Being safe around collaborative and versatile robots in shared spaces

Protocol

Maintain safe distance – Test robot Arm for Maintaining a one-dimensional Safe Distance to Humans

(ROB-MSD-1)

The specific purpose of this protocol is to validate the safety skill "maintain safe distance" by measurement. Its scope is limited to robot arms operating in the domain Manufacturing and Logistics. The validation of this protocol requires that the reader has a device to measure one dimensional braking distance and stopping time.

Readiness Level	Description
8	Tested and improved by at least three different parties

Project consortium

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CONTENTS

1 Introduction

The purpose of this protocol is to validate by measurement that a safe distance between a robot manipulator and the operator is maintained within a specified threshold. This protocol is specific for validating a one-dimensional safety distance.

Example: A robot carrying out a pick and place task. Except for the front side, a fence surrounds the workplace. The front side is accessible for an operator and is equipped with a laser scanner to detect a human operator, when entering the workspace of the robot. A typical case of foreseeable misuse is the operator accessing spontaneously into the robot's workspace to pick up a component that slipped out of the robot gripper. In such a situation, the system must guarantee that the robot stops, before the threshold for a minimum safety distance is undercut.

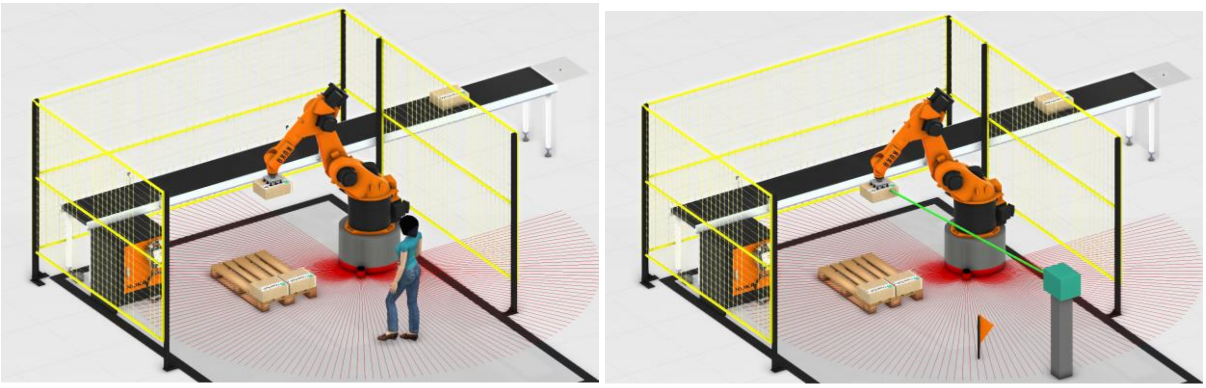

Figure 1: Exemplary situation of a safe distance monitoring and the principle test setup to validate such an application

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Maintain safe distance
System	robot arm
Sub-System	n/a (no subsystem)
Domain	manufacturing, logistics
Conditions	environment: indoor-factory obstacle: fixed object
Measurement Device(s)	- device to measure one dimensional braking distance (string potentiometer) and stopping time - Various actuators to initiate a protective stop - Control unit to control the transducer and the actuators and to deliver the data to a PC

⚠	**Warning**
	This protocol supports users to validate the effectiveness of the skill listed in the profile above. The skill should be a technical measure of the system integrator applied to mitigate the risk of one potentially hazardous situation as identified in the risk assessment which the reader has to be done before using this protocol. In general, the risk assessment is a mandatory and helpful source to identify test situations and conditions relevant for a proper validation.

1.2 Definitions and Terms

Industrial robot (source: EN ISO 10218-1 [4])

Automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can either be fixed in place or mobile for use in industrial automation applications.

Industrial robotic system (source: EN ISO 10218-1 [4])

System comprising:

- Industrial robot
- End effector(s)
- any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot performing its task

System integrator

Company or person who created the collaborative robot and brought it into productive operation. The system integrator is responsible for doing the risk assessment and must ship the collaborative robot with an instruction manual, which refers to the residual risks of the robot system.

Application (source: EN ISO 10218-2 [5])

Intended use of the robot system, for instance, the process, the task and the intended purpose of the robot system (for instance, spot welding, painting, assembly, palletizing).

Distance measuring system

System to measure the one-dimensional distance over time between two objects

Protective event

The term for the protective event is used as summary of all steps, which are triggered by the skill ”maintain safe distance”. A violation of a safety-measurand detected by the sensor system starts the event. Next the robot controller initiates a protective stop, which is then performed by the manipulator. The protective event is finished, as soon as the robot has stopped.

2 Concept and Objectives

The concept of the verification process is to simulate a violation of the skill to “maintain safe distance” with an actuator to initiate a protective stop and measure the behavior of the robot. During the test, the robot must operate under the same conditions, as it will be in its real application. The objective of the test is to validate by measurement whether the applied safety skill “maintain safe distance” prevents the robot from exceeding a predefined distance to a fixed object.

2.1 Hazardous Situations

The risk assessment specifies under which hazardous situations the robot can operate. The validation measurement determines whether the applied safety skill (and ultimately the chosen safety functions) mitigates the risk sufficiently.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill to be validated is to maintain a specified safety distance between the robot and the safety-related object.

The target metric indicates if the validated skill is effective enough to achieve the specified level of risk reduction. The values for the target metric should be determined during the risk assessment. For this validation protocol, the target metric is the resulting distance after a full stop between the robot and the safety-related object [m], specified by the point X_H. The target metric may vary for different dimensions of obstacles, robot manipulators and sensor systems, so it is crucial to report the values of the target metric for each test.

If not specified by the risk assessment, the required protective separation distance S_D that the robot must maintain at the end of the event can be calculated based on the concepts used to create the minimum distance formula in ISO 13855:2010 [3].

$$S_D = C + \mathrm{Z_D} + S_H \quad .$$

The intrusion distance C as defined in ISO 13855:2010 [3], specifies the distance that a part of the human body can intrude into the sensing field before it is detected. This value changes not only with the sensor type, but also in dependence of the mounting position and orientation and the resolution of the sensor. A second factor is the position uncertainty of the operator Z_D, which depends on the resolution and tolerances of the sensor system. Also, the change of the operator's location during the protective event S_H must be consiederd. In case the speed of the human cannot be safely monitored, a speed of $v_H = 1.6\ \mathrm{m/s}$ is used, which leads to the contribution of the human

$$S_H = v_H\, T_{PE}$$

with T_{PE} being the time the protective event occurs (including reaction time T_R and stopping time T_S). To represent the worst-case scenario, the movement of the human is considered to be directly towards the robot manipulator.

Example: Required Safety Distance after protective event

Formula Name	Formula Symbol	Example 1	Example 2
Intrusion Distance	C [m]	1 e.g. arms are not detected	0.15 e.g. fingers are not detected
Position uncertainty	Z_D [m]	0.01	0.02
Human Speed	v_H [m/s]	1.6 (default value for human)	1.0 (human is safely monitored)
Stopping Time	T_{PE}[s]	0.02	0.5
Human Reposition	S_H[m]	0.032	0.5
Safety Distance	S_0 [m]	**1.042**	**0.62**

3 Conditions

In case the conditions under which the hazardous situation may occur can change, the user of this protocol shall develop a test plan containing all reasonable and relevant combinations. The user must test the applied skill for each combination of this list. Therefore, it is important to know the conditions with the most significant influence on the target metrics. Please report all conditions, represented by values, for each test using the form in Annex A.

3.1 System

The term *system* refers to the robot system consisting of:

- Type of arm
- Type of tool
- Type of workpiece
- Type of sensor

The protocol user must consider all changing parts of the system as different system-related conditions. For instance, if the robot picks up a workpiece, the system conditions change the moment the gripper is connected to the workpiece.

Note: For specific applications, it is possible that the robot operates with more than one tool or handles different workpieces for a particularly hazardous situation. Refer to the risk assessment to identify which task-related conditions can change. In case the robot utilizes more tools and / or workpieces, validate the skill capabilities for all possible combinations per hazardous situation. Each additional combination extends the number of tests since each test covers only one system configuration and one hazardous situation.

Please report the system configuration for every single test using the form in Annex A.

Example: System Configuration

Robot arm	
Manufacturer	The Robot Company
Model	cobot 10
Software Version	coControl, version 10.5.1
Robot tool	
Manufacturer	The Tool Company
Model	cotool 5
Short description	Magnetic gripper, weight of 2 kg
Work Piece	
Manufacturer	My Company
Model / type	Screw M12
Short description	20 cm long, weight of 10 g
Safety Sensor	
Manufacturer	The Safety Sensor Company
Model / type	Sensor 15.1a
Short description	Laserscanner, $Z_D = 0.01$ m, $C = 0.3$ m

When the safety skill takes over control, the configuration of the applied safety skill likely has a significant influence on the robot behavior. Hence, it is also necessary to record the applied safety configuration in the form. The situation requires the user to record the available and activated configuration properties, including the assigned values formlessly. The following example shows how the formless recording can look.

Example: Safety Skill Properties

Trigger Distance	$S_T = 1.5\ \mathrm{m}$ (distance within which the sensor is triggered)
Sensor Position	$X_R = [0, 5, 0]\ \mathrm{m}$ (Position in world coordinate frame of the robot)
Trigger Event	Safety Related Emergency Stop Category S1
Trigger Object	Flag Actuator

In addition to the configuration of the robot system, the state of the robot in the moment the safety stop occurs also has a significant influence on the output values of the validation test. The following items describe the robot state:

- Joint configuration (axes positions)
- Direction and magnitude of TCP velocity (depends on the axes velocities)

Both conditions are part of the robot path, which is technically a time-dependent sequence of states. For a proper validation test, it is necessary to establish the same robot state as the one the robot would have at the time of a potential violation of the safety distance, whereby the safety skill takes over control. Therefore, the point of interest for the test is the point of the robot path at where the limits are undercut most likely. The risk assessment should clarify the exact moment and position of this point. Therefore, the risk assessment is the primary source to identify the robot state for the test.

Every point along the robot path corresponds to a specific tool position. The timeline of the path implicates a tool velocity. The robot kinematics create a relation between the position of the robot axes (joint space) and each point on the path (workspace), so the axes positions match to the tool position. In general, the teach-pendant of the robot allows to determine the current axes position quickly. The user can then extract the velocity of the tool or the TCP (tool center point) from the robot program. Please report both for every single test using the form in Annex A.

Example: System State

Program name	Palletize Items
Program section	Line 16; LIN-Movement P6 to P7
Operating mode	AUT
LIN Velocity [mm/s]	1250
PTP Velocity [°/s]	NaN
Override [%]	95

The user must derive appropriate test points on the robot paths from their risk assessment. These points should be related to cases of foreseeable misuse.

Note: This protocol does not consider a robot manipulator with a sub-system (mobile platform, etc.).

3.2 Environment

In general, the system should operate under the same conditions, as it will be in its real application. In case of optical sensors, the illumination, reflective properties and air pollution of the environment have an influence on the target values.

3.3 Miscellaneous

Other relevant conditions are:

- Location of the contact area on the robot structure (incl. tool or workpiece; according to the risk assessment)

4 Setup

4.1 Equipment

The following sensors are required to perform the test:

- Wire encoder/ string potentiometer to measure distance over time
- Actuator to initiate the protective stop
- Control unit to control the transducer, the actuators and to deliver the data to a PC

The resolution of the sensor to measure the one-dimensional distance should at least be a hundredth of the expected breaking distance. The resolution must be added to the final result of the safety distance.

Example: Distance to be measured: $S_B \geq 270 \text{ mm}$

Sensor Resolution: $R = \frac{S_B}{100} = 2.7 \text{ mm}$

4.2 Method

Figure 2 illustrates the positioning of the equipment. The wire encoder measures the one-dimensional distance between the robot and the fixed obstacle. It is placed at the position X_M, where the human enters the workspace of the robot as identified by the risk assessment. If several directions to enter the workspace exist, the wire of the encoder must show into the direction of the robot's trajectory. The loose end is fixed to the point on the robot's surface with the smallest distance to the wire encoder and highest velocity (e.g. with magnetic hooks). The actuator is positioned at a location where it triggers the sensor system reliably. The control unit operates the procedure. It triggers the actuator, processes the incoming data from the wire encoder and outputs the distance over the time elapsed from the beginning of the event. To determine the distance S_H, the stopping time T_{PE} is evaluated. To minimize the error with respect to S_H a sampling rate of at least 1 kHz is recommended.

Use the form in Annex A to report the capabilities of the sensors and actuators used for the validation.

Example: Sensors and Actuators

Feature	Distance Sensor	Actuator
Manufacturer and type	Sensor Company, Wire encoder	Sensor Company, Flag
Resolution	1 mm	
Sampling rate	1.5 kHz	
Software Version	8.5	8.5

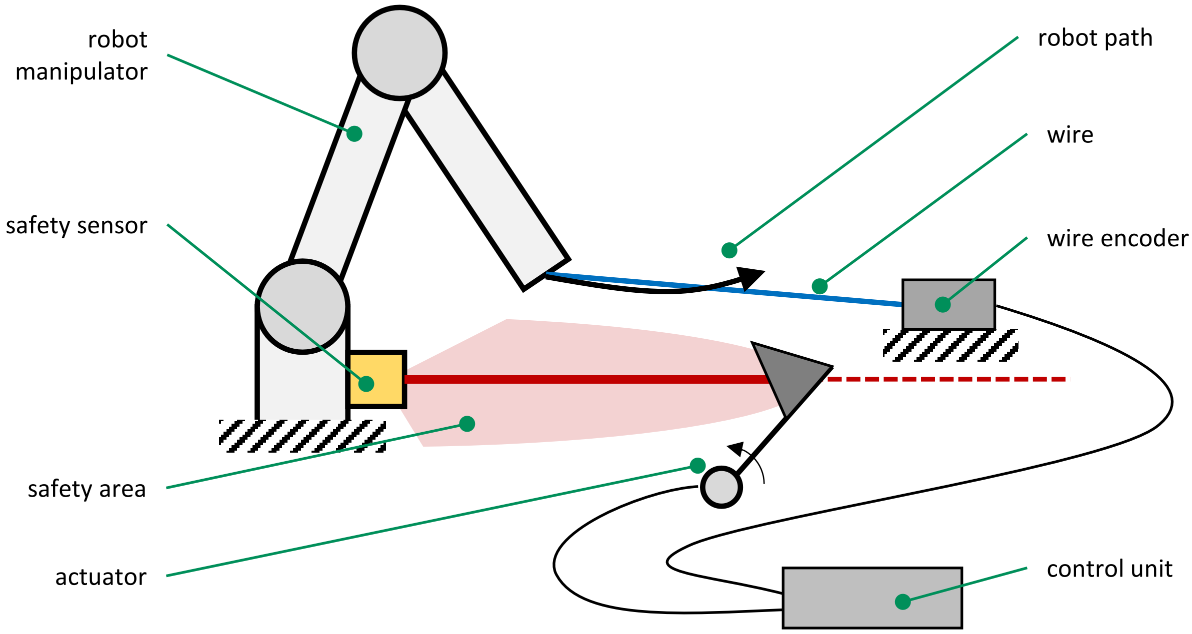

Figure 2: General design of the validation setup

Essentials for data acquisition:

- Computer for measurement control
- All devices and software (running on the computer) necessary to control the sensing devices and to record their signals (incl. data logger, etc.)

Note: The manufacturers of the commercially available measurement systems usually provide software to control their devices and to analyze the results. Please ensure that you have access to such software, especially for your particular device.

5 Procedure

The protocol user must test each event identified by the risk assessment as potentially hazardous. In the sense of testing, this means to provoke a hazardous situation between the robot and a proper measuring instrument. The purpose of the test is to prove whether the robot exceeds the metrics or not.

5.1 Test Plan

The test plan is a summary of all situations, in which the safe distance could be violated and the risk assessment identified as hazardous, incl. all combinations of applicable conditions. Therefore, the test plan provides a detailed summary of which tests are necessary to validate the skill for the considered application.

According to Chapter 3.1, the protocol must consider the following conditions:

- Robot system
  - Type of arm
  - Type of tool

    - Type of workpiece
    - Type of safety sensor
    - Joint configuration
    - Direction and magnitude of TCP velocity
- Sub-system
    - Not available
- Environment
    - Obstacles
- Miscellaneous
    - Location of the contact area on the robot structure

For the validation test, it is necessary to measure all possible combinations of conditions that apply to the considered hazardous situation. Therefore, a single combination corresponds in conjunction with the considered hazardous situation to a particular test case. It is recommended to prepare a list that organizes all hazardous situations and applicable conditions row-wise. Each row represents a particular test case that the protocol user must run and report using the form in Annex A. The protocol user should repeat each test ten times.

Note: In case the safety zone and the robot's trajectory, velocity and payload are dynamically adjusted, it is recommended to create a grid related to the relevant workspace, the movement directions, override and payload of the robot. Depending on the resolution of the grid, this approach leads to an elaborate test plan and it might make sense to automate the test procedure. In case the safety zone is not dynamically adjusted, it is sufficient to perform the tests with the highest expected payload and velocity.

5.2 Preparation

5.2.1 Test Arrangement

Measurement Equipment

- Connect all sensors to their loggers and the loggers to your control unit. Make sure that you can start and stop the recording of all signals from your control unit and that the acquisition works as configured.

Distance Sensor

- Install the wire encoder at the position where the human could enter the workspace. If several directions to enter the workspace exist, the wire of the encoder must show into the direction of the robot's trajectory.
- Make sure to fix the device properly and place it out of the movement range of the robot to protect it from damage.
- Fix the loose end of the wire encoder on the point on the robots closest to the wire encoder.

Actuator

- Install the actuator at the position where the human triggers the sensor under real conditions.
- Make sure that the actuator only triggers the sensor in the activated state.

5.2.2 System Conditions

The protocol user must configure the robot in the exact way it will run in the application, which includes at least the following steps:

- Switch on the robot one hour before beginning the tests (warm-up phase).
- Install all tools and provide all workpieces the robot will use or handle later in the application.
- Install the final program that contains all movements and actions the robot will execute in the application.
- Configure all available safety-functions.

	Warning
⚠	The safety configuration, and therefore the safety skill, is often a part of the robot program or inseparably connected with it. For this reason, the protocol user must not change the robot program after completing the validation. It is highly recommended to store a backup of the positively tested program and to lock the robot control unit so that only authorized people can modify the program or the safety configuration. Any modification to the program requires a new validation of the safety skill.

Note: If the speed of the robot is not safety-monitored, the application cannot guarantee that the defined speed in the robot program is never exceeded. Hence, it is necessary to perform the tests at the maximum velocity of the robot, to ensure safety for the worst-case scenario.

5.2.3 Environmental Conditions

The environment could change the behavior of the safety sensors. Therefore, it is highly recommended to run the tests in the same environment in which the robot system will operate later.

5.3 Test Execution

Apply the following steps for each test case:

- Move the robot to the beginning of the trajectory X_0 you want to validate (see test plan or risk assessment).
- Check if the measuring instrument is in the right position and orientation. It is in the right position if the robots path lies in the direction of the tensioned wire. In case the position and orientation of the instrument are not OK, adjust both until they are.
- Check if the actuator is in the right position and orientation. It is in the right position if the sensor system is reliably triggered only if the actuator is activated.
- Take a photo of the test situation (recommended).
- Start the measurement systems.
- Start the robot movement and record a test stroke of the robot moving along its trajectory without protective stop
- Select different trigger points X_T within the recorded velocity over distance profile of the test stroke. As the safety distance depends on the velocity profile of the trajectory, movement type and configuration of the robot, the worst-case trigger point cannot be determined beforehand. Hence, the test must be executed at different points. (To accelerate testing, start with a rough grid to identify the most critical section within the trajectory and then increase the resolution).
- Move the robot backward along the path. If possible, always choose the same start position X_0
- Set the trigger point specified by the test grid in the control unit of the measurement device
- Start the robot movement. The control unit will activate the trigger at the given trigger point.

- After the robot has stopped, take another photo of the situation (recommended).
- Save the recorded signals.
- Evaluate the braking distance $S_B = S_R + S_S$ and the stopping time $T_{PE} = T_R + T_S$, both including the reaction and the actual stopping distance/ time.
- Calculate S_D, X_D and compare it to the actual position of the sensor system (X_M, S_M).
- In case the requirements
  - are NOT met, adjust the sensor system or robot velocity
  - are met, repeat the tests at least five times an continue with the tests for the other trigger points

5.4 Data Analysis

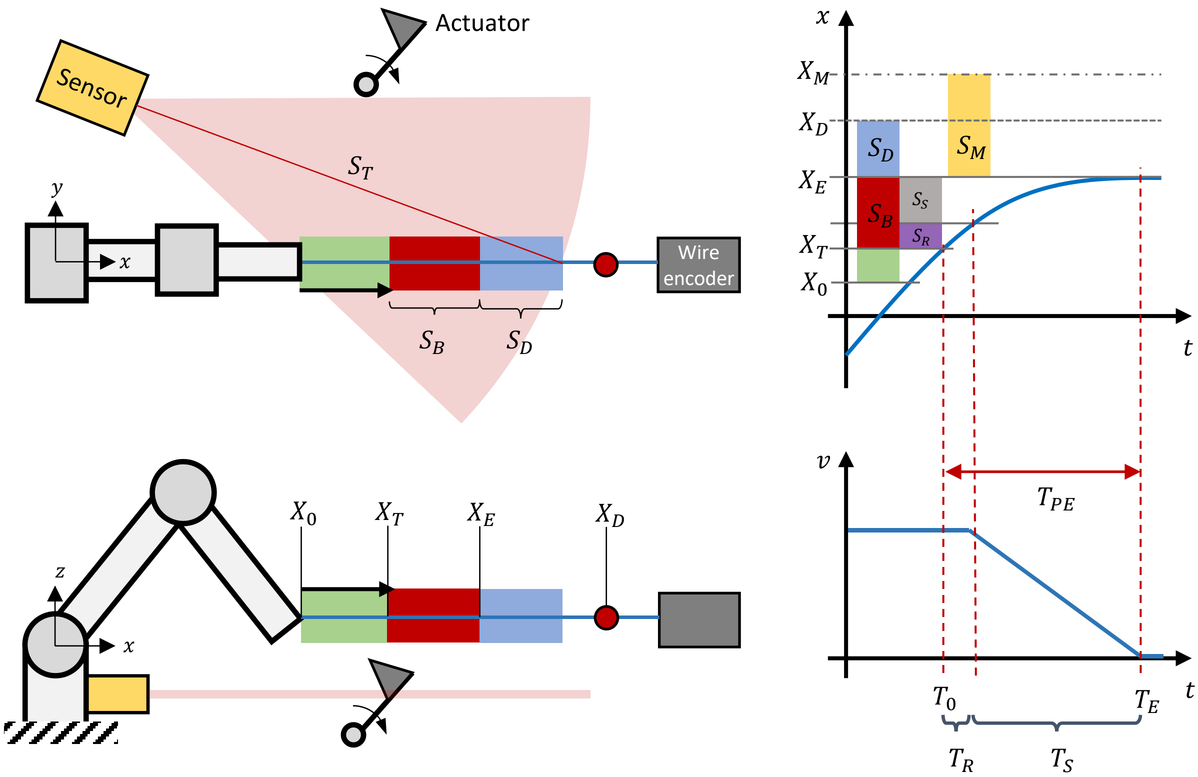

Figure 3: Measured distance and velocity of the wire encoder with the relevant events

The evaluation uses the trigger signal to define the beginning of the measurement determined by the time T_0 and the location X_T. The zero crossing of the velocity signal defines the end of the protective event T_E. The final position X_E is given by $x(T_E)$.

Note 1: In case the trajectory follows no linear movement, it can happen that position X_E is smaller than a position reached during the braking trajectory. In this case, the maximum value measured during the emergency stop

$$X_E = \max\{x(t = [T_0, T_E])\} \quad ,$$

is used.

Note 2: Especially robots with compliant joints tend to oscillate after an emergency stop. Thus, the time T_E might be difficult to determine. In this case, consider the very first zero crossing of the velocity signal as T_E and X_E.

Based on these values the braking distance $S_B = X_E - X_T$ is calculated. The braking distance includes the reaction distance S_R and the stopping distance S_S. The required protective safety distance S_D is given by

$$S_D = C + Z_D + S_H \quad ,$$

with the intrusion distance C, the position uncertainty of the operator Z_D and the humans share

$$S_H = v_H \, T_{PE} \quad .$$

In case the velocity of the human is not explicitly measured use $v_H = 1.6\, m/s$. The position at which the sensor must trigger at the latest is specified by $X_D = X_E + S_D$. The system passes the test for $S_D \leq S_M$ or $X_D \leq X_M$; otherwise it fails. In the latter case, it is recommended to modify the trigger distance S_T of the sensor and to start over with the validation test. Other options could be adjustments to the robot's program (for instance reducing the speed) or to reposition the sensor.

Example: Result from Data Analysis for Velocity Step 1

	C [m]	Z_D[m]	T_{PE}[s]	v_H[m/s]	S_D[m]	X_E[m]	X_S[m]	X_M[m]
Test 1	0.2	0.05	0.49	1.6	1.034	0.81	1.844	1.85
Test 2	0.2	0.05	0.53	1.6	1.098	0.80	1.898	
…								
Test 10	0.2	0.05	0.51	1.6	1.066	0.82	1.886	

5.5 Report

Use the form in Annex A to report all conditions and results of the tests. After finishing the validation successfully (all tests passed), add the forms to your risk assessment. They are proof that the applied safety skill is active and gives the expected protection to the robot operator working beside the robot. Use the last section in the form to record the overall result of the test (passed/failed).

Example: Summary

	Test 1	**Test 2**	**…**	**Test 10**	**Test Passed**
Velocity Step 1	Passed	Failed		Failed	Failed
Velocity Step 2	Passed	Passed		Passed	Passed

6 Bibliography

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[2] *Safety of machinery - Emergency stop function - Principles for design*, DIN EN ISO 13850, International Organization for Standardization (ISO), May. 2016.
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[5] *Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration*, ISO 10218-2:2012.
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7 Annexes

A Report Form

Use the form on the next pages to record the data for each test.

Test ID / Test no	
Hazard ID	
Description	
Photo	

Setup

Sensors

Feature	Distance Sensor	Actuator (Trigger)
Manufacturer and type		
Software Version		

System Configuration

Robot Arm	
Manufacturer	
Model	
Software Version	
Robot Tool	
Manufacturer	
Model	
Description	
Work Piece	
Manufacturer	
Model / Type	
Description	
Safety Sensor	
Manufacturer	
Model / type	
Short description	

Safety Skill Properties (can be test-specific)

Test Specifics

System State

Program name	
Program section	
Operating mode	
LIN Velocity [mm/s]	
PTP Velocity [°/s]	
Override [%]	

Sensors and Actuators

Feature	**Distance Sensor**	**Actuator**
Manufacturer and type		
Resolution		
Sampling rate		
Software Version		

Misc. Conditions

Contact Area (on robot structure)	
Location	
Photo	

Result from Data Analysis

	C [m]	Z_D[m]	T_{PE}[s]	v_H[m/s]	S_D[m]	X_E[m]	X_T[m]	X_M[m]
Test 1								
Test 2								
Test 3								
Test 4								
Test 5								
Test 6								
Test 7								
Test 8								
Test 9								
Test 10								

Summary

Velocity [mm/s]	
Trigger Point [mm]	
Test 1	
Test 2	
Test 3	
Test 4	
Test 5	
Test 6	
Test 7	
Test 8	
Test 9	
Test 10	
Test passed	