Being safe around collaborative and versatile robots in shared spaces

Protocol

Test 3D Safety Sensors in Speed and Separation Monitoring Cobot Applications

(ROB-MSD-3)

The purpose of this protocol is to validate suitability of 3D sensors, particularly LiDAR scanners, for improving the skill "Maintain Safe Distance" in advanced Speed and Separation Monitoring (SSM) cobot applications. Besides the sensors' technical characteristics, the data processing, and decision-making abilities of an associated intelligent control system (ICS) are the subject of validation. Such ICS periodically acquires the positions of a COBOT and an operator, eventually predicts their positions in a near future, and adjusts the COBOT's velocity to keep their mutual distance above the accordingly updated protective separation distance (PSD). The validation test checks with assistance of a high-speed high-resolution camera whether the ICS implements the SSM functionality successfully to prevent collisions between the robot and the operator in a systematically chosen repertoire of collaborative situations identified as potentially hazardous in the risk assessment. This protocol was developed in the COVR funded FSTP project "CobotSense" by FOKUS TECH, the University of Maribor, and FANUC ADRIA, and was published as a deliverable for that project.

Readiness Level	Description
7	Published in toolkit. Undergoing community testing.

COVR is a community effort and values any honest feedback to our services. Please feel free to express your opinion about this protocol. The feedback form is only one click away. Thanks for making COVR even better!

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1 Introduction

The purpose of this protocol is to validate the usability of 3D sensors in supporting the Speed and Separation Monitoring (SSM) mode of operation in COBOT applications. This mode prescribes that the velocity of the robot must be related to the protective separation distance (PSD), so that at any time the robot has the necessary deceleration capability to achieve a complete stop before coming in contact with the operator. This protocol is specific for validating a two-dimensional safety distance.

Example: A robot is used to carry out a pick and place task. The workspace is accessible for an operator and is equipped with a LiDAR sensor system including an Intelligent Control System (ICS). The ICS aligns geometric datasets from the sensor and the robot controller in a voxelised virtual environment, tags different objects (human, robot, static obstacles) and calculates the minimum distance between the human and the robot. Based on the distance, the braking characteristics of the robot and the system dynamics, the ICS calculates the PSD and controls the speed of the robot. This procedure is periodically repeated, and the ICS must guarantee that a specific PSD is not violated.

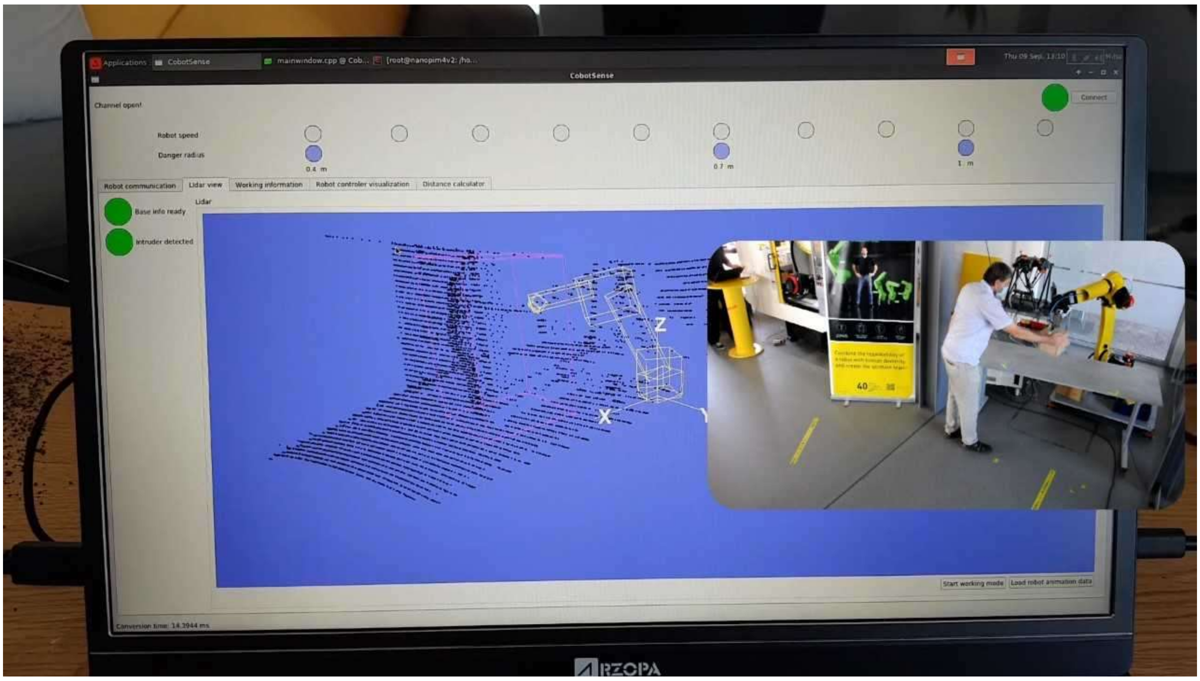

Figure 1: Synchronized operation of the COBOT, operator and ICS.

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Maintain Safe Distance
System	Robot arm, 3D laser (LiDAR) sensor(s) with embedded intelligent control system
Sub-System	-
Domain	Manufacturing, logistics
Conditions	Indoor – factory, warehouse
Measurement Device(s)	High-speed high-resolution camera

	Warning
⚠	This protocol supports users only to validate the effectiveness of the skill listed in the profile above. The skill should be a technical measure for the robot system to mitigate the risk of one potentially hazardous situation as identified in the mandatory risk assessment. Consequently, the risk assessment must be done before using this protocol.

1.2 Definitions and Terms

Protective separation distance (source: ISO/TS 15066:2016)
Shortest permissible distance between any moving hazardous part of the robot system and any human in the collaborative workspace. This value can be fixed or variable.

Collaborative robot (source: SIST EN ISO 10218-2:2011)
A robot designed for direct interaction with a human within a defined collaborative workspace.

Collaborative workspace (source: ISO/TS 15066:2016)
Space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

3D safety sensor
Device for real-time acquisition of point on surfaces of 3D objects in the collaborative workspace. In this protocol, the LiDAR-based sensor is used.

High-speed high-resolution camera
Device capable of capturing moving images in megapixel resolutions with frame rates of several hundreds or even thousands of images per second.

Intelligent control system – ICS
Real-time software subsystem of the intelligent sensor system aimed to calculate safe protective separation distance for SSM. Its main tasks are thus to predict positions of the operator within some predefined time interval, and to generate instructions for robot speed control to prevent collisions.

LiDAR
Light Detection and Ranging. An active remote sensing technology which uses laser to determine exact distances between the sensor and acquired points. Airborne and terrestrial devices are used, and the latter may be either static or mobile.

2 Concept and Objectives

The protocol proposes a test to validate whether a 3D sensor and an associated ICS are capable to maintain a specific separation distance during operation. The validation process uses a camera on top of the scene and a grid on the floor to monitor the distance between human and robot arm at all time. For safety reasons, a human operator must be replaced by a test dummy, particularly in the tests with higher robot speeds. 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 violating a predefined distance to a moving object.

2.1 Hazardous Situations

The risk assessment specifies for which hazardous situations the protocol user must validate by test and whether the applied safety skill allows the robot to mitigate the risk effectively or not. For the test, the occurrence of the hazardous situation characterizes the main event.

2.2 Target Behaviour and Metrics of the Safety Skill

The target behaviour of the skill "Maintain safe distance" to be validated is the capability to decelerate or to stop the robot when the distance between the robot system or workpiece and the safety-related object (the human operator) would become shorter than the adequately assessed PSD if progressing with the current robot speed. Similarly, the speed may be increased towards the value from the robot program when the hazardous situation has been successfully resolved.

The distance between the robot system or workpiece and the operator computed by the ICS represents the main metrics to be validated within the protocol. The protective separation distance PSD between the human operator and the robot system representing the threshold for their minimal mutual distance is computed by the Eq. 1, described in the technical specification ISO/TS 15066:2016:

$$PSD = S_H + S_R + S_S + C + Z_R + Z_D. \quad (1)$$

Here S_H, S_R, and S_S represents the contributions to the PSD related to the operator's change in location, the robot system's reaction time, and the robot system's stopping distance, respectively. C is the intrusion distance safety margin based on the expected human reach. Z_R is the robot position uncertainty (often negligible) and Z_D is the operator position uncertainty (e.g. due to the point cloud registration error, voxelization, and low scanner's resolution). One can strictly follow the specifications of individual terms from the ISO/TS 15066:2016 or, more frequently, simplified equations are used. Eq. 2 is used in the example that we follow in several places throughout this document:

$$PSD = (v_R + v_H)(t_{Sensor} + t_{ICS}) + \left(\frac{v_R}{2} + v_H\right) t_{Stop} + C + Z_R + Z_D. \quad (2)$$

Here v_r is the robot's velocity towards the operator, v_H is the operator's velocity towards the robot (maximal value 1.6 $\mathrm{m/s}$), t_{Sensor} is time between two sensor scans, t_{ICS} is the delay caused by the ICS data processing, and t_{Stop} is the robot's smooth stopping time after the stop command was received. It (t_{Stop}) is a function of the robot's velocity and its load. If the functional dependency of t_{Stop} or at least some reference values are not given then the worst-case (corresponding to maximal velocity and load) value must be used in the equation, usually resulting in much higher PSD than necessary (which is good for safety, but less good for the robot's efficacy). Finally, the term C is determined as the distance between the most exposed points of the human model (voxelised point cloud) and its safety buffer in direction towards the robot.

Example: Required Protective Separation Distance

Formula Name	Formula Symbol	Example 1	Example 2
Intrusion Distance	C [m]	0.3	0.3
Position uncertainty human	Z_D [m]	0.1	0.1
Position uncertainty robot	Z_R [m]	0.0001	0.0001
Human Speed	v_H [m/s]	0.4	1.6
Robot Speed	v_R [m/s]	0.2	1
Stopping Time	t_{Stop}[s]	0.512	0.512
Sensor Detection Time (ICS + LiDAR)	$t_{Sensor} + t_{ICS}$ [s]	0.4	0.4
Protective Separation Distance	PSD [m]	**0.896**	**2.515**

Note: The PSD must be maintained between all joints of the robot system and the human operator. Typically the tip, the tool, and/or the load are the most exposed parts of the robot system, and the experiment can then be planned in a manner that they are also the nearest to the operator all the time. Consequently, the ICS for the validation purposes may be simplified. However, the ICS data processing time t_{ICS} must still reflect the full version behaviour as the protocol is aimed to validate the usability of sensors in real applications and not only in simplified testing environments.

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 their reasonable and relevant combinations. The user must test the applied skill for each combination from the test plan. Therefore, it is important to know the conditions with the most significant influence on the target metrics.

3.1 System

The hazardous situation to be prevented by the ICS is a violation of the PSD (Protective Separation distance) between a robot system or workpiece and a human operator. The operator is assumed to move with the speed not higher than $1.6\ \mathrm{m/s}$. The operator is assumed to be outside the PSD-protected area before she/he is detected for the first time. Consequently, the monitored area should be large enough. The maximal speed of the robot tip and its stop time are also prespecified in accordance with the test plan. An exemplary setup of the scene is shown in Figure 2~~Figure 2~~. It shows a collaborative workspace and the surrounding area covered by the LiDAR sensor.

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	Gripper, weight of 5 kg
Work Piece	

Manufacturer	My Company
Model / type	Wooden cube
Short description	LxWxH: $20x20x20\ \text{cm}^3$, weight $0.5\ \text{kg}$
Safety Sensor	
Manufacturer	The Safety Sensor Company
Model / type	3D LiDar sensor
Short description	$Z_D = 0.1\ \text{m}, C = 0.3\ \text{m}$
Operator Test Dummy	
Manufacturer	The Dummy Company
Model / type	Model "Eve"
Short description	Human, female, 50th percentile, with arms outstretched forwards

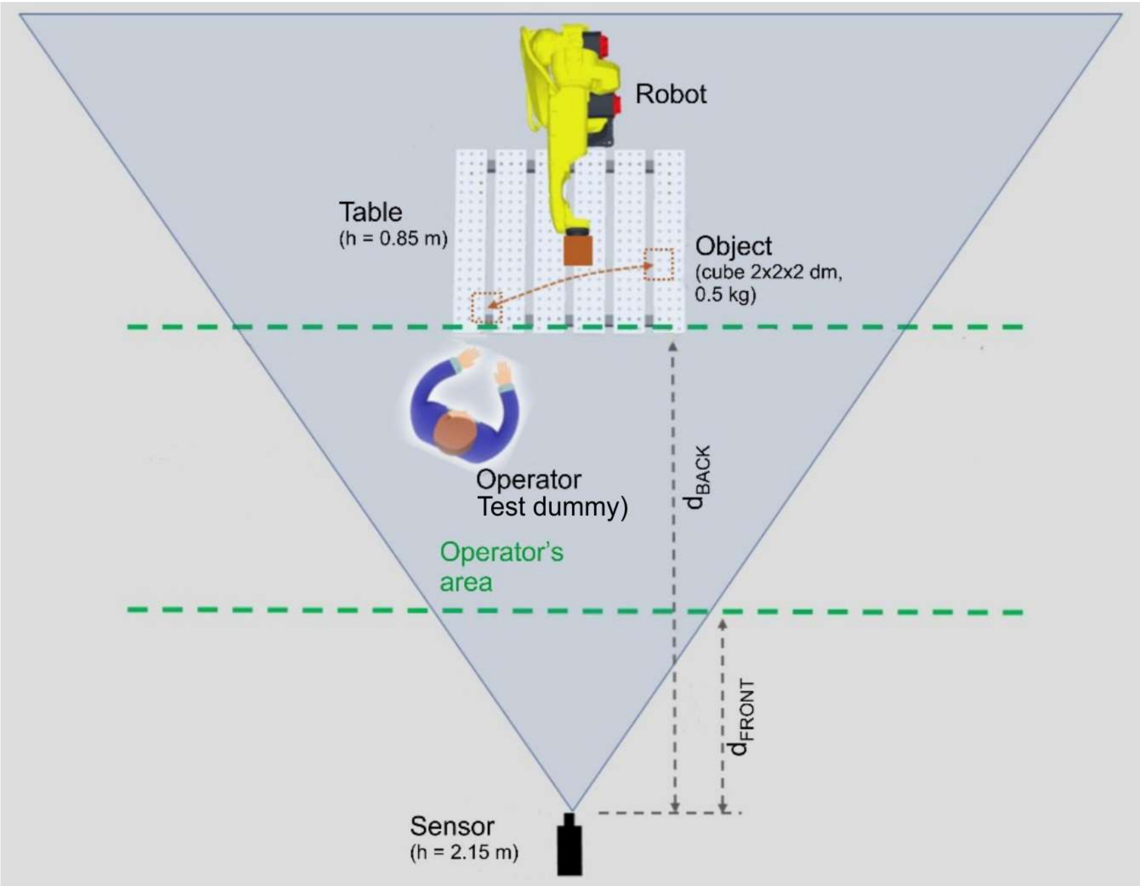

Figure 2: LiDAR sensor and robot arm arrangement (the image is not to scale), with the camera's field of view marked in blue.

Example: Safety Skill Properties

Speed of individual robot segments	Circular moves are linearly interpolated. The bounding boxes of the robot segments and the safety buffer of the operator are oversized to provide safely extended PSD.
Stopping time of the robot t_{Stop} [s]	0.512 **Note:** In case no other data is available, the worst-case value for stopping time has to be used (Highest speed and payload).

Positioning of the sensor	Side of the workspace (see Figure 2: $d_{FRONT} = 2.2\ \mathrm{m}$, $d_{BACK} = 3.8\ \mathrm{m}$, sensor height $2.15\ \mathrm{m}$, sensor inclination 22° forward down) **Note:** The positioning of the 3D sensor significantly influences the ability to detect the human operator. Due to the limited detection angle the placement of the sensor above the robot is often not feasible, although it would be the best option for accurate object detection. The best of the suboptimal single-sensor arrangements is a compromise that must consider all the obstacles and limitations of the workspace, while still monitoring the mentioned space between the robot and the operator for as much time as possible.
Number of sensors	1 **Note:** Grey zones may be successfully safeguarded and thus eliminated by employing two or more sensors. However, the system's frame rate could be reduced due to additional computing effort.
Sensor Resolution	142x47 **Note:** Resolution should be high enough to provide that the narrowest objects or their parts with safeguarding relevance would still be clearly detected. A human arm is a reference object requiring that two scanning rows or columns at the operational distance should not be more than 5-6 cm apart.
Sensor Frame Rate [fps]	5 **Note:** Higher frame rates decrease t_{Sensor} and t_{ICS} but often come with lower resolution.
Detection angle [°]	40°
Movement predictions	On **Note:** The role of the predictions is not to provide safety, but to make the robot operation smoother and more efficient. A system is best designed if a full SSM functionality is provided without predictions already.

Note: It is of high importance that all the parameter values which cannot be accurately determined are estimated, rounded, or otherwise simplified in a manner to increase the PSD and not to decrease it. Namely, the robot efficiency may be sacrificed for good of safety, while the opposite is not allowed.

3.2 Environment

Environmental characteristics expected in the industrial environment, such as the presence of gas, smoke, dust, high level of electro-magnetic fields and/or metallic obstacles, must be replicated during the validation. The risk assessment procedure should define appropriate action if any of the unexpected environmental events causes delay or absence of the sensor systems feedback.

4 Test Setup

4.1 Equipment

The following measurement device and accompanying equipment are required to perform the test:

- Highspeed Camera with at least 100 fps,
- Grid on the floor with 5 x 5 cm raster,
- Software to analyze the video.

The resolution of the sensor to measure the one-dimensional distance between robot and human should at least be a tenth of the used grid size. The resolution must be added to the final result of the safety distance.

Example: Calculation of the minimum camera resolution

Variable Name	**Formula Symbol**	**Formula**	**Value**
Distance to be measured	S_B [mm]		50
Required detail resolution	D [mm]	$\frac{S_B}{10}$	5
Installation height of the camera	H [m]		3
Opening angle of the camera	α [°]		60
Detection area of camera	A [m^2]	$\left(2\tan\left(\frac{\alpha}{2}\right)H\right)^2$	3.5 x 3.5
Minimum required camera resolu-tion	R	$\frac{\sqrt{A}}{D}$	700 x 700

Use the form in Annex 0 to report the capabilities of the sensor used for the validation.

Example: Measurement Device

Feature	**Description**
Manufacturer	The Camera Company
Type and model	High-speed high-resolution optical camera
Technical specification	Resolution 2048 x 2048, 1000 frames per second

4.2 Method

Figure 3~~Figure 3~~ illustrates the positioning of the camera and shows the grid on the floor. The measurement device (camera) must be placed far away from the reach of the robot arm or test dummy. While the sensor and ICS actively participate in the SSM safety operations, the testing measurement device is passive and, depending on its position and size, it can be eventually detected by the sensor either as a static scene component (hopefully), but also as an intruder or noise.

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	Warning
	Tests must be carried out with test dummies, especially at higher speeds of the robotic system, in order to avoid possible injuries to the operator. Depending on the

	application and risk assessment, the dummy could be a passive mannequin that represents either the most common or the most disadvantageous body dimensions for the investigated scenario. It can be manually moved on a wheeled platform.

It should be considered during the test design that ICS generally calculates the PSD and the minimum distance between a human and a robotic system in 3D space, and the camera captures only 2D images. In order to be able to directly compare the distances determined by ICS in 3D and captured by a camera from above, the tests must be designed so that a human and a robot operate at as similar height as possible. This height (h_{TEST} on Figure 3b) must be pre-determined, as well as the installation height of the camera (h_{CAMERA}). The method based on counting the pre-drawn dots on the floor measures the distance between two points projected onto the floor by the top perspective projection and not between the points at their original height. Therefore, the measured distance SD_{MAN} must be multiplied by the ratio between the heights of two similar triangles in Figure 3b to obtain the distance SD_{TEST}, which can then actually be compared with the ICS results. The procedure is described in more detail in Section 5.3.

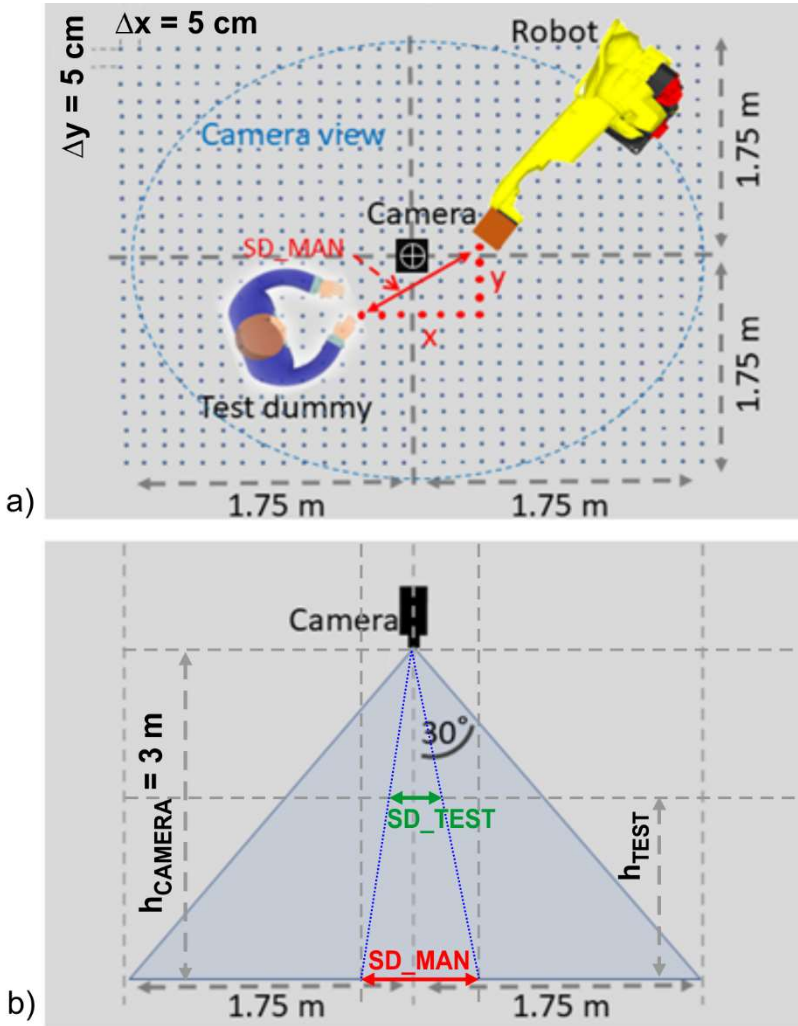

Figure 3: Video camera test setup: a) top view, b) side view (the image is not to scale)

Note: The values of all parameters that could affect the test results should be listed in the test reports (see Annex 0) together with the description of the scene arrangement and eventually some graphical schema. This is particularly important for systematic evidence of repetitions of the test with the same or modified parameter values. If multiple sensors are used, they must be described separately as they may differ in some attributes, including the spatial resolution and frame rate.

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 0, 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 tool center point (TCP) velocity
2. Sub-system
   - Not available
3. Environment
   - Obstacles
4. 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 0. The protocol user should repeat each test with the same parameters ten times, and the test is considered successful if all ten runs' results pass the validation criterium.

Note: For systems under development no specific risk assessment might be available. Annex 0 describes a set of typical scenarios to be tested.

5.2 Preparation

Before executing a particular test from the test plan, it is necessary to prepare the test setup and the ambient light conditions properly (the dots on the floor must be seen clearly by the camera), by choosing proper camera parameters (speed, resolution).

5.3 Test Execution

The test of the ICS's calculation of the PSD must be done by repeating the movements of the test dummy towards the robot arm with several speeds (the highest approx. $1.6\ \mathrm{m/s}$ and the lowest speed approx. $0.2\ \mathrm{m/s}$). The robot speed must also be tested in a range of the considered model's specifications. Each test case must be repeated 10 times. Apply the following steps for each test case:

1. Move the robot to the beginning of the trajectory you want to validate (see test plan or risk assessment).
2. Switch on the test camera, the ICS with the sensor, and the robot system.
3. Run the robot program, which moves the robot arm towards the test dummy with predefined speed.
4. The test dummy starts to move towards the robot arm with predefined speed. The dummy must approach to the robot arm in a manner that it allows an undisturbed view of the camera to the robot arm and to the dummy itself. If necessary, move the camera to a new location to allow for an undisturbed view of the robot arm and the dummy itself.
5. Depending on the ICS logic, the robot gradually decelerates until only a complete stop remains the only safe possibility.
6. The robot arm stops. It is important that the speed of the test dummy remains unchanged at least till this moment. After that, it can be stopped to avoid a collision with the stopped robot.
7. Save the recorded video for off-line processing and archiving.
8. The first frame of the movie after the robot stops (its position is different from that in the previous frame, but the same as in the next frame) labeled T_{E_MAN} in Fig. 4b is considered off-line. The distances *x* and *y* (Figure 3a) are obtained manually as the numbers of dots between the closest parts of the test dummy and the robot arm in both coordinate directions multiplied by Δx and Δy, respectively. The distance SD_{MAN} (MAN stands for manually measured) is then calculated as the Euclidean distance (Eq. 3):

$$SD_{MAN} = \sqrt{x^2 + y^2}\ . \tag{3}$$

   As explained in Section 4.2, SD_{MAN} is the actual distance projected onto the floor. The real distance SD_{TEST} to be compared with the corresponding terms from Eq. 1 is then obtained (see Fig. 3b) as:

$$SD_{TEST} = \frac{h_{CAMERA} - h_{TEST}}{h_{CAMERA}} SD_{MAN}\ . \tag{4}$$

   SD_{TEST} from Eq. (4) represents the manually measured distance between the closest parts of the test dummy and the robot arm immediately after the latter stops.

9. The distance SD_{TEST} must be compared to the distance SD (Eq. 5) between the same pair of points but obtained by using Eq. 1 after the robot is stopped:

$$SD = C + Z_R + Z_D. \tag{5}$$

10. The comparison of SD_{TEST} and SD is described in Fig. 4. If $SD_{TEST} > SD$ then the test is **PASSED**, otherwise **FAILED**.

    Note: When the test is passed, the measured time before the robot stops (at frame T_{E_MAN}) is shorter than the corresponding computed time ($t_{Sensor} + t_{ICS} + t_{Stop}$ from Eq. 2). The test criterion uses '>' and not '≥' sign because the SD is calculated for the worst case, when t_{Stop} is the stopping time at the highest speed of the robot arm and at the heaviest load which is practically never met.

Note: The raster of dots can be utilized also to measure the (average) speed of an object (test dummy or robot arm) in some time interval:

$$\Delta t = \frac{Number\ of\ movie\ frames\ in\ the\ considered\ interval}{Camera\ speed\ [fps]}.$$

Let $dots_X$ and $dots_Y$ be the numbers of dots covered in both coordinate directions in Δt, respectively. The speed of the object at height h_{TEST} above the floor is then computed with Eq. 6.

$$\vec{v}_o = \frac{h_{CAMERA} - h_{TEST}}{h_{CAMERA}} \left(\frac{dots_X}{\Delta t}, \frac{dots_Y}{\Delta t}\right). \tag{6}$$

The speed calculation might be used to design additional tests similar to the described one, but with the robot arm decelerating or even accelerating instead of completely stopping.

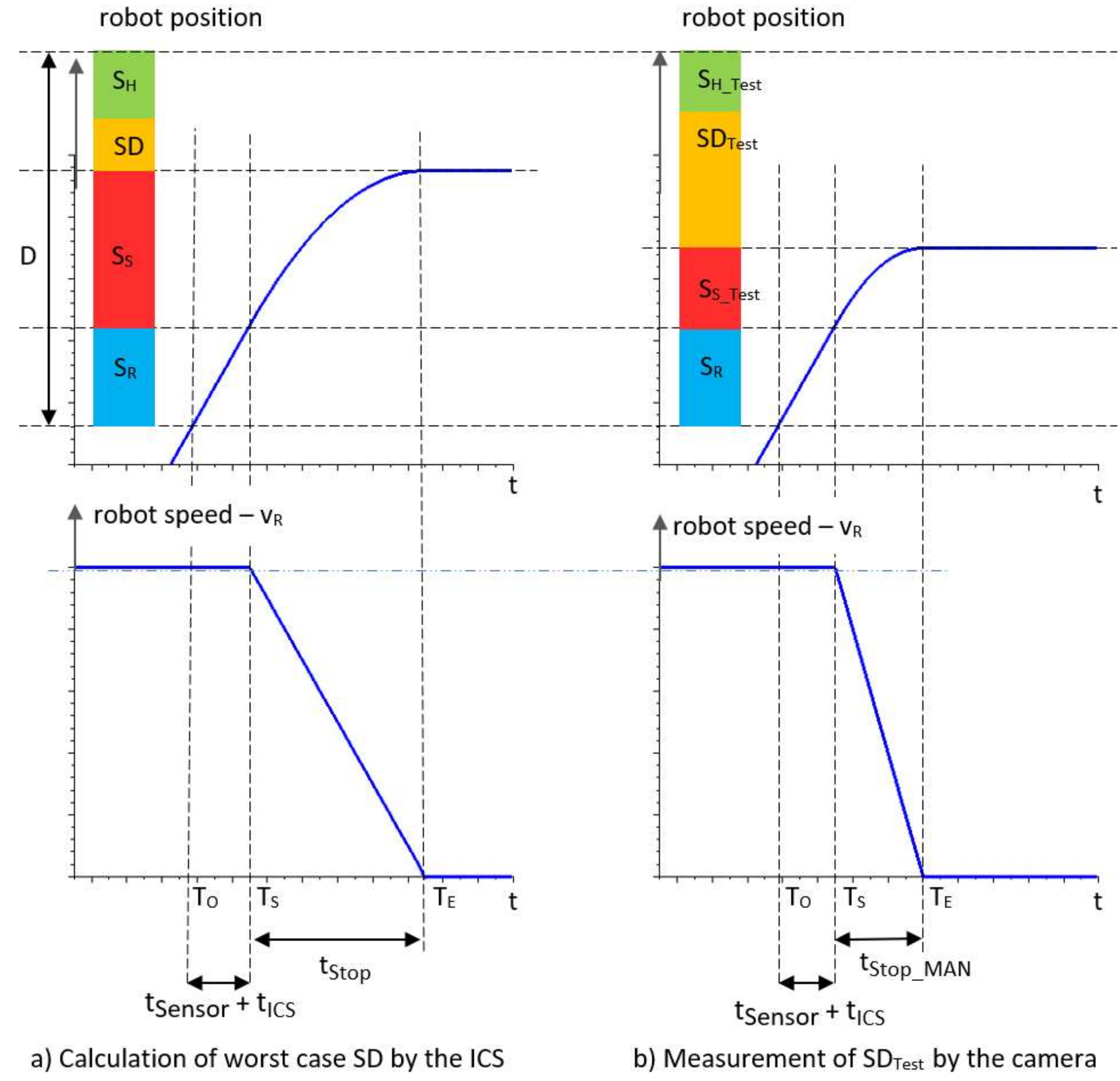

Figure 4: Description of the validation test in a case when it is successfully passed (SD_{Test} > SD).

5.4 Data Analysis

The results of all ten repetitions of a particular test are collected in the table "Results of the individual Test ID X" (Annex A). Besides the values SD_{Test} (Eq. 4) and SD (Eq. 5) which are compared for the Passed/Failed decision, the listed results also include the measured robot stopping time t_{Stop_MAN} which might be helpful to estimate how much is the (worst-case) stopping time t_{Stop} in Eq. 2 oversized.

The example below shows the specifications and results of a test with relatively high robot's and operator's speed $v_R = 1.2\ \mathrm{m/s}$ and $v_H = 1.6\ \mathrm{m/s}$, respectively, which passed in six repetions and failed in four. The summary results of this and another test with the same setup but significantly lower speeds ($v_R = 0.2\ \mathrm{m/s}$ and $v_H = 0.2\ \mathrm{m/s}$) which (comfortably) passed in all ten repetitions, are listed in the table in Section 5.5.

Example: Specifications and results of Test ID 1 safety parameters and results of ten repetitions

Test ID	1 (Velocity Step 1)		
t_{Sensor} [s]	0.2	t_{ICS} [s]	0.2
t_{Stop} [s]	0.512	C [m]	0.3
Z_R [m]	0.0001	Z_D [m]	0.1
v_R [m/s]	1.2	v_H [m/s]	1.6

Test ID	Repetition	t_{Stop_MAN} [s]	SD_{Test} [m]	SD [m]	Result [Passed / Failed]
1	1	0.41	0.46	0.4001	Passed
1	2	0.39	0.51	0.4001	Passed
1	3	0.48	0.35	0.4001	Failed
1	4	0.42	0.43	0.4001	Passed
1	5	0.45	0.42	0.4001	Passed
1	6	0.47	0.41	0.4001	Passed
1	7	0.50	0.35	0.4001	Failed
1	8	0.47	0.38	0.4001	Failed
1	9	0.41	0.45	0.4001	Passed
1	10	0.46	0.36	0.4001	Failed

Although the values of all parameters are constant through all ten repetitions, the measured values of SD_{Test} vary in range between 0.35 m and 0.51 m, while t_{Stop_MAN} is between 0.39 s and 0.50 s. The reason for these oscillations is that the exact speed of the test dummy for all 10 repetitions is difficult to achieve. Furthermore, the synchronization between the test dummy and the robot is also practically unrepeatable in all ten runs. Consequently, longer t_{Stop_MAN} does not necessarily mean shorter SD_{Test} although the trend is evident.

5.5 Report

Before performing a particular test with ten repetitions, a testing person describes the test setup (Annex 0 except the last two tables). The results of all iterations of the test are collected in the penultimate table of the Annex A (Results of the individual Test ID X). The summary statistics on the validation of multiple tests (typically addressing the same test setup, but with different robot and/or dummy speeds) is finally made (example below). A test is successfully passed when the '% Passed value' is 100. The validation is successfully passes if this value in the TOTAL line is 100. In all other cases (when the validation fails) the testing person is invited to describe what could be the reason for a particular repetition, test, or the whole validation to fail. The results are important to explicitly write the detected limitations (e.g. in maximal robot and/or operator speed at the current sensor system abilities) into the risk assessment and also as hints for future system improvements or replacement.

Example: Summary of the results of two tests

Test ID	Number of repetitions	% Passed	Reason when Failed (more answers allowed)
1 **Velocity Step 1**	10	60	A) Grey zone. B) Inability to detect narrow objects. (C) Safety margin violation. [circled] Other: Low sensor's scanning speed and long stopping time (t_{Stop_MAN}) due to high v_R and/or heavy load
2 **Velocity Step 2**	10	100	A) Grey zone. B) Inability to detect narrow objects. C) Safety margin violation. Other: ______
TOTAL	20	80	A) Grey zone. B) Inability to detect narrow objects. (C) Safety margin violation. [circled] Other:

6 Bibliography

ISO/TS 15066:2016 (Robots and robotic devices — Collaborative robots)

IEC 61496-3:2018 (Safety of machinery - Electro-sensitive protective equipment - Part 3: Particular requirements for active opto-electronic protective devices responsive to diffuse Reflection (AOPDDR))

IEC 62046:2018 (Safety of machinery - Application of protective equipment to detect the presence of persons)

IEC 60204-1:2016 (Safety of machinery - Electrical equipment of machines - Part 1: General requirements)

ISO 13855:2010 (Safety of machinery, Positioning of safeguards with respect to the approach speeds of parts of the human body)

ISO 13849-1:2015 (Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design)

ISO 13849-2:2012 (Safety of machinery — Safety-related parts of control systems — Part 2: Validation)

SIST EN ISO 10218-1:2011 (Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots)

SIST EN ISO 10218-2:2011 (Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robot systems and integration)

Annexes

A Report Form

Use the forms on the next pages to record the setup data for each test, to collect the test results, and to display the overall statistics of all tests.

Test ID / Test no	
Hazard ID	
Description	
Photo	

System Configuration

Robot arm	
Manufacturer	
Model	
Software Version	
Robot tool	
Manufacturer	
Model	
Short description	
Work Piece	
Manufacturer	
Model / type	
Short description	
Safety Sensor	
Manufacturer	
Model / type	
Short description	
Operator Test Dummy	
Manufacturer	
Model / type	
Short description	

Safety Skill Properties (can be test-specific)

Speed of individual robot segments	
Stopping time of the robot t_{Stop} [s]	
Positioning of the sensor	
Number of sensors	
Sensor Resolution	
Sensor Frame Rate [fps]	
Detection angle [°]	
Movement predictions	

Sensors / Measurement Device

Feature	**Description**
Manufacturer	
Type and model	
Technical specification	

Specifications of the individual Test ID X

Test ID			
t_{Sensor} [s]		t_{ICS} [s]	
t_{Stop} [s]		C [m]	
Z_R [m]		Z_D [m]	
v_R [m/s]		v_H [m/s]	

Results of the individual Test ID X

Test ID	**Repetition**	t_{Stop_MAN} [s]	SD_{Test} [m]	SD [m]	**Result [Passed / Failed]**
	1				
	2				
	3				
	4				
	5				
	6				
	7				
	8				
	9				
	10				

Summary of test results

Test ID	Number of repetitions	% Passed	Reason when Failed (more answers allowed)
1			A) Grey zone. B) Inability to detect narrow objects. C) Safety margin violation. Other: Low sensor's scanning speed and long stopping time (t_{Stop_MAN}) due to high v_R and/or heavy load
2			A) Grey zone. B) Inability to detect narrow objects. C) Safety margin violation. Other: ____________________
…			
TOTAL			A) Grey zone. B) Inability to detect narrow objects. C) Safety margin violation. Other:

B Typical situations to test

In industrial applications, the risk assessment defines which scenarios need to be tested by the protocol. The following list provides a set of typical critical situations for the given sensor system. The list could help to identify critical scenarios in the risk assessment or provide a dataset for sensor systems under development, for which a risk assessment does not yet exist.

Technical challenges of a LiDAR sensor system

A) Grey zones. This problem may result in an undersized safety buffer of the operator and, consequently, in undersized term C in Eqs. 1 and 2. If we imagine a (rare, but still possible) situation, where the operator is entirely hidden to the sensor, it will even not be considered in the PSD assessment. Similarly, the undersized or even negative operator's speed v_h will be used if his hidden part moves towards the robot with higher speed than his visible part.

B) Inability to detect small, narrow objects or their parts with safeguarding relevance. A human arm is suggested as a reference object requiring that two scanning rows or columns at the operational distance should not be more than 5-6 cm apart. However, if the operator carries some tool or other narrow object below this pre-set limitation towards the robot, then the PSD will quite likely be violated. The problem is related to a narrow detection angle of the scanner, its low horizontal/vertical resolution, and too long distance (d_{BACK} in Fig. 2) between the sensor and the region of interest.

C) Violation of the safety margin. The risk assessment should predict a monitored region satisfactorily large, providing that the operator will not enter the PSD-protected area before the first scan is processed. However, a quite similar (although not the same) problem is met if the operator is already moving in the monitored area when the scanning starts. Similarly, the »returns« from grey areas could be problematic and dangerous.

Typical critical scenarios

1. Operator and robot are moving towards each other, both with constant speed. The sensor is monitoring the situation from side (nearly orthogonally to the motion). No grey zones are expected. Different v_R and v_H must be tested in separate repetitions. The test is expected to positively pass the validation.
2. The scenario is similar to the previous one, but the operator extends his arms forwards. The criterion B is tested here. If the threshold for narrow objects is set properly, the test is expected to positively pass the validation.
3. The scenario is similar to the previous two, but the operator caries some narrow (under the threshold) object, e.g. a stick in front of them. Their arms can be either extended or not. The criterion B is tested here again. The test results will strongly depend on luck whether the laser beam manages to hit the stick near its end or not. A higher number of repetitions with the same and/or different v_R and v_H is therefore needed to estimate the probability of successfully passing the test.
4. Similar tests to the above three, but with the sensor behind the operator's back, will mostly check the criterion A, as the extended arm with or without a stick (or the stick may point towards the robot even when the operator's arm is not extended) behind (actually in front of) the operator is hidden to the sensor, i.e. in a grey zone. The test result depends on ability of ICS to safely adapt (oversize) the term C in Eqs. 1 and 2.
5. Operator moves from the left to right (as in situation 1) and extends his left arm towards the robot. This arm is again in a grey zone, although the operator is not moving frontally towards the robot.

The test is supposed to not pass, except the safety buffer and the corresponding term C are strongly oversized all the time.

6. Additional tricky situations with grey zones between the operator and the robot can be produced if the operator is walking backwards or sideways and simultaneously has his arm (or stick) extended in the hidden direction. The same conclusion on the test results can be made as in situation 5.
7. Depending on the risk assessment, the intended collaborative operations, and the equipment, the situations with the operator moving around the robot and/or such with additional (static) obstacles should also be included into the test plan. With the use of a single laterally positioned sensor, such tests do not make sense.