, that means controlled stop, will be used according to IEC 60204-1. The results will be given in mm, clearly stated from which test, by which robot and with which speed and payload.

1.2 Aims

- Measure braking distance from experiments on three types of robots, small, medium and large. The same movements will be performed on all three types of robots, with both linear and joint movements.
- Various payload and speed will be used among all robots, to analyse these factors that influence the braking distance.
- Analyse the results, draw conclusions and identify correlations between models when applying load and in various speed.
- Identify risks and dangers when working with virtual safety zones, why and when some precautions need extra consideration, to help robot safety personnel in their work of risk assessments.
- How are the measurement results relative to the results from a robot manufacturer?
- Is it worth investigating this braking distance for future work?

1.3 Limitations

- The virtual safety zone controller that is being used is SafeMove.
- Three robots will be selected out of available models from one manufacturer.
- Three pre-determined movements will be used, involving axis 1, axis 2 and axis 3.
2 Literature study

This section presents the required literature as the basis for the knowledge in this thesis. All machines shall follow the machinery directive for safety reasons. Also, ISO Standards describes more in detail safety around e.g. safety devices, specific types of machines, and risk assessments and specific requirements of collaboration robot workspaces. The safety separation distance, which is the minimum distance that the standard requires between an operator and robot is described. This chapter also has a subsection that describes the related work of braking distances. Collaboration and safety has its own subsection, and in the final part scientific papers of safety in collaboration robots are investigated.

2.1 Machinery directive

All machines in Europe shall follow the machinery directive. Machines that are delivered or taken into operation before December 29, 2009, shall follow the Directive 98/37/EC. After that date, the Directive 2006/42/EC is valid and shall be used [1]. The equivalent directive in Sweden of the later one is called AFS 2008:3 [2] and is handed out by the Swedish standard institute Arbetsmiljöverket. There is also a distinction between “old” and “new” machines. Old and new machines are distinguished by the date January 1, 1995, where they have been delivered or taken into operation in the European zone.

The definition of a machine that is given in Directive 2006/42/EC, is “an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application” [1]. A machine can be anything from a handheld electrical device to a whole production line. Machines that are not included in this definition are vehicles, medical technical products, tractors and military equipment.

Safety components which are intended to fulfil a safety function are also included in the machinery directive. These are components, that if a failure or malfunction occur, can endanger the safety of a person. Safety components that is intended to be used as spare parts should not be included into the machinery definition. These safety components should also be intended to replace identical components and be supplied by the manufacturer of the machinery to not be included in the definition. An indecisive list of safety components for guideline is also available [Annex V].
The machinery directives and ISO standards are harmonized into several levels according to their depth of security aspects. These levels are A, B1, B2 and C, see Figure 3. The standard in level A is a more general description of machines and their basic concept, then the standards in level B. The B-standards describes e.g. safety devices, safety distances, noise level, light-beams, vibration levels, and symbols for marking. The C-standards are describing the security of a specific kind of machines e.g. robots. The collaborative robot part in the ISO standards 10218-1 [3] and 10218-2 [4] will be introduced further.

The machinery directive requires that the machine manufacturer or its representative ensures that a risk assessment is done to determine the health and safety requirements applicable to the machine. The machine must then be designed and constructed with the result of this risk assessment. Also, when changes have been made in a machine, a new risk assessment must be done. To give support of what should be included in a risk assessment the standard EN ISO 12100 [5] is of help. However, the standard does not give a specific method for it. It is up to the manufacturer to use a suitable method.

1. Eliminate risk by design and construction
2. Move the work out of risk areas
3. Use protection and safety devices
4. Develop safety routines, educate/inform
5. Use signs and warnings

Figure 3. Machinery directive levels

Figure 4. Five step priority order
The risk assessment shall always be documented in writing, and the risks and how serious they are shall be stated. To help prioritize in the removal of risks, the machinery directive gives a five-step priority order of measures. This method is helpful to ensure production-friendly measures and is illustrated in Figure 4. The further out from the centre of the circle, the greater responsibility for the protection is put on the user.

### 2.2 ISO Standards

All machines should be evaluated in a risk assessment. Old and new ones, and those without a CE-mark. The International Standardization Organisation (ISO) states in EN ISO 12100 [5] the requirements of a risk assessment of a machine. EN ISO 1200 is the foundation of EN ISO 13849-1 [6] which is a guideline of safety design in safety-related parts in control system. This guideline is presented in this chapter and some parts are interpreted together with the machinery directive.

#### 2.2.1 Work method of risk assessment process

According to the machinery directive, anyone who builds or changes a machine is obligated to do a risk assessment that follows the standard EN ISO 13849-1 [6]. This is a requirement to be able to work with the standard. The risk reduction is described in detail in EN ISO 12100 [5]. The work method of the risk assessment is divided into three steps. These steps and the flow of the described work method can be studied in Figure 5.

In step 1, a risk assessment needs to be done to determine the limits of the machinery. After that the sources of risk must be identified, and then rated according to the Required Performance Level (PLr). The PL rating is described further in chapter 2.2.2. The risk is then evaluated and a decision is taken whether the risk is reduced enough or not. If the risk is considered acceptable then the risk assessment is completed. Otherwise step 2 is initialised.

In step 2, the machinery directive’s “five step” method of priority shall be followed to reduce the risk. If the risk reduction is performed due to safety devises, then the control system that monitors the devises needs to be designed according to EN ISO 13849-1. Then the process goes into Step 3. If the safety measures do not require a control system, then Step 3 is not initialised.

In Step 3, design and calculation of safety functions, every safety function need to be evaluated according to Performance Level before and after the design and implementation. An example of such function is emergency stop and safety stop from e.g. gates or light beams. Then a comparison is made to see if PL is at least as high as PLr.
2.2.2 Performance level

In every source of risk, a risk assessment need to be done [6] as described in the previous chapter. The risk is estimated due to three factors, the severity of injury (S), frequency of risk exposure (F) and the possibility to avoid or limit the damage (P). To every factor, there are two options, depending on the level of severity, frequency and possibility. In severity of injury (S), the difference between the options is low severity (S1), and high severity (S2). The frequency of risk exposure (F) has the same grading, low (F1) and high (F2) frequency. The possibility to avoid or limit damage (P) is depended on factors like workspace, machine movements and force. The difference here is whether there is high (P1) or low (P2) possibility to avoid or limit the damage. The second option of each factor is the inferior one. The boundaries between the alternatives are not clearly stated in the standard, but some regular interpretations [7] are shown in Figure 6, together with the risk graph for determining the required performance level. When all factors have been assessed, a performance level is obtained between a-e.
The performance level estimation in step 3 of the risk assessment working method process is a little more comprehensive than in step 1. To calculate PL for a safety function, divide them separately into well-defined blocks, or subsystems. In every block, PL is calculated, or maintained from the manufacturer of the component. Today, the manufacturer of safety components usually provides this information [7] [8]. But if that is not the case, and the calculation needs to be done manually, there are three factors that must be considered: Category, DC (Diagnostic Coverage) and MTTFd (Mean Time To dangerous Failure). Depending on which category the security function belongs to, and the values of DC and MTTFd, a PL can be obtained. An overview of this relationship can be viewed in Figure 7.

The structure of the components in the subsystem is judged to determine what category it corresponds to (B, 1-4). This judgement and how every category is defined can be seen in Table 1. MTTFd is calculated with the following formula [7]:

\[
MTTFd = \frac{B_{10d}}{0.1 \cdot n_{op}}
\]

\[
n_{op} = \frac{d_{op} \cdot h_{op} \cdot 3600}{t_{cycle}}
\]

Where

\(B_{10d}\) = Mean value of cycles until 10% of the components have errors
\(n_{op}\) = Number of cycles per year
\(d_{op}\) = Operational hours per year
\(h_{op}\) = Operational hours per day
\(t_{cycle}\) = Cycletime in seconds

A simple method of determine DC is given in Appendix E in EN ISO 13849-1 [6].

Figure 6. Risk graph for determining required PLr for safety function
Table 1. Safety system categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category B</td>
<td>Base functionality, one failure can lead to missing functionality. One safety channel.</td>
</tr>
<tr>
<td>Category 1</td>
<td>Well-tried components and safety principals. One failure can lead to missing functionality. One safety channel.</td>
</tr>
<tr>
<td>Category 2</td>
<td>One missing function is detected by a separate test by the control system. Can lead to missing functionality between the tests. One safety channel.</td>
</tr>
<tr>
<td>Category 3</td>
<td>One missed function does not result in missing safety function, detected before next operation. Two safety channels with cross monitoring.</td>
</tr>
<tr>
<td>Category 4</td>
<td>One missed function does not result in any loss of the safety function, continuously detected. Two safety channels with cross monitoring.</td>
</tr>
</tbody>
</table>

2.2.3 Requirements of collaborative workspaces

In areas where a robot and one or more operator can interact with each other, special precautions must be taken into consideration [4]. These workspaces shall be clearly defined with for instance floor marking or signs. Operators shall be safeguarded by a combination of the robot performance features that are allowed in ISO 10218-1 [3] and protective devices. If an operator is involved in a collaboration operation, a supervisory control must protect the operator. This control shall be complied with the performance requirements [4]. The collaborative workspace shall enable the operator to easily perform its tasks without any risk of interfering with equipment or machinery. If it is possible, safe axes should limit the free motion. It states that a minimum clearance of 500 mm (20 in) should be provided in the robot system. This distance is measured from the operating space of the robot to areas of building, structures, utilities or other machines that may create a pinch point where an operator can be trapped. If this minimum clearing distance is not provided, additional protective measures shall be taken in to provide protection when an operator is within the minimum clearing distance. In practice, this means that a robot can slow down its motion speed when an operator is at a certain distance, to avoid the risk of being injured. There has been a study of this in a master
thesis work [9], where the author presents a safe solution for human robot collaboration with laser scanners and SafeMove together with trap routines.

2.3 Collaborative operations and safety

Collaboration between industrial robots and humans can be divided into two parts. Either the robot and human can have physical contact with each other and share the same workspace, or there is a separation between them where they do not share the same working area. In the collaboration in shared working area, there are five diverse types of conceptual applications of collaborative robots, according to ISO 10218-2 [4]. The definition of a collaborative operation is, a state in which purposely designed robots work in direct cooperation with a human within a defined workspace. The interpretation is that the actual operation is in the shared working area, and that it is being used for predetermined tasks. The operation should only be possible when all required protective measures are enabled and active. The five different conceptual applications are, respectively:

- a) Hand-over window
- b) Interface window
- c) Collaborative workspace
- d) Inspection, and
- e) Hand-guided robot

These can be seen in Figure 8. The Hand-over window (a) is characterised by an autonomous operation within the safeguarded space. When the interaction is to be made, the robot moves to the window and waits for the operator to perform the intended task. During the access, no interruption is made of the automated operation. The safeguards are inter alia reduced speed and reduced working space near the window.

In the Interface window (b), the robot stops at a predefined interface window, and can be moved manually outside that interface. It has similarities with the hand-over window, but in Interface window there is a hold-to-run control for guided movement. This conceptual application is mainly used for automatic stacking, guided assembling, testing, benching and cleaning.

Collaborative workspace (c) is an autonomous operation within a common workspace that is shared both by robot and operator. Then the operator enters the common workspace, the robot reduced its speed and/or stops. This feature is obtained by a person-detection system with one or more sensors. It is used in collaboration assembling, common handling and testing.

Inspection (d) is the application where the robot continues with the operation with reduced speed if a person enters the collaborative workspace. This also requires a person detecting system. The inspection application is used for inspection and tuning of processes e.g. welding applications.

Hand-guided robot (e) is in an application-specific workspace, where the robot is moving with help of the operator’s hands to guide it along a path. The safeguards are reduced speed and hold-to-run control.
In each conceptual application, there can be one or more methods for the collaborative operation. A method is a way of handling or monitoring the security and risks, depending on the type of operation and work that is being done in the workspace. These methods are described in ISO/TS 15066/2016 [10] and are as follows:

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

In safety-rated monitored stop, the purpose is to make the robot stop or pause its movements when an operator enters the collaborative workspace. When the operator is not inside the collaborative workspace, the robot operates non-collaborative. The idea of this is that the robot can resume and start moving again when the operator has exited the collaborative workspace, without any intervention by the operator.

Hand guiding is when an operator uses a handheld device for transmitting motion commands to the robot. This method intersects with safety-rated monitored stop, because when the operator enters the collaborative workspace to perform the hand guiding, the robot stops as described earlier. The operator cannot perform the hand guiding if the safety-rated monitored stop has not been issued. When issued, the operator can start the hand guiding task, during that time the safety monitored stop is cleared and not active. It becomes active again when the operator releases the device.

Speed and separation monitoring is a used method when the operator and robot shall move at the same time inside the collaborative workspace, like many collaborative operations does in e.g. assembly tasks. To maintain the requirements of risk reduction, there needs to be a safety separation distance (or protective separation distance) between the operator and robot. This is further described in chapter 2.4: Safety separation distance.

Power and force limiting is a method to limit the damage when a robot (robot system) gets in physical contact with the operator. This method requires a robot system that is specifically designed for this type of operation. The contact can be intentional or unintentional. It can be part of a sequence and therefore intentional, or an operator may...
not be following the work procedure correctly and an unintentional contact may occur. This is a critical issue in the risk assessment, to reduce the risk of potential contact between the operator and robot. Measures like passive and active risk reduction, control limits and speed limits will not be described further in this literature study, but referenced to the technical specification ISO 15066:2016 [10].

2.4 Safety separation distance

When working in a collaboration workspace, the distance between the operator and robot needs to be at such distance, that there is minimum risk of contact. The safety separation distance is valid when using interlocking devices, like light-beams and proximity sensors. This distance is a crucial part of the risk assessment and risk reduction. The method of calculating this minimum distance can be obtained from ISO 13855 [11], where the formula of the safety separation distance also is stated. The simplified formula is defined by:

\[ S = K_H (T_R + T_B) + K_R T_R + B + C \]

Where S is the minimum separation distance, \( K_H \) is the speed of the body or part of the body, \( T_R \) is the reaction time of the robot system including sensors and safety PLC, \( T_B \) is the braking time of the robot, \( K_R \) is the speed of the robot, \( B \) is the braking distance of the robot, \( C \) is additional safety distance margin due to resolution and position of the actual safety sensor. [11, 12]. The separation distance is dynamic and changes whenever the variables change.

Calculating the speed of the operator and robot is a challenging task. The speed of the operator, \( K_H \), is assumed to be a maximum of 1.6 m/s in a worst-case scenario, based on the specifications in ISO 13855 [11, 12]. The robot speed, \( K_R \), is an even more complex story. Even if a specified speed is entered in the robot program, the real measured speed may differ depending on travel direction and joint movements [13].
The braking time of the robot, $T_B$, and the braking distance of the robot, $B$, are not constants, but rather functions of e.g. robot configuration, planned motion, speed and load. $T_B$ is measured from the activation of a stop until the robot has halted, and $B$ is measured from the activation of a stop to a complete halt. The speed and load of the robot are variables that have significant impact on the braking time and braking distance, think of it like a car that brakes and stops at different speed and weight. The braking distance differs between manufacturers and models, depending on size, load capacities and working ranges of the robot’s manipulators [14]. The braking distance between different loads is illustrated in Figure 9. If the robot has a mechanical limit, this also determines the braking distance. If the robot reaches the end of its reachability, it can no longer continue. There can also be a mechanical limit installed onto the robot, to limit the reachability, if desired.

N. Yan has calculated the safety separation distance in her thesis according to the mentioned formula [9]. The specifications that were used for the calculation have further been used as a template in this work, to illustrate how much the safety separation distance ($S$) increases when the robot speed ($K_R$) increases. This can be viewed in Figure 10. The range of the robot speed goes from 0.1 m/s to 2.5 m/s. The chart has two lines, the lower one is when Axis 1 is active, and the upper one is when Axis 1 is not active. This affects the breaking time $T_B$, since the robot can stop much faster when Axis 1 is active and used. However, Axis 1 is not used as often as Axis 2 and Axis 3, so depending on the robot movement, the safety separation distance changes drastically. This relation between safety separation distance and robot speed is linear, since the formula is likewise.
2.4.1 Braking categories and braking factors

In IEC 60204-1 [15], it is stated that stopping of moving equipment falls into two categories: “Controlled stops” and “uncontrolled stops”. The moving equipment from IEC 60204-1 will be referred to as robot for the sake of the understanding and implementation in this text. In a controlled stop, the speed of a robot axis is reduced to zero while electrical control of the actuators still is maintained. This means that the motions can be directed until the robot has stopped. In an uncontrolled stop, the electrical control and power is removed from the actuators. This results in a loss of ability to control the motion of the robot while the system stops. The uncontrolled stop only refers to the removal of electrical power, and not to a mechanical stopping device. IEC 60204-1 also states three categories of stop functions. The categories are based on: removal of power, application of brakes, and control of the robot during braking. The three categories are shown in Table 2. In the first category, STOP0, the robot movement is stopped by removing the electrical power and applying the mechanical brakes. This is an uncontrolled stop and is intended to stop the equipment as quickly as possible, which can often make the motion of the actuators deviate from the intended path [13]. In STOP1, the robot does a controlled stop, which means that the power to the actuators is maintained until it does a complete stop, then the power is removed and brakes are applied. In the last category, STOP2, the robot does a controlled stop, but without any braking and the electrical power to the actuators is not removed and monitored by a safety control system.

Factors that affects the braking in a mechanical system are inherently non-linear [13]. And different braking categories (STOP0, STOP1, STOP2), has different braking functionality and they are triggered in several ways depending on the operational mode. This can also vary between robot manufacturers and their preferences. An example of different triggers and the category response is illustrated in Table 3. This example is from the National Institute of Standards and Technology (NIST) Collaborative Robotics laboratory [16], and shows two different modes, Teach mode and Automatic Mode, of a 7 DOF collaborative robot.

Figure 10. Safety separation distance with respect to robot speed
As mentioned in the previous chapter, the reaction time of the system $T_R$ is a factor of the safety separation distance formula. This is also coherent with the braking time and braking distance, since the reaction time is the time passed since an operator was in the actual location. If there is a long lag between an event that occurs and when the event is registered, it is a safety risk, regardless of the accuracy and precision of the data that is registered. For instance, if an operator walks towards a robot at 2 m/s, and the operator is registered a half second later, the safety separation distance may be 1 m shorter than indicated.

Table 2. Stopping categories as defined in IEC 60204-1

<table>
<thead>
<tr>
<th>Stop category</th>
<th>Controlled (Yes/No)</th>
<th>Power removed (Yes/No)</th>
<th>Brakes applied (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOP0</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>STOP1</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>STOP2</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3. Stopping responses of industrial robot with teach mode and automatic mode

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Stop category response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teach mode</td>
</tr>
<tr>
<td>Safety gate opened</td>
<td>-</td>
</tr>
<tr>
<td>E-stop pressed</td>
<td>STOP0</td>
</tr>
<tr>
<td>Enable withdrawn</td>
<td>STOP0</td>
</tr>
<tr>
<td>Start key released</td>
<td>STOP2</td>
</tr>
<tr>
<td>“Drives Off” key pressed</td>
<td>STOP0</td>
</tr>
<tr>
<td>STOP key pressed</td>
<td>STOP2</td>
</tr>
<tr>
<td>Operating mode changed</td>
<td>STOP0</td>
</tr>
<tr>
<td>Encoder error</td>
<td>STOP0</td>
</tr>
<tr>
<td>Motion enable cancelled</td>
<td>STOP2</td>
</tr>
<tr>
<td>Controller turned off/power failure</td>
<td>STOP0</td>
</tr>
</tbody>
</table>

2.4.2 Measured stopping time and stopping distances

The safety separation distance is influenced by factors like breaking time and braking distance. Even if the mathematical theory may be accurate as the result of experiments and testing, robot manufacturers like ABB provide tables of stopping time and stopping distances for all the robot models in their product line [17]. These measurements are all according to ISO 10218-1, and are intended to help personnel in the planning of safeguard placement in robot system design. It is important to mention that only axis 1, 2 and 3 are being used for calculations and measurements, and only one axis at a time per measurement. The tests use two categories of stop, STOP0 and STOP1, as defined in IEC 60204-1. The time and stopping distance in STOP0 is measured when the robot arm is fully extended, with maximum speed and maximum payload. In the data of category STOP1, the measurements are divided into three types of extension zones. The extension zones are dependent on how far the Wrist Center Point (WCP) is extended from the centre of the robot base. If the radius goes from 0 %, which is in the centre, to 100 %, which is the maximum reach of the WCP, then the zones are divided according to this radius. Zone 0 is the radius from 0-33 % of the maximum reach, Zone 1 is from 33-66 %, and Zone 2 is from 66-100 %. The extension zones are illustrated in
The stopping distances that are available from ABB are presented as angles. Angles of each axis from the initialization of stop, to where the robot has stopped. Large stop angles do not necessarily mean long stopping distance. If Tool Center Point (TCP) is close to centre, slight changes in TCP movement may correspond to substantial changes in angles of axis. This counter-intuitive data is something that particularly happens in Zone 0.

For every model in the ABB robot line, category STOP1 gives two diagrams of each of the tested axis, of each extension zone, a total of eighteen diagrams. In category STOP0, where the time and stopping distance was measured with maximum payload and speed at full extension, a table is given with data of each axis with stop time and stop distance. For the model, IRB 6700 2.65 m 235 kg, these values can be viewed in Table 4.

Table 4. Stopping distance and time, category STOP0, IRB 6700 2.65 m 235 kg

<table>
<thead>
<tr>
<th>Axis</th>
<th>Distance (degrees)</th>
<th>Stop time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>16.7</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>12.3</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The values obtained from the STOP1 diagrams gives an indication of how the robot behaves in different zones, loads and speed. These values are also for validation of braking functionality that should be performed every once a year. The angles and times are given for one axis at a time, which may not be realistic because the robot is usually not moving in only one axis at a time. At least it is something that automation engineers and planners can rely on when designing a robot cell.

2.5 Scientific papers in collaboration

Research in collaboration robots is something that is a hot topic at the time. Flexible manufacturing requires robots and systems that can cope to change in the production, complemented with human labour. The interaction and cooperation between robots and humans needs, undisputable, to be safe and secure first-hand. There are several different solutions how to obtain a collision-free, safe environment. It usually means a vision-based solution with cameras. For small robots, collision detection with proximity/contact force sensors that registers impact is observed. In [19], Y. Tian et.al has
done research in sensor-less collision detection, and observes the friction in a joint collision torque. This reduces the need for any extra sensors, and can be applied directly into the collaboration system. Studies have also been done by H.M. Do et al. with counterbalancing mechanisms in the end manipulator, that reduces the gravitational force and collision impact [20].

There are also solutions that makes the robot retract away from the human so that a safety distance is always obtained. S. Augustsson et al. [21] has presented a study of this kind of solution. This has a behavioural advantage in the human psychic, and makes the operator feel safer when entering a robot cell. The robot can for instance be handling a nail gun, and therefore a safety distance that cope with human movement is desirable. B. Schmidt et al. [22] shows that once the robot has retracted, it can regain the path to continue its task when the operator has cleared. This active real-time collision avoidance enables safety in the collaborative work. 3D models are connected to a set of motion and vision sensors for collision detection in an augmented virtual world. This approach is used to improve the overall manufacturing performance that is cost-effective and increases productivity and flexibility. It also fulfils the operator’s safety without using any fence [22]. Even after a collision, the robot can react in such way that is goes away and not just limiting the damage. A. De Luca et al. [23] have successfully made experiments with a KUKA LWR-IV robot with this feature. It can also react to hand gestures and voice commands, depending on the intentions. The authors present a framework for safe pHRI (physical Human-Robot Interaction) based on a hierarchy of consistent behaviours, using collision avoidance algorithms and joint position measurements.

There are various sensors with advantages and with different purposes. Vision technology and scanners are mostly being used for the utilizing of safety zones. To notice an operator or object, there must be a sensor that detects either light or emitting particles for reflection. Scanners used for safety zones were studied by N. Yan [10]. The concept of safety zones as a dynamic system for human-robot interaction was studied by S. Augustsson [24] with the conclusions that safety zones are preferably used with 3D cameras with some modifications. The use of cameras to conduct safety zones might have a higher initial cost compared to fences, but are easier to move when there is a need for change in production i.e. more flexibility.

It is also possible to integrate multiple sensors into the robot system for potentially increased safety. M. Bdiwi presents a work [25] of integrating vision, force and sensitive skin sensors in hand-over and assembly operations with an industrial robot. The vision system is used for human detection, face recognition and object detection in the hand or if the operator hand is empty. The vision sensor also helps recognizing from which direction force is applied, and dangerous directions of the robot for the operator. The force sensor is used for the robot’s reaction in the hand-over, and the sensitive skin is for collision prevention. The work assumes that the operator is the faulty link in the collaboration, and that may be a good assumption, since humans tend to do mistakes when unfocused or sloppy. This argues for increased use of various sensors for human safety. The author did also implement voice commands for information about robot position to the operator. Tactile sensors are something that also could be implemented in the system, and is suggested as future work.

2.5.1 Current research

When a company installs and implements a collaborative robot, the task and path programming can take time, also if there is a change in the work task and the collaborative
robot needs to be reprogrammed. Robotic expertise isn’t something all companies have a need for in a high extent, and software that enables personnel to easily create tasks for collaborative robots is something that is valuable. It is a step towards smart factories, and may provide a gateway to the Industrial Internet of Things (IIoT). The Interact 5 collaborative robot from Rethink Robotics [26] uses a train-by-demonstration interface and claims to be the fastest-to-deploy robot in the world. This new feature in the industry reduces the time of how quickly robots can be deployed on factory floors. Software that enables programming of collaborative robots and are easy to use for non-experts, utilizes company resources. Even if collaborative robots from Rethink Robotics mostly are available for research, the possibilities for the future can be seen at a glimpse.

A project [27] led by Madeline Gannon, founder and principal researcher at ATO-NATON (former Madlab), where an ABB IRB 6700 industrial robot is transformed into a “living, breathing mechanical creature”, shows the possibilities and future of collaborative robots where human-like characteristics like empathy and companionship are shown by the robot. The robot responds to gestures and follows human movements, and the robot was placed in an exhibition from November 24th, 2016 to April 23rd, 2017. Other projects done by the team shows how the interaction between human and robot is on uprising where industrial robots are moving from machines to companions in the workplace.

The world leading manufacturers in robotics do all have light weight collaborative robots. There is clearly a trend of this in the industry. KUKA LBR IIWA is a 7 DOF collaborative robot from KUKA Robotics, that has joint torque sensors in all seven axes. When an external force is applied, the robot retracts, which makes it safe to work around [28]. Universal Robots also has a collaborative robot line, with the UR3, UR5 and UR10 [29]. The named collaborative robots are all one-armed, but ABB Robotics has a two-armed collaborative robot: the ABB YuMi. It is the “world’s first truly collaborative robot” and is claimed to be safe to work around for the operator without any safety zones. The advantage for a dual arm can be that the robot performs the required motions to an assembly of small parts, within human arm reach.

Since there is a rapid development of collaborative robots and increasing number of applications, risk assessments becomes more critical even if the collaboration operations becomes safer. The risk assessment is still the foundation of risk reduction and most of the approaches are focused on safety evaluation and safety control strategies, to avoid collision between robot and human or obstacles. M.P. Polverini et.al [30] presents a new safety assessment, named kinetostatic safety field, that calculates the risk near an operator or obstacle moving in R3. The calculations give a dynamic field that is influenced by the position and speed in real-time. The source of danger is located using triangular mesh representation, and the calculations are depended on relative position and relative velocity between the danger source and the dynamic field. Even if there are no safety guaranties, this novel approach may be more useful because of the relative velocity consideration, compared to other studies [31] [32] which are only using the relative position with bounding volume and linear representation. The experiments of the study of the kinetostatic safety field where conducted on a ABB YuMi (FRIDA) collaborative robot. The experiments where successfully made, which also supports the authors approach.
3 Method

- Literature study
An extensive literature study was done to investigate various safety solutions in industrial robot cells that are available and ongoing in the research, that this study can base its approach on and to present the knowledge needed for this work. The machinery directive and ISO standards must be considered when the work is about risk assessment and safety aspects around industrial robots. How the braking distance relates to the safety separation distance, and how collaborative operations and safety are interpreted in today’s research. Industrial robots are used more and more in collaborative operations, hence the increased research in safety around these operations. This information is necessary to understand the fundamentals and to show credibility of the thesis work.

- Experiment setup
Three various robots were obtained to perform the experiments on, these should differ in size and payload capacity for comparison of results and to draw substantial conclusions. The robots were tested with various payloads and speed; therefore, weight was added on the end effector, at various levels with the highest weight close to the robots’ maximum payload capacity. To be able to perform and carry out this feature, a weighting device needed to be constructed, to easily change weights. Varying the speed during the experimentation is maintained in the robot program, where TCP speed can be set as a variable in the path execution between two points. To determine the positions from where the trajectory path should be executed from, and to a target position, focus is put on reality scenarios and collaboration operations. These positions are developed together with robotics safety experts that designs robot cells and are doing risk assessments for intended purposes. The starting positions and trajectory movements was the same for all robots, but inherently not the same in real position, due to various size and reaching positions between the robots. The starting position was strived to have the same axis angles and configuration of all testing robots.

- Virtual safety zone design
To trigger the stop of the robot that is explained in the problem description, a virtual safety zone needed to be constructed. As mentioned, the used safety solution for this project was called SafeMove, due to the brand of the robots. The virtual safety zones where built up using a software for robot cell design; RobotStudio. A target position outside the safety zone is set for the robot to aim at, whereas the robot is triggered to stop after going outside the allowed virtual premises. The virtual safety zone must therefore be designed to allow the robot to accelerate enough to obtain the desired testing speed, and at the same time be able to brake and stop before the robot has reached its maximum reaching capability. The geometry of the virtual safety zone is a cubic box which is surrounding the robot, with alternations and variations. Inherently, this area differs among the robot models and possibly
the testing scenarios as well, depending on the various purposes of the testing scenarios.

- Measurement technique
As the setup for the experiments are done, and the virtual safety zones are constructed, a method for effective measurement of the braking distance had to be considered. Current tool position can be observed in the FlexPendant, which calculates the pose by the robot’s joint angles. The x-position and axis angles is of interest in this study, because the trajectory will be constructed in a 2D-plane, along the base cartesian x-axis and around the z-axis. The x position is controlled and verified with physical measurements by ruler and digital scaler. When designing the safety zone, the position and distance from the robot’s base, to the virtual safety limit is known since it is manually set. To verify that the safety zone limit is correct in reality, the robot will be jogged at a speed of 5 mm/s to breach the safety zone limit. When the safety system triggers the robot to stop, the braking distance will be negligible since the robot speed is extremely small, and the robot should stop very close to the safety zone limit. This recorded position of the tool is compared to the pre-set values in the safety zone limit, which is expected to be within a margin of 1 mm to be acceptable. In the experiments, a tool0 position was used, which is the default position where the centre point of the end effector is located, and is consistently used throughout the study. Hence, the actual value of the braking distance is where the safety zone limit is, to where the robot tool0 position is after the robot has stopped. This measurement was noted and recorded in mm, and in some scenarios degree angle.

- Results
When the braking distance measurements were recorded and registered, the values were collected and put into tables for drawing graphs and diagrams for further investigation, comparison and conclusions.
4 Work

The experiments and testing needed sufficient planning and preparation. This chapter describes this work of how the experiments were conducted and executed. The selection of the three types of robots that were used, how the various speed and weight were chosen, how the virtual safety zones were constructed in RobotStudio, and how the testing scenarios were designed.

4.1 Robots

Three types of ABB robot models were used for the experiments. They all differ in size and payload capacity, and are intentionally selected for comparison of the outer extremes. The three robots were:

- Small robot: IRB 140 0.81 m 6 kg
- Medium robot: IRB 4400 1.95 m 60 kg
- Large robot: IRB 6700 2.65 m 235 kg

There are many other robots that could have been selected, but these were the ones that were available for use during the time of the project, and matched the desired preferences of robot size. All the robots had the IRC5 controller cabinet and RobotWare 6.03.02, with the safety controller module SafeMove installed.

4.2 Testing scenarios

There were three various testing scenarios of the experiments, the first two was involving axis 2 and 3, while the last one was only involving axis 1. Test 1 and 2 therefore has an operating space of the x-z plane, while test 3 has it in the x-y plane. The intention of the experiments was to see how far the robot stops after the virtual safety zone limit has been breached, aka the braking distance, so the target point of the first two test is an offset in positive x-direction given in mm. And in test 3, the braking distance is given as an angle.

The virtual safety zone limit is different depending on the test and robot model. The choosing of how far in the x-direction the limit should be was tried out with respect to how far the robot can reach, and to gain sufficient speed before the limit in the higher speed tests. The robot must still be able to do a complete stop before the maximum reach point, to make sure that the stop is done by the electrical brakes and not the joint limits. This was also an incentive to not place the boundary too far away from the robot, because this would not give a correct result if the reaching limit of the robot would have been reached, even if more speed could have been accumulated by the longer acceleration distance.

The three tests are described with tables of axis angles and figures of the set-up, target point, and virtual safety zone limit, now referred as SafeMove. All figures are illustrating the robot IRB 4400, the same angels apply for all the robots, but not the SafeMove limit and distances.
4.2.1 Test 1

The pre-set-up of test 1 has specified axis angles that are shown in Table 5. Axis 2 has a negative angle of 45 degrees, while axis 5 is set to 90 degrees. This arrangement sets the position of the robot as shown in Figure 12. The movement is mainly involving axis 2 and 3, and in some extent axis 5, although axis 5 does not make any difference in the change in position. As axis 1 and 4 is not involved in this test, there is no change in the y-direction, which makes the test to be executed in the x-z plane.

The idea was to place a target point beyond the SafeMove limit, near the maximum reaching point of the robot, to enable a long acceleration distance and braking distance if necessary, when higher speeds are obtained. Same reasoning is applied to the starting position, the robot’s axis is tilted backwards to enable a long distance from start to target point. Axis positions are set to even degrees for readability and to easily replicate the tests between the robot models. Axis 5 is set to point directly down in negative z-direction for the addition of weights on to the fixture.

The target point will be reached by two various movements by the robot, linear and joint movement. The difference between them are that a linear movement has the characteristics of moving the TCP the closest way possible, a straight line, to the intended target. On the other hand, a joint movement is when the axis' are moving the most efficient way possible to get to the target, the robot calculates the axis angles of the target and then rotates the axis’. This will result in two different motions to get to the same target, and both are tested for comparison an analysis.

Why this test only involves axis 2 and 3, making a “pushing” motion forward in the x-direction, is to simulate a hand-over motion in a collaborative operation. In the conceptual application hand-over window, there usually is a pushing motion when the collaboration between the robot and operator takes place. Therefore, this test is focusing on this pushing motion for collaborative applications. And why the target position has the same level in z-direction, is to get a maximum value of the change in x-direction. If the trajectory movement would have been diagonal, it would arguably not have reached as far as a straight line, since it is the value in x that is being measured.

Table 5. Axis configuration in testing scenario 1

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>-45°</td>
<td>0°</td>
<td>0°</td>
<td>90°</td>
<td>0°</td>
</tr>
</tbody>
</table>
4.2.2 Test 2

This scenario has practically the same movement as test 1, but with a lower starting and target point in the z-direction. Linear and joint movements are executed in the same manner as the previous test. The values of the six axis angles in the starting point are shown in Table 6.

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>-30°</td>
<td>30°</td>
<td>0°</td>
<td>60°</td>
<td>0°</td>
</tr>
</tbody>
</table>

Figure 12. Testing scenario 1

Figure 13. Testing scenario 2
These values of the axis’ give the positioning and visual representation of the robot as shown in Figure 13. The target point is, as in test 1, located close to the maximum reach of the robot in the x-direction. This point was obtained by jogging the robot from the starting point in the x-direction as far as possible. Virtual safety limit has the same coordinates as in test 1, making the difference between the test rather minimal. It is just the starting position and consequently, the target position that differs between test 1 and 2. Why test 2 has this difference in the starting position is to evaluate if this change makes a difference in the results of braking distance. Both tests have the pushing motion which was supposed to simulate the collaborative operation and application hand-over-window. The acceleration distance is shorter then in test 1 because the robot end effector is not placed as far back as in test 1. This may result in that the robot cannot gain as high speed at the SafeMove limit, due to the shorter acceleration distance.

4.2.3 Test 3

The final test is a validation of table values from previous test results, where axis 1 is moved in extension zone 2 with a category STOP1. The set-up with axis values are shown in Table 7.

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°</td>
<td>75°</td>
<td>20°</td>
<td>0°</td>
<td>-20°</td>
<td>0°</td>
</tr>
</tbody>
</table>

This alignment of the axis makes the robot to extend far out from its centre, shown in Figure 14, where more force will be needed to stop the robot movement. This scenario differs from the first two because only one axis is used, and this results in a joint movement only, and not any linear movement test. When the robot is jogged at slow speed (5mm/s) and stops at the SafeMove limit to verify its position, that angle is then from where the measurement takes place to the actual stop. To clarify, the angle that axis 1 has at the SafeMove limit, to the angle that axis 1 has at the completed stop, is the braking distance angle that will be the measurement.

Figure 14. Testing scenario 3
How far the acceleration distance is before the SafeMove limit may be crucial for the limit entrance speed. Depending on free space around the workspace of the robots, the acceleration distance may vary in this test between the robot models.

4.3 Speed and payload

To obtain useful data for plotting graphs for later comparison and conclusions, various speeds and payloads were used. The various speeds were tested each one separately in all tests, together with the payloads. The speed in the experiments is referred as the TCP speed, and does not necessarily correlate to the speed of the robot axis movement. Especially in extension zone0, where small TCP movements can correspond to large axis movements and turns. There are various speeds that can be selected by default in the RAPID code, and some where added by the author. The speeds that were used in the experiments were:

- \( v_{500} \)
- \( v_{800} \)
- \( v_{1000} \)
- \( v_{1250} \) (not default)
- \( v_{1500} \)
- \( v_{1750} \) (not default)
- \( v_{1850} \) (not default)
- \( v_{2000} \)
- \( v_{2500} \)
- \( v_{3000} \)
- \( v_{4000} \)
- \( v_{5000} \)

All three robots used in the experiments had various payload capacity, hence various payloads where added in the tests. Three payloads were used on each robot, no one were tested with no load at all, with the argument that an industrial robot rarely operates without any tool or equipment attached and is therefore not a subject of investigation. And the data that was used for validation is presented as 33, 66 and 100 % of maximum payload, which this project also has tried to implement. The respective testing weights on each robot can be seen in Table 8. The Payloads on IRB 6700 do not match the percentage ratio, because a lack of heavy parts and material on sight. Although, 141 kg is still a noticeable payload, the results will not be of the desired percentage ratio.

<table>
<thead>
<tr>
<th>Robot</th>
<th>Payload 1</th>
<th>Payload 2</th>
<th>Payload 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRB 140</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>IRB 4400</td>
<td>23</td>
<td>36</td>
<td>56</td>
</tr>
<tr>
<td>IRB 6700</td>
<td>34</td>
<td>91</td>
<td>141</td>
</tr>
</tbody>
</table>

To be able to change payloads easily and safely on the robots, payload devices was constructed to each model. These payload devices were attached to the robot’s standard tool fixture. All the robots inherently had different fixtures because of the size of the robot. And the payload devices were constructed in a way, that made it possible to add weight plates to obtain the desired payload. Pictures of the three payload devices can
be viewed in Appendix: Pictures of payload devices A. The payloads were also checked against load diagrams of each robot to see if the load was inside the allowed extension. The lowest payload on IRB 6700, 34 kg, is the payload device without any weighting plates on.

The payload device was added as a tool for the robot system, and the tool data of the mass was changed accordingly as the various testing weights was attached. A Tool Center Point (TCP) for the tool was also defined, thou this is the reference point from where the measurements took place. The TCP for the payload devices are all set as the same value as tool0, meaning zero offset in all directions, which is the original reference point of the robot system. This defined TCP is the one that is being used as reference for the measurements of the braking distance, and in this thesis referred to as tool0 because the coordinates are the same, and tool0 is a well-known reference point within the robotics industry and by robotics personnel.

4.4 Virtual safety zones

The main scope of this project is to observe how far out the robot can breach through the virtual safety zone before it does a complete stop. Depending on robot manufacturer, there are different product names of various virtual safety zones, and the tested feature of virtual safety zones in this project is called SafeMove. This is because of the brand of the robots that the experiments where performed on. The virtual safety zones in SafeMove can be built up with various geometries according to the safety user’s specifications. For the experiments in this project, cubic zones around the robot was built up, but only one side will be used for triggering the safety stop in the experiments. There needs to be a closed geometry to allow the safety function to work. Every robot had diverse sizes of safety zones because of the difference in robot size and reaching capability. Every robot model had a specified virtual safety zone, respectively. These are presented and explained further. Tables of coordinates of edges and height of the zones can be viewed in Appendix: SafeMove vertices B.

4.4.1 Small robot safety zone

The virtual safety zone of robot model IRB 140 was constructed as a cube, where the triggering point for the SafeMove limit was located at x=535 mm. This point enabled a sufficient acceleration distance while still having a possibility to stop after the virtual safety zone limit. A complete coordinate description of the virtual safety zone is presented in Appendix: SafeMove vertices B. All three test scenarios were triggered by the same limit. When test 3 is running, and the axis 1 movement triggers the stop at x=535 mm, axis 1 has an angle of 45°. This angle represents the start reference point of the braking distance measurement in test 3.

4.4.2 Medium robot safety zone

In this virtual safety zone, two different triggering points were used among the test scenarios. The first two scenarios with the pushing motion had a SafeMove limit and triggering point at x=1300 mm. This made the acceleration distance and maximum reaching distance acceptable, according to the argumentation in the testing scenarios. But to gain sufficient acceleration in test 3, the same triggering point could not be used, and needed to be adjusted. Therefore, the SafeMove limit for test 3 was set to x=1800, which corresponded to an angle of 30° of axis 1, and is further presented in Results: 5.2.3. This difference in triggering points tests resulted in a virtual safety zone that can
4.4.3 Large robot safety zone

Similar to the other two virtual safety zones, it is only the x-direction that is of interest since that is where the stop triggering point is located, at least for test 1 and 2. But because of the surroundings in this robot cell, there is a slight difference in test 3. This is further described in the results. For test 1 and 2, the SafeMove limit is located at \( x = 1400 \) mm. And for test 3, the limits were rearranged to fit the axis 1 movements, and the SafeMove limit was placed at \( 75^\circ \) of axis 1. Meaning that when axis 1 exceeds \( 75^\circ \), the robot stops.

4.5 Measurement technique

The main results from this project comes from the measurements of the braking distance, this is the distance from the virtual safety zone limit to the Tool Center Point (TCP) of when the robot has stopped. The coordinates of TCP can be obtained by reading the robots joint values and do calculation with forward kinematics. This is done automatically by the robot system, and is giving the coordinates of tool0 in x, y and z. Because the starting and target point is only a difference in the x-direction, the x-coordinate is the variable of interest. The braking distance is obtained by the formula,

\[
B_x = P_x - S_x
\]

Where
- \( B = \) Braking distance in x-direction
- \( P = \) Position of tool0 after a complete stop in x-direction
- \( S = \) Safety zone limit in x-direction

All values were measured from the base coordinates of the robot system. It was in this case the same as world coordinates, with origin in the robot.
In testing scenario 3, the robot movement is only done by axis 1, with a joint movement, wherefore the braking distance measurement will be inadequate when the x-direction is considered. Instead, the measurement of braking distance in test 3 will preferably be in axis degrees.
5 Results and discussion

This chapter presents the results of the tests that were performed according to previous chapter. The three tests were executed on the three robot models, and is respectively shown with results and graphs. Comparison and discussion of the results is done as the results is presented in the text, and a generalized discussion of the results at the end of the chapter. Every robot model and test set-up has, inherently, different starting points with respect to base coordinates, SafeMove limit, and target points. These are presented prior to the actual test results, and are needed to fully understand the results. The graphs that are presented are visual representations of the measured test result values, which all can be viewed in Appendix: Test results C.

5.1 Small sized robot

As it turned out, the axis angles in the set-up that were supposed to be that same for all robot models, didn’t show the same alignment for all robots. The small testing robot, IRB 140, has a different axis origin than the other robots, making the robot arm to stand in another position visually in comparison to the figures of testing scenarios. However, this error in axis angle 3 were an offset of 45 degrees, and was easily corrected to make the starting position in the same alignment as intended. The starting position axis angles of each test are shown in each associated subsection.

5.1.1 Test 1

With the given start position angles, shown in Table 9, tool0 had a starting position in the x-direction of x=195 mm. The SafeMove limit was located at x=535 mm, and the target point was located at x=750 mm. Acceleration distance was therefore 340 mm, while the maximum braking distance was 215 mm. All the described measurements can be viewed in Figure 16.

Figure 17 shows the results of testing scenario 1 with a linear movement. There are three lines that each represent various payloads, with marked data values from the experiments. TCP speed (mm/s) is on the graphs x-axis, and the Braking distance (mm) is on the y-axis. Maximum braking distance was obtained with 6 kg payload at 1250 mm/s and above, and had the value of 150 mm. This means that the TCP speed didn’t exceed 1250 mm/s in this experiment.

Test 1 execution with joint movement results can be viewed in Figure 18, and obtained a longer braking distance overall compared to the linear movement. The maximum braking distance was 173 mm at maximum payload at 1250 mm/s and above. At lower speed, the payload does not affect the braking distance as much as in increased speed. And it seems that in joint movement, there is a clearer braking distance distinction between the payloads.

Table 9. Axis configuration test 1 IRB 140

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>-45°</td>
<td>45°</td>
<td>0°</td>
<td>90°</td>
<td>0°</td>
</tr>
</tbody>
</table>
**Results and discussion**

**Figure 16.** Key coordinates test 1 IRB 140

**Figure 17.** Test 1 results IRB 140 with linear movement and various payloads

**Figure 18.** Test 1 results IRB 140 with joint movement and various payloads
5.1.2 Test 2

Test 2, with a lower starting and target point in z-direction compared to test 1, had the starting position axis values presented in Table 10. Because of these angles, the starting point is located at \([x, y, z] = [257.95, 0, 500.42]\). Since the x-position of the starting point is 257 mm, this means that the acceleration distance is shorter in test 2 compared to test 1, since the SafeMove limit is at the same point. At this lower position of the robot, it can reach a little longer, and the target position is at \(x = 760\) mm.

Figure 19 shows the results of the linear movement of test 2. At 1000 mm/s a small braking distance distinction between the various payloads starts to show, and at 1250 mm/s and above, the braking distance does not change. Similarly, to test 1, the TCP speed cannot exceed 1250 mm/s from these given conditions, and the maximum braking distance is 150 mm, same as in test 1. Despite the shorter acceleration distance, the TCP speed got up to the same value as in test 1, 1250 mm/s.

When looking at the joint movement in Figure 20, same reasoning as in test 1 joint movement is applied. A clearer distinction of the braking distances as the TCP speed increases, and with a maximum braking distance at 183 mm at maximum payload. When TCP speed was 1250 mm/s and above, the braking distance did not change, again meaning that the maximum achievable speed was 1250 mm/s from given position. One can see that the braking distance increases as the payload increases.

<table>
<thead>
<tr>
<th>Table 10. Axis configuration test 2 IRB 140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis 1</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>0°</td>
</tr>
</tbody>
</table>

Figure 19. Test 2 results IRB 140 with linear movement and various payloads
5.1.3 Test 3

Since test 3 differ from test 1 and 2, only involving axis 1 in a circular movement, the start and target points are presented as degrees of axis 1. Hence, axis 2 and 3 are set to be able to extend the robot as far out as possible, and retain their angles throughout whole test 3. Table 11 presents the starting position axis angles of test 3. Since the cell of IRB 140 had physical fences that were interfering with the working area, the range of axis 1 could operate freely between 160° to -40°. Start and target point is placed close to those points, with a fence margin at the target. Figure 21 shows angles of these points, as well as the axis 1 angle of where the SafeMove limit is located, at x = 535 mm.

The results of test 3 can be studied in Figure 22, where the braking distance is measured in angles of axis 1. Maximum obtained TCP speed was 3000 mm/s, since the braking distance angle is the same after that point. The braking distance angle at 3000 mm/s and above was 36° with 6 kg of payload.

Table 11. Axis configuration test 3 IRB 140

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
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<tr>
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</table>

Figure 20. Test 2 results IRB 140 with joint movement and various payloads

Figure 21. Key angles of test 3 IRB 140
5.2 Medium sized robot

The medium sized robot, IRB 4400, is larger than IRB 140, which gives longer distances in actual numbers. One remarkable result from test 1 was that the same braking distance was obtained with all three payloads at 1850 mm/s and above. This does not apply in test 2, where there is a clear distinction between the results that follows a clear trend throughout the whole TCP speed range. Linear and joint movements have the same pattern in test 1, with a maximum braking distance at 400 mm. While in test 2, linear movement had a longer breaking distance than the joint movement. The braking distance was overall longer in test 2 than test 1, even though test 2 had a shorter acceleration distance due to the starting position. This indicates that test 2 obtained a higher speed before the SafeMove limit than test 1, which also can be seen on the graphs that is presented in this chapter.

The test results are presented respectively, with essential information about the specific coordinates of the starting and target positions in the x-direction. Discussions are being presented in conjunction with the results, together with a generalized discussion at the end of the chapter. Axis configuration are not given prior to the results in this section, because these values are already given in chapter 4.2: testing scenarios.
5.2.1 Test 1

With the given axis angles of test 1, the tool0 coordinates in the starting position are \([x, y, z] = [450.68, 0, 1319.33]\). The SafeMove limit that will trigger the stop is located at \(x=1300\), which gives an acceleration distance of almost 850 mm. The maximum reach of the robot with fixed \(y\) and \(z\) is in \(x= 1770\). This means that the distance from the SafeMove limit to maximum reach is 470 mm. However, if the maximum reach position was obtained, the weight plates intersected with the robot and made the force controller interrupt the sequence. Therefore, a target point was placed at \(x=1709.32\), where axis 2 has the value 45°. This issue could have been solved by tilting axis 5, but that would have changed the conditions of the test. The maximum reach position was also not used as a target point, with the argument that it may do unnecessary damage to the mechanical system of the robot, when weights are applied and in high speed. Again, values of \(y\) and \(z\) are fixed in the starting and target point, making the direction linear. Figure 23 illustrates the coordinates of the presented points.

The linear movement of test 1 can be studied in Figure 24. The braking distances between the payloads are similar up to 1250 mm/s, and increasing in the 56-kg payload at 1500 mm/s. After 1750 mm/s, the braking distance is the same for all three payloads, 406 mm, which also is the maximum obtained speed of this test. The difference of braking distance between the payloads are hard to distinguish, since they measure relatively the same throughout the whole TCP speed range. One exception is at 1500 mm/s, where the payload of 56 kg stands out from the lower payloads.

Joint movement test results, Figure 25, has a clearer distinction between the payloads at 1000-1750 mm/s, in comparison to linear movement. The same phenomenon appears here as in the linear movement, the same braking distance between the payloads at 1850 mm/s and above.

![Figure 23. Key coordinates test 1 IRB 4400](image-url)
5.2.2 Test 2

With the given axis values of Test 2 on medium robot IRB 4400, the tool0 starting position was in \([x, y, z] = [592.10, 0, 1000.67]\). The SafeMove limit has the same \(x\)-coordinate as in test 1, 1300 mm, since the same safety zone was used, and the same type of movements in test 1 and 2. Figure 26 illustrates concerned key coordinates like the start and target point.

In test 2, the acceleration distance is just over 700 mm long, and the distance from the SafeMove limit to the target point is almost 600 mm. Even though the acceleration distance is shorter in test 2 than in test 1, the TCP obtains a higher speed with the linear movement, 2000 mm/s. This entails that the braking distance gets longer in the linear movement as one can see in Figure 27, where the maximum braking distance with a payload of 56 kg is 527 mm. This braking distance is obtained at 2000 mm/s and above.
Figure 26. Key coordinates test 2 IRB 4400

Figure 27. Test 2 results IRB 4400 with linear movement and various payloads

Figure 28. Test 2 results IRB 4400 with joint movement and various payloads
Figure 28 represents the results of test 2 with joint movement, and the braking distance gets shorter here compared to test 2 linear movement. Maximum braking distance at 56 kg payload is 460 mm. There is a slight difference in the braking distance between 1750 and 1850 mm/s, and the braking distance does not change after 1850 mm/s. Therefore, the maximum obtained TCP speed is somewhere in that interval. There is a shorter braking distance overall with the joint movement compared to linear movement in test 2, and this applies within all the measured points.

5.2.3 Test 3

Axis configuration set up for test 3 of IRB 4400 can be viewed in Table 7 from chapter 3 in the explanation of testing scenarios. To clarify, Figure 29 visualizes the important points within the test, start and target point, and SafeMove limit. These points are presented as angles of axis 1. Acceleration distance is at -50° and the allowed maximum braking distance angle is at 80°.

When studying the graph in Figure 30, the braking distance angle increases significantly as the TCP speed increases, all the way to a TCP speed of 5000 mm/s. There was no indication that this was the maximum obtainable speed, and this was an incentive to try the test with TCP speeds above 5000 mm/s. But at the complete stop at 5000 mm/s, the robot arm was dangerously close to a fence, and the risk of causing damage to the cell enclosure made it inappropriate to continue. So, for this test, where the maximum tested speed of 5000 mm/s, the braking distance angle was 72° for all payloads.

The reason for this might be that the target point is at such a distance, that the robot system calculates the path and makes the robot decelerate before the SafeMove limit, to effectively reach the target as it is intended to. Test 3 demonstrates that axis 1 is capable of reaching higher speeds then the other tested axis’, due to the rotational movement and its size of motors. At the same time, more weight and torque are affecting axis 1, as well as moment of inertia, making axis 1 weak in its position. These factors, in that high speed, makes the braking distance longer, especially in extension zone 2.
5.2.4 Discussion

One interesting thing is the result of test 1, all payloads on both linear and joint movement has almost identically braking distance at the speed 1750 mm/s and above. Compare that to test 2 where there is a clear trend that the braking distance increases when the weight increases. And it keeps it that way along the entire curve with even distribution. How and why this occurs in test 1 are left being unsolved. But the shorter distance to the target point might be a possible explanation. In test 1, target point is located at x=1709, and in test 2 it was x=1892.

In test 3, the acceleration distance was stretched out to its maximum, due to a physical obstacle in the shape of a pillar, which was in the way for the robot end effector. The same issue was at the target point, there was a physical fence that interfered with the robot, which limited the robot’s movement. Axis 1 has a working range of 360 degrees, which could have made the tool0 speed to be stretched to higher levels then what these tests could have, if the acceleration distance was longer and nothing interfered in the robot’s trajectory.

5.3 Large sized robot

Final testing robot, IRB 6700, had no surrounding physical fences at the time of the experiments. Only a control cabinet station which interfered some in testing scenario 3. Otherwise, relatively free space for testing compared to the other tested robots. The results of the tests performed on IRB 6700 shows some irregularities compared to the other robots. For instance, low payload had a longer braking distance than higher payload in most of the results. This is counterintuitive, but one explanation might be that because of the high payload, it is harder to gain speed due to the inertia. This probably makes the entrance speed to the SafeMove limit lower than with a lower payload.

5.3.1 Test 1

Axis configuration of the starting position of test 1 had the same alignment as presented in Table 9 from IRB 140 test 1. The linear movement of test 1 in Figure 31 had a longer braking distance at the lowest payload, 34 kg, compared to the other two payloads.
a TCP speed of 1000 mm/s, the braking distance among the payloads was relatively the same, around 275 mm. After this speed, the braking distances distinguishes from each other and has the same braking distance at 1250 mm/s and above. 36 kg payload obtains a braking distance of 305 mm, while 91 and 141 kg payloads obtain 283 and 273 mm, respectively.

By studying the joint movement of test 1 in Figure 32, there is a marginal difference among the braking distances between the various payloads. The three lines follow each other throughout the TCP speed range. One even more distinctive characteristic may be, that after 1250 mm/s, the braking distance decreases a bit at the following tested speeds. The peak at 1250 mm/s is 292 mm of braking distance, and at 2000 mm/s it is 278 mm. And this happened with all three tested payloads. Joint movement in this case, makes the TCP move in an upward circular trajectory to the target, if that has something to do with the result, and that the payloads are heavy.

Figure 31. Test 1 results IRB 6700 with linear movement and various payloads

Figure 32. Test 1 results IRB 6700 with joint movement and various payloads
5.3.2 Test 2

In the starting position for test 2, the robot had the axis configuration as presented in Table 12. These values are placing the TCP in a different position compared to test 2 in the other robot models. This difference is marginal in the x-direction, but needed since the weighting device has a geometry that made it interfere with the robot.

When analysing the linear movement results in Figure 33, from 500-1250 mm/s speed, the braking distance is almost identical among the payloads. Above 1250 mm/s, the lower payload of 34 kg stand out and has the longest braking distance of the three payloads, 357 mm. The other two heavier payloads do not obtain the same braking distance, may due to the reasoning that the lower payload gain a higher TCP speed before the SafeMove limit. As stated, otherwise there is not much of a difference between the payloads in the linear movement of test 2.

Representation of joint movement of test 2, Figure 34, has a similar graph like the linear movement. This may be an indication that the movements are alike in its execution. Although this would also be the case in the other robot models, so that reasoning is not practically valid. For robot model IRB 6700, it might be that the inertia plays a role, since the joint movement is partly upwards, and moving against the gravity. The longest braking distance 347 mm is measured with 91 kg of payload at 1500 mm/s and above. With the 34-kg payload, the braking distance is basically the same, 346 mm. It is just the higher payload, 141 kg, that departs and has a maximum braking distance of 320 mm.

Table 12. Axis configuration test 2 IRB 6700

<table>
<thead>
<tr>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
<th>Axis 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
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<td>60°</td>
<td>0°</td>
<td>60°</td>
<td>0°</td>
</tr>
</tbody>
</table>

Figure 33. Test 2 results IRB 6700 with linear movement and various payloads
5.3.3 Test 3

Final test of this project, test 3 of the large sized robot, IRB 6700, had a large range to move within since there were no fences interfering, except a controller station. However, a non-movable table forced some changes to the axis’ to avoid collision, and can be viewed in Table 13. Axis 5 angle is making the payload device to point outwards, making more weight to be put far away from the centre in extension zone 2. The testing movement of axis 1 in test 3 is elucidated in Figure 35.

<table>
<thead>
<tr>
<th>Axis configuration test 3 IRB 6700</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axis 1</strong></td>
</tr>
<tr>
<td>-30°</td>
</tr>
</tbody>
</table>

An analysis of the results of this test in Figure 36, shows that the braking distance angle is fairly even up to 2500 mm/s between the payloads. At 3000 mm/s, a remarkable result of a smaller braking distance angle of the lowest payload is shown, while the other two payloads are at a 20° braking distance angle. After that, the braking distance angle is about the same between the payloads. One possible explanation of this, is that the heavier payloads do not make the robot to accelerate to the designated TCP speed of 4000 mm/s, but it does with the 34-kg payload. This makes it look like the payloads

![Figure 34](image.png)

**Figure 34.** Test 2 results IRB 6700 with joint movement and various payloads

![Figure 35](image.png)

**Figure 35.** Key angles of axis 1 test 3 IRB 6700
all have the same braking distance angle at 4000 mm/s, which they do, but it is not the whole truth. In fact, if the robot manages to accelerate to a higher speed with the low payload than the other two, this makes the entrance speed to the SafeMove limit higher, and therefore an even braking distance angle is shown. The heavier payloads do probably not measure the same speed at the SafeMove entrance, and therefore not a larger braking distance angle, as it should have been, inherently, if the speeds were the same.

5.4 Discussion of results

The positions that are given in the results of the braking distance are tool0 positions, this means that if the tool or gripper with attached object and its volume need to be added in the results. The robot will “reach” longer because of the geometry of the gripper and object. Even if there is no tool or gripper attached, the robot itself also reaches longer than the tool0 position because of the end effector geometry and that the tool0 position is in the centre of axis 6. This does not affect the braking distance, since that is a measure of two coordinates, but the geometry needs to be taken into consideration if the actual safety distance will be calculated.

The results of test 1 might be shorter braking distance because of the lower reaching ability of the robot from that starting position. It can also be because joint 3 increases and the decreases in angle as the robot moves towards the target. This might make the speed to be slowed down at the entry of the SafeMove zone.
6 Conclusions

The underlying question that have been the basis of this project was: Do we obtain usable knowledge by doing braking tests of our own, in addition to existing ones? And is it worth to continue doing more of them to back up the risk assessment process? This is something that is answered in this section, together with the stated aims.

One aim was to perform all three testing scenarios on three robot models, which is considered to have been done. And, the tests are described in such a detailed way, that makes it easy to replicate for further work. The tests were performed according to the specifications of speed, positions, payload ratio, and with both linear and joint movements, except in test 3 where it was not appropriate. In the performed tests, TCP speed is the most significant factor when it comes to braking distance, even though payload has an impact of the result.

The results that are presented in this thesis are intended to help personnel to estimate and calculate the safety separation distance when doing risk assessments. The information could also be useful when designing robot cells and their layouts. One risk factor that was an incentive for this work was, that the robot system may malfunction and move uncontrollably and supposedly cause danger for operators. This scenario is unlikely to happen, but it is still a risk and should be taken into consideration. By having more in-depth knowledge about the braking distance of a robot and in extension, the safety separation distance, robots can operate more safely. Virtual safety zones are intended to complement or replace other safety systems such as physical fences, when working in collaborative operations with industrial robots. The collaborative operation, when an operator is at a reachable distance for the robot, is the most crucial moment that need extra precautions. This is a scenario where safety separation distance and braking distance comes in as a determinant factor when doing risk assessment.

6.1 General conclusions of test results

Comparison between test 1 and 2 results on medium sized robot showed that test 1 had a shorter braking distance overall. A reasonable conclusion to this, is probably that the target point of test 1 is located much closer to the SafeMove limit than in test 2. The reason for this was that the payload device was interfering with the robot arm at that position in test 1, and that the reaching ability of test 2 is longer due to the lower position. The shorter distance from the SafeMove limit to the target point affect the braking distance, because the trajectory is probably calculated in such way, that the robot will not obtain higher speed since it will need to slow down anyway. This could, and should have been corrected with a shorter acceleration distance by moving the SafeMove limit closer to the robot, making the target point further away from the SafeMove limit. But in reality, the robot couldn’t have reached longer from that overhead position as well, so still there is a benefit of these kind of tests. And to see if the same distances would be valid between test 1 and 2.

In test 3 of the medium sized robot, the angle got large at high speed, and it is possible that the robot system might have taken into account that the target point is close and reached at high speed, and might have started retracting already before the SafeMove limit. To investigate test 3 further, there needs to be total free space around
the robot, to make it move up to 330° from start to target position. And place a SafeMove limit at perhaps 180°. This would really stretch the robot to gain a higher speed than the test in this project achieved. In the project, there were physical fences that were in the way for the small and medium sized robots to move freely, making the acceleration distance and angle not long enough for reaching speeds over 5000 mm/s. This high speed may have been sufficient for this experimentation, but it still would have been interesting to investigate the full range. One option could also have been to investigate the braking distance angle from another extension zone, closer to the robot’s centre. The information provided by the robot manufacturer are also giving measurements from extension zone 1 and 0, which could have been validated against. However, the worst-case scenario in extension zone 2 was the most interesting part to investigate, according to stakeholders of this project. At the same time, the risk of being injured or hit by a robot is higher in extension zone 2 because of the robot’s extension towards the operator at a handover. Also, if a robot malfunction and starts moving within extension zone 0 for instance, the risk of it hitting something is considered less risky, even if a malfunction itself is erratic.

The general conclusion between the robot models is that axis 1 can generate the highest speed, and therefore has the longest braking distance.

6.2 Safety separation distance comparison

Recall the equation for the safety separation distance, with variable explanation from chapter 4.5:

\[ S = K_H (T_R + T_B) + K_R T_R + B + C \]

And we alter the calculated braking distance of the robot, \( B \), to the values from test 2 on medium sized robot, IBR 4400, and compare the results in a graph we obtain Figure 37. The upper line represents the calculations made on IRB 4400 prior to the test, while the lower represents measured values. Measured braking distance is shorter than calculated and therefore a shorter safety separation distance is obtained as a result.

![Safety separation distance comparison](image-url)

**Figure 37. Safety separation distance comparison**
This concludes that these kinds of test may have an important impact when considering the safety separation distance in a risk assessment. The difference in distances between the calculated and measured are up to 1 m.

6.3 Future Work and Research

This project involved three types of movements for experimentation, the first two were very similar whereas the third was a joint movement of axis 1. A study of these kinds of movements involving several axis is something that have not been done together with virtual safety zones. Involving multiple axis in braking tests opens up a new dimension of testing scenarios, and for robotics manufacturers to supply this kind of information would be endless work. The number of positions would be close to infinite. However, this work has presented an introduction to multi-axis braking distance measurements to support personnel when doing risk assessments. For future work, more axis may be involved when moving from one target to another. And from other positions that simulates collaborative operations or other interpreted situations. There can be a pushing motion but from the side of the robot, which involves axis 1, 2 and 3 simultaneously. This movement was tested off-the-record by the author, and with a linear movement the robot did not obtain as high speed as the ones in this thesis. Joint movement was like test 3, and therefore test 3 was already sufficient. But these results have not been recorded, and is something to consider for future work. To back up the statement that this type of movement does not obtain a higher braking distance, the safety separation distance is shorter when axis 1 is involved, as described in chapter 2.4.

To make the robot obtain higher speed than the ones achieved in this project, a start position in negative x-direction may be an option. This will result in that the robot “leans back” and will start the movement further back and may generate a higher speed to the SafeMove limit. This will result in a sweeping motion from the back of the robot, and still not be involving axis 1.

For future work, time measurement may be of interest. This can be calculated of the braking distance and known speed, but for completion it may have its benefits.

6.4 Critical Discussion

The author could have used better positions of the experiments. The maximum reach may not have been sufficient, or the acceleration speed. The issue that the maximum reach position could not be reached because of the geometry of the payload device was a problem, but the position could have been altered like the test 3 position, placing the payload device in 90° of its current position.

The system response time is included in the braking distance, in the safety separation distance that factor is separated, but is not mentioned as a factor in the experiments, which it maybe should have been. The actual result is braking distance plus response time. The response time have not been calculated, and it is left unknown for this project.

It is hard to know if the braking distances of test 3 would have been longer if the target position was further away, and if the complete range of axis 1 could been used if not physical obstacles were in the way in the testing area. If the robot system did not accelerate to higher speed and already decelerating because of the enclosing target.

At test 3 on IRB 6700, the braking distance became shorter at speed over 4000 mm/s. That may be because the robot calculates the path and slows down in advance,
before the SafeMove limit, because the target point was too close for the robot to retract in that high speed. This only applied for the large robot, which is confusing due to that the large robot had the longest acceleration angle and maximum braking angle. The large robot stopped long before the target point, and had almost 60° left to the target point after a complete stop at maximum payload. However, this test robot IRB 6700 was a modified test robot that had enhanced sensitive movements, and not a regular industry application robot. This could have influenced the results in a negative way.

To investigate the actual robot speed at the SafeMove limit, a log function should have been implemented. This is something that already exist, and would have helped a lot when analysing the results.

6.5 Comparison to previous test results

One of the aims was to validate the braking distance against the measures from the robot manufacturer, for comparison to the worst-case scenario. To analyse and compare one-axis movements to two-axis movements results is not easy, especially when the measures are in degrees of affected axis, and this thesis measures the travelled distance in x-direction. However, test 3 was measured in degrees and was the subject for validation.

On the small sized robot, IRB 140, the angle is almost identical at 2500-3000 mm/s. At speeds under 2500 mm/s the test results show a smaller braking distance angle than the measured values provided by the robot manufacturer. The payload ratio is also in exact comparison. An overview and comparison between test results and measures from the robot manufacturer can be viewed in Appendix: Comparison to ABB results.

IRB 4400 test 3 results show an overall smaller braking distance angle compared to the manufacturer results. Somewhere between 15-30% less angle over the whole speed range. At speeds above 4000 mm/s, the test results cannot be guaranteed due to the close target position as stated earlier.

With the IRB 6700 test results, the braking distance angle is 5-30% smaller up to 3000 mm/s, similar to the other robot models. But above 3000 mm/s, the test results differ much more. While the test results from this project consolidate, previous test results reach angles up to 50° at the heaviest payload. A comparison of the results in Table 4 shows that a category STOP0 emergency stop obtains a braking distance angle of 36°, at full speed and full payload. While measurements from the robot manufacturer shows that a category STOP1 obtains higher angle values than that, the test results from this project shows a braking distance angle under 36°. It is confusing that the provided measures show that there is a shorter braking distance in category STOP0 compared to STOP1, since STOP1 is supposed to have the faster braking capability.

6.6 Generalization of the result

The final conclusion is, that it is worth doing these kinds of tests when investigating industrial robot braking distance with virtual safety zones, because the safety separation distance differs in reality versus theory in a way, that makes it more applicable to rely on experiments on braking distances, even if it needs many more observations and conclusions to act upon.
7 References


A. Appendix: Pictures of payload devices
B. Appendix: SafeMove vertices

![Diagram showing SafeMove vertices]

Reference
Task frame
Height Top. Bottom (mm)
1200.000  0.000

Vertices X, Y (mm)
1: -800.000  -400.000
2:  535.000   400.000
3:  535.000   900.000
4: -800.000   900.000

Reference
Task frame
Height Top. Bottom (mm)
3000.000  0.000

Vertices X, Y (mm)
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### C. Appendix: Test results

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| Joint  | 500   | 52,14       | 53,85       | 54,96            |
| Joint  | 800   | 84,34       | 90,13       | 93,32            |
| Joint  | 1000  | 112,94      | 125,79      | 142,76           |
| Joint  | 1250  | 147,12      | 162,51      | 173,14           |
| Joint  | 1500  | 147,12      | 162,51      | 173,13           |
| Joint  | 1750  | 147,12      | 162,51      | 173,13           |
| Joint  | 1850  | 147,12      | 162,51      | 173,13           |
| Joint  | 2000  | 147,12      | 162,51      | 173,13           |
| Joint  | 3000  | 147,12      | 162,51      | 173,13           |
| Joint  | 4000  | 147,12      | 162,51      | 173,13           |
| Joint  | 5000  | 147,12      | 162,51      | 173,13           |

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<th>Test 2 (mm)</th>
<th>Test 3 (degrees)</th>
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IRB 140
### Appendix C: Test results

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<th>Test 3 (degrees)</th>
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Appendix C.3
D. Appendix: Comparison to ABB results

![Test 3 IRB 140 Joint Movement](image1)

![Test 3 IRB 4400 Joint Movement](image2)

![Test 3 IRB 6700 Joint Movement](image3)