COVR

Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Robot Arm Does Not Overreach Vertical Planes

ROB-LRM-1

The purpose of this protocol is to verify the ability of the robotic system to limit its movements in 3D space. In this version of the protocol, it is checked that the robot, with all its segments and end effector, does not pass beyond a vertical plane placed in the robotic cell. The validation test is performed using a moving frame representing the vertical plane or part of it.

Readiness Level	Description
7	Protocol is published over the toolkit, under evaluation, and open for community feedback.

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!

DANISH TECHNOLOGICAL INSTITUTE
Fraunhofer IFF
cea
National Research Council of Italy
Roessingh Research and Development

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1 Introduction

The purpose of this protocol is to check the ability of the robot system to limit its movement in 3D space. This ability, i.e. safety skill, is used to avoid a collision of the robot with a person passing or working close to the robot.

Typical situation: An industrial (collaborative) robot work cell is fenceless and operators can pass close to the robot along a pathway. The maximum space*[1] reachable by the robot is restricted in order to ensure it does not enter the human pathway.

Safety skill and testing scenario: This safety skill can be realized by different means, for instance:

- mechanical stops
- proper positioning of the robot inside the cell or with respect of the user
- safety controller functions (soft axis and space limiting)
- external monitoring system (monitoring the robot position).

The validation protocol is independent of the skill practical realization.

In this protocol version, the robot not crossing a vertical surface placed in the robot cell will be tested.

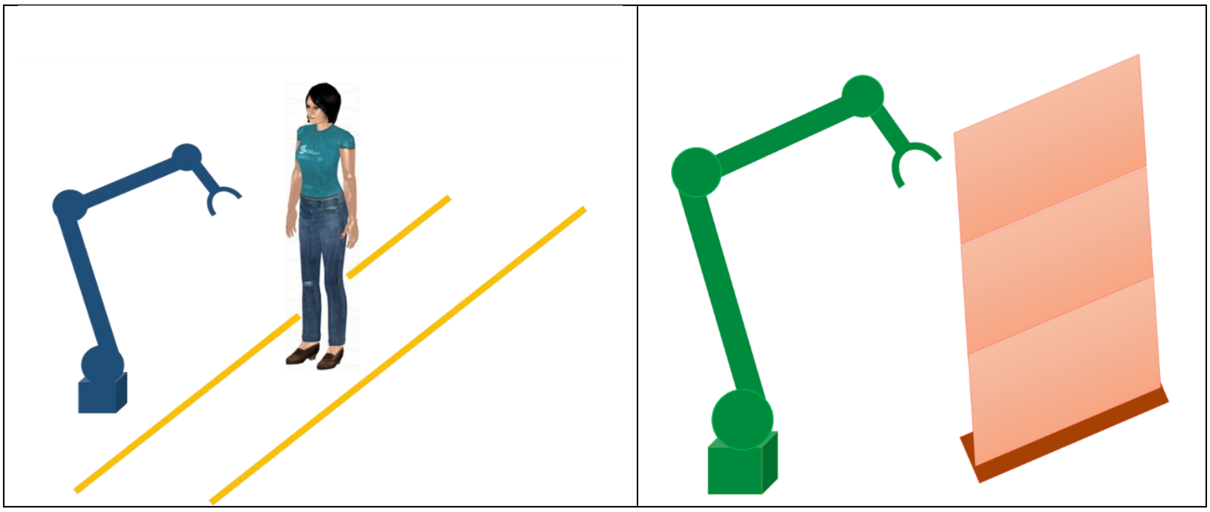

Figure 1: Exemplary application featuring situation (left) where space has to be restricted and testing situation (right)

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	limit range of movement
System	robot arm
Sub-System	n/a
Domain	cross-domain
Conditions	Indoor, space limit: (composed of) vertical plane(s)
Measurement Device(s)	Device that mimics a space restriction as a vertical surface (light board).

This safety skill is a space limitation that cannot change dynamically. Note that the case of a space limit dynamically changing with the human position is handled by the “maintain safe distance” skill.

[1] All terms followed by an asterix * are defined in section §0

This version of the protocol is dedicated to validate the skill when the space (or part of the space) is limited by vertical surfaces.

	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 have 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

Link (source: EN ISO 8373, §3.6)

Rigid body connecting neighbouring joints

Manual reduced speed mode (source: EN ISO 10218-1, §5.7.3)

This mode is used for jogging, teaching, programming and programme verification of the robot; it may be the mode selected when performing some maintenance tasks. Previously, this mode was also known as T1, or teach.

Maximum space (source: EN ISO 10218-1, §3.24)

space which can be swept by the moving parts of the robot as defined by the manufacturer plus the space which can be swept by the end-effector and the workpiece [ISO 8373:1994, definition 4.8.1]

Operating space (source: EN ISO 10218-2, §3.13.1)

Portion of the restricted space* that is actually used while performing all motions commanded by the task program.

Restricted space (source: EN ISO 10218-2, §3.13.2)

Portion of the maximum space* restricted by limiting devices that establish limits which will not be exceeded.

Crossing point (source: local to the document)

The crossing point is the point of the crossing segment* where the crossing segment would cross the target plane* if the robot could follow the programmed test trajectory.

Crossing segment (source: local to the document)

The robot link* or end-effector that would cross the target plane* if the robot was following the programmed test trajectory.

Target plane (source: local to the document)

The flat surface that the protocol will check as not being crossable by the robot

Target point (source: local to the document)

The point on the target plane* where the crossing point* would cross the target plane if the robot could follow the programmed test trajectory.

2 Concept and Objectives

To validate the skill, the robot will be programmed to go beyond a plane, called the **target plane***, and the fact that the robot cannot cross this target plane will be checked. In this protocol version, we consider the target plane to be a vertical plane section.

2.1 Hazardous Situation

The hazardous situation considered here is an unintended movement causing the robot to enter the space the humans are passing through, although this space is not in the (regular) operating space* of the robot.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill to be validated is that the robot does not cross the target plane*: it must stop before the surface or slide at distance along the surface.

For each test, a robot trajectory is programmed that would bring the robot to cross the target plane if the skill was not effective. The robot link* or end-effector that would cross the target plane if the robot was following the programmed test trajectory will be called the **crossing segment***. The crossing segment can be an end-effector, a link* of the robot, but also more specifically a joint cover or any piece attached to the robot (cables, cover).

The **crossing point*** P_{cross} will be defined as the point of the crossing segment*, where the crossing segment would cross the target plane, if the robot was following the programmed test trajectory. The point on the target plane, where P_{cross} would cross the target plane, is called the target point* P_{target}.

For validating the robot skill [Limits its maximum space], the output target is:

- observation that no part of the robot crosses the target plane* [boolean], (target value) = 'do not cross'

Please report the values of the target metric for each test using the form in the Annex.

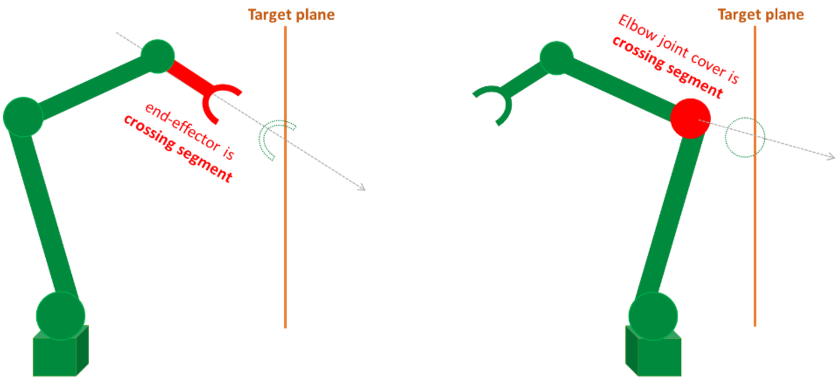

Figure 2: Different cases of crossing segment

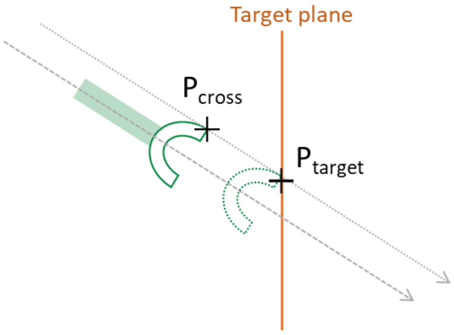

Figure 3: Points where the robot would cross the target plane

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 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.

3.1 System

The system considered here is the industrial robot manipulator with its end-effector(s) and possibly a workpiece. The types and serial (or identification) number of the system components must be reported in the testing report.

In case the application uses several tools and/or workpieces, the system configuration must be chosen according to the configuration involved in the hazardous situation in the risk assessment. Possibly several system configurations need to be considered.

Example: System Configuration

Robot cell	
Project reference	My product 007 - assembly
Robot arm	
Manufacturer	The Robot Company
Model	robot 15
Identifier/serial number	Manufacturer serial number 7864 / my material identifier 2019.031
System configuration	Electric flange
Control software	coControl, version 2.3.1
Robot mounting condition	Suspended from ceiling
Robot tool	
Manufacturer	The Tool Company
Model	ESD-10, with flange interface (ref. plan Proj94.0083)
Short description	Electric screwdriver, 4 kg, 42 cm long

The safety configuration of the robot must be precisely reported. It can include hardware configuration as joint mechanical stop, and software safety functions.

Note: The software safety functions can be considered and used during the test only if their safety level (PL or SIL) is in agreement with the risk level identified.

Example: Robot safety Configuration

Hardware safety configuration	
Mechanical stops	Joint 1 [-100°,+100°], joint 2 [-40°,+50°]
Software safety configuration (all PL-d)	
Checksum	5AB3FJ43
Soft axis limiting	Joint 6 [-30°, +60°]
space limit TCP	Apply on TCP position (at the screw-driver head) space limited in a square vertical box *(when possible include drawing and parameters of the robot safety function screen shot)*
Space limit robot	Not available
Safety-rated monitored speed Axes	Joint 5 [60 °/s]
Safety-rated monitored speed TCP	400 mm/s

The conditions that may change according to the hazardous situation are:

- the position of the target plane and of the target point ;
- the approaching trajectory of the robot.

As the target plane is vertical, its position can be determined by a segment on the floor [P_1P_2]. The position of the target point P_{target} in the target plane is defined by its height and lateral distance to P_1 (see Figure 4).

- Target plane base point P1 and P2 (to be reported in a drawing, by default with coordinates given in robot base coordinate system but can be more conveniently given with respect to some environment elements of the cell)
- Target point height htarget [from risk assessment] mm
- Target point lateral distance dtarget from point P1 [from risk assessment, by default half of the target plane width] mm

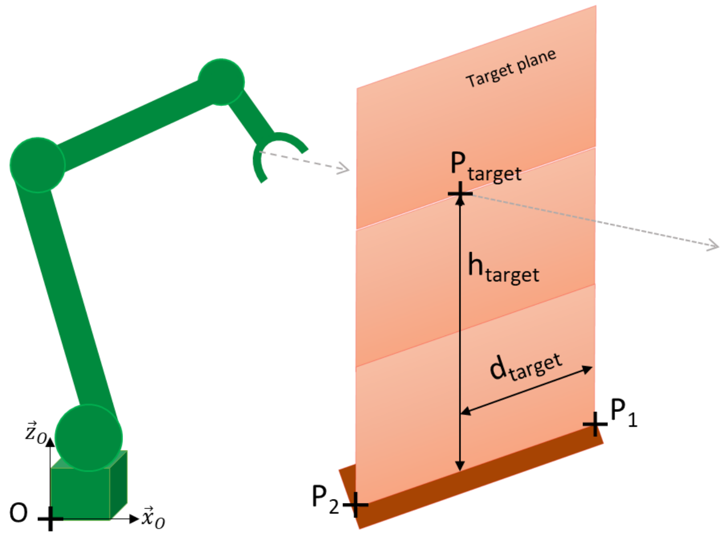

Figure 4 Position of the target plane and target point

Regarding the robot approach path, we will consider two types of travel: a translation and a rotation trajectory of the crossing segment.

For a translation approach of the crossing segment, the attributes are (Figure 5):

- The approach angle θa between the straight trajectory and the target plane surface [value from test plan, °]
- The approach orientation αa projected on the target plane, if θa is not 90° [value from test plan, °] (may also be given as a cardinal direction between top-bottom, left-right)
- The linear velocity $v_{crossing} = v_{target\ point}$ of the crossing segment [value from risk assessment, by default maximum robot speed, which can possibly be limited by safety functions, mm/s]

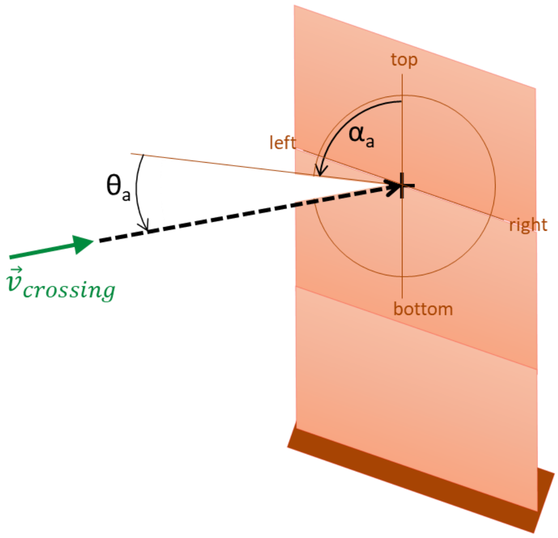

Figure 5: Attributes defining a translation approach of the crossing segment

For a rotating approach of the crossing segment, the attributes are (Figure 6):

- The position of the rotation center C_r
- The length between the rotation axis and the target point l_r

- The orientation of the rotation axis $\vec{u}_r$
- The angular velocity ω_r of the crossing segment [from risk assessment, by default maximum robot / programmed speed, which can possibly be limited by safety functions, °/s]
- The linear velocity at the target point: $v_{target\ point} = l_r\ \omega_r$

Note that a rotating approach is more easily programmed and interpreted using the rotation of a single joint.

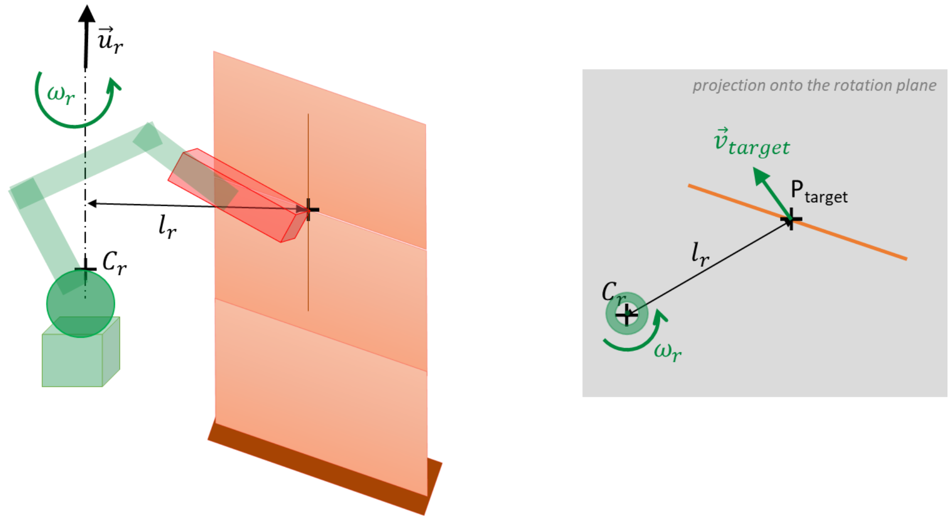

Figure 6: Attributes defining a rotating approach of the crossing segment

3.2 Sub-System

This protocol does not consider a robot manipulator with a sub-system (mobile platform, etc.). Note that the tool and workpiece are included in the system description.

3.3 Environment

The protocol user must consider whether a part of the robotic cell restricts the possible approach paths to the target plane. This will influence the test plan and possibly reduce the approaching velocity.

The test must be carried out in the operating condition allowed by the robot cell in agreement with the robot specification.

4 Setup

4.1 Test Arrangement

The space limit to be checked is materially represented by a vertical movable frame. If the space limit is wider than the frame, several positions of the frame must be tested.

We recommend defining the target plane position (segment [P_1, P_2]) in relation to some elements of the cell environment, which determine the area someone can pass, like a wall, another machine or a marked path. Thus, the validation will remain consistent even if the position of these elements has changed somewhat during the actual installation of the work cell.

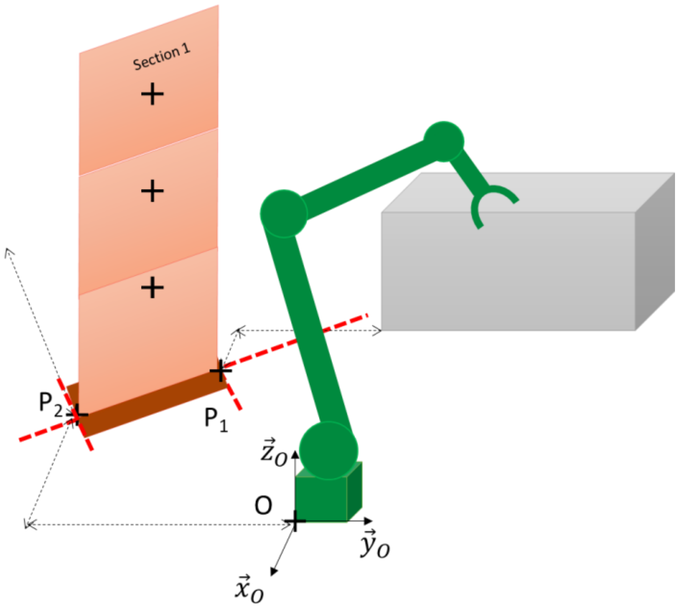

Figure 7: General structure of an appropriate test setup

4.2 Sensing devices

4.2.1 Target plane frame

Any surface kept vertical by a rigid movable frame can be used as target plane.

Target plane size

The surface size depends on the cell configuration and on the risk assessment.

To cover the most common cases, we propose a size of 60x 180 cm, for which we can have a standard material. Concerning the width, it is possible to test portions of the considered surface separately. We choose 60 cm wide portions in accordance with the proposed guideline for the test plan (see §5.1). We consider that testing at a height up to 180 cm is generally sufficient, except in case of a suspended robot or a large size robot which could reach human from top (the robot then being able to reach the head of a person over 180 cm high without reaching a point at a lower height).

Target plane material

The material is preferably light. If a collision occurs (negative test), it will move or fall, making the result more visible. It should be rigid enough to have a vertical face, so that a maximum error of 5 mm is observed on the plumb test.

Possible materials are foamed polystyrene blocks with a rigid cover on one side, or rollup banners with stand keeping the banner stretched and vertical.

Target plane plumb checking

To check the verticality of the target plane, either an inclinometer (range >180°, accuracy <2°), a plumb line or a laser plumbing tool is needed.

4.2.2 Camera and Video

It is recommended to take pictures of the stopped position for each test and a video when possible.

4.3 Data Acquisition

Not applicable.

5 Procedure

5.1 Test Plan

The test plan is listing all specific test cases to be considered for validating the skill.

The skill considered here is that the robot is not crossing a specific vertical surface placed in the robot cell. When the width of the target plane is large, we recommend subdividing it into several sections.

The test plan will list for each section the target points and the approach paths to be tested (type of trajectory, approach speed and approach orientation).

The test plan must also specify the robot tool and/or workpiece configuration.

Proposed guidelines for the test plan (to be adapted at your case considering the risk assessment)

- Target plane sections: 60 wide cm
- If several workpieces are considered, the test can be limited to the wider piece and to the heaviest one.
- 3 target points centered on the target plane at heights 0.45m 1m and 1.55m,
- If the crossing segment is the end-effector, use 3 translation paths at angle of approach: 90° and two opposite ±30°
- If the distance between a point of the crossing segment and the wrist center (if applicable) is more than 30 cm, add 3 rotation approach paths involving the wrist joints
- If the crossing segment is an intermediate segment like the elbow, consider doing a rotation approach involving all joints located between the robot base and the crossing segment
- First test with low speed (possibly with manual reduced speed mode*) or hand guidance, approaching the target plane.
- Look for the minimal distance approach to refine your test plan.
- If, at low speed, the robot stops at a distance greater than 150% of the maximum stopping distance (derived from the robot specification), skip the high-speed test for this single test.
- If, at low speed, the robot stops due to a hardware limit and more than twice the target distance, skip the high-speed test. High-speed test: if the speed is limited by a safety function, test at the safety-rated monitored speed (PL-d). Otherwise, test at the robot maximum speed.

5.2 Preparation

5.2.1 Setup

Target plane frame

- Mark the position of the target points on the target plane (if not already pre-marked)
- Mark the position of the target plane on the floor (segment [P1,P2]).
- If needed, check the distance between the target plane and specific elements. In case the cell arrangement differs slightly from what was planned, report the change and the updated chosen target plane position.

- Place the frame on the floor such as its surface base segment coincides with the marked segment [P1,P2].
- Check the verticality of the surface. If required, the frame is moved forward so that the highest target point to be tested is plumb on the target plane segment.

Video recording

- Place the camera in a way it can register the crossing segment approaching the target plane. For a translation approach, it can be placed on the side of the planned path. For a rotational approach path, the best is to put the camera on top of the rotation plane.

5.2.2 Environmental Conditions

The variation in operating indoor conditions of the robot cell are not supposed to influence the result of the "space limit" validation protocol.

However, it is recommended to run the tests in the same environment the robot system will run later. In case this environment is very specific, please note the general environmental conditions (for instance foundry).

5.2.3 System Conditions

The protocol user must configure the robot in the exact way it will run in the application. This 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.
- Configure all available safety-functions.

5.3 Test Execution

Apply the following test procedure for each specified test case separately. Note that the sequence of low speed preliminary test can be executed separately from the high-speed test, which can be carried out for a series of test cases.

Preliminary low speed test

- Move the robot slowly (hand guidance or manual reduced speed* mode) to approach the crossing point to the target point in the given approach angle θa (translation approach) or from the given position of the rotation center C_r (rotation approach)
- Take a photo of the achieved position closest to the target plane
- If the robot has touched the target plane, stop the test and reported it negatively (no need to carry out the high-speed test)

High-speed test

- Move the robot backward the path. Choose a proper start position on this path from which the robot has enough time to accelerate to its programmed speed before stopping or deviating from the programmed path. Choose the end position at a location where the robot would cross the target plane.
- Take a photo of the test situation (recommended).
- When using a video recording, check its view angle and start the video.
- Start the robot programmed movement.

- Observe if the robot collides with the target plane (in particular, check if the target frame has moved) and report the test result as positive or negative.
- Take a photo of the crossing segment stopping position (highly recommended)
- Release the robot by moving it under manual control.
- Reposition the target plane in case it has moved.

5.4 Data Analysis

Not applicable.

5.5 Report

The form proposed in **Fehler! Verweisquelle konnte nicht gefunden werden.** can be used to report the test conditions and results.

6 Annexes

A Test Report Form

Test ID / Test no	
Date and person	
Hazard ID or description	
Photo	

System Configuration

Robot cell	
Project reference	
Robot arm	
Manufacturer	
Model	
Identifier/serial number	
System configuration	
Control software	
Robot mounting condition	
Robot tool	
Manufacturer	
Model	
Short description	
Work Piece (if available)	
Manufacturer (optional)	
Model / type	
Short description	

Robot safety Configuration

Hardware safety configuration	
Mechanical stops	
Software safety configuration (all PL-d)	
Checksum	
Soft axis limiting	
space limit TCP	
Space limit robot	

Safety-rated monitored speed Axes	
Safety-rated monitored speed TCP	

Target plane and target points

Target plane position
Insert plan with the position of the target plane considered. Mark the point P_1 *If the target plane is divided into several sections, for which a target plane frame will be positioned, give a number to each section and gives the position of each section on the plan or schematic diagram, marking for each section the position of point* P_1.
Target points positions

Point n°.	*(if the target plane is divided into sections)* Section n°	**Point position**	
		Height h_{target} (mm)	Lateral distance d_{target} from point P_1 (mm)

Tests with translation approach (and no distance measurement)

test n°.	**Point n°.**	**Translation approach**			**Test result**
		Linear speed (mm/s)	angle of approach θ_a (deg)	orientation of approach α_a (deg)	
1	*1*	*300*	*90°*	--	*Positive (do not cross)*
2	*1*	*idem*	*30°*	*0° (or top)*	*Negative (cross)*
3	*1*	*Idem*	*30°*	*-90° (or right)*	*Positive (do not cross)*
4	*2*	*Idem*	*90°*	--	*Positive (do not cross)*