Being safe around collaborative and versatile robots in shared spaces

Protocol

Test mobile robot arm to limit the range of motion

MRO-LRM-1

The purpose of this protocol is to validate the skill "limit range of motion" for industrial mobile robots and their payload, including a robotic arm mounted on it. In this context, the skill limit range of motion is used to avoid the mobile robot, the arm and its payload to go through a forbidden space location. The validation protocol is aimed to check whether the footprint of the system is correctly set or not.

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!

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CONTENTS

1 Introduction

The purpose of this protocol is to check the ability of a mobile robot to limit its movement in 3D space. This ability, i.e. safety skill, is used to avoid the entrance of the system in areas where it is not allowed to enter (Figure 1). The safety skill to limit the robot travel area can be implemented for instance because its sensors won't work or there is too many people in a given area.

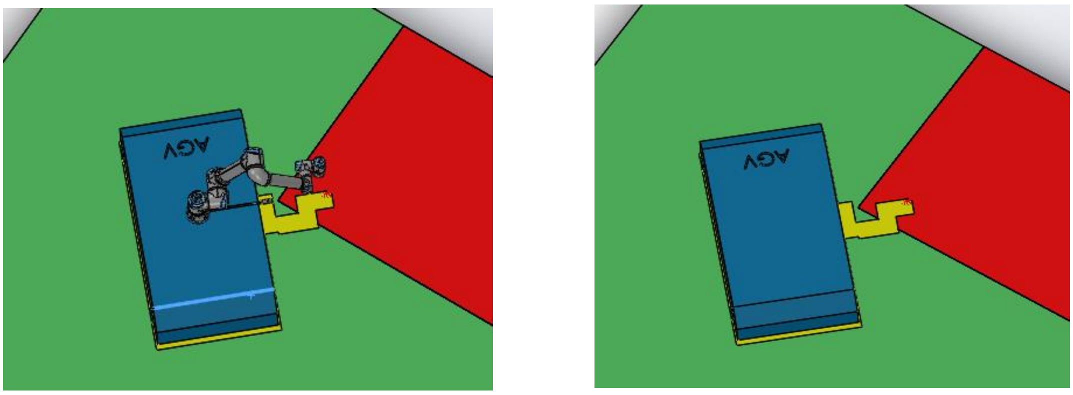

Figure 1: Exemplary application featuring situation. In red is the forbidden area, in green the allowed area, and in yellow the footprint of the mobile robot and its payload.

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Limit range of movement
System	Mobile platform
Sub-System	Robotic arm
Domain	Manufacturing, Logistics, Others
Conditions	Indoor
Measurement Device(s)	Device measuring a position (position tracker, video 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

Robot (source: ISO 8373:2012)

Actuated mechanism programmable in two or more axes with a degree of autonomy moving within its environment, to perform intended tasks

Mobile robot (source: ISO 8373:2012)

Robot able to travel under its own control.
NOTE: A mobile robot can be a mobile platform with or without manipulators.

Mobile platform (source: ISO 8373:2012)

Assembly of all components of the mobile robot, which enables locomotion.
Note 1 to entry: A mobile platform can include a chassis, which can be used to support a load.
Note that in this protocol, the mobile robot considered is a mobile platform (without a manipulator).

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

System including:

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

Application (source: EN 10218-2:2011)

Intended use of the robot system, i.e. the process, the task and the intended purpose of the robot system.

Allowed area (local to the document)

Area where the mobile robot and its payload (including the robotic arm) is allowed to move. It is defined by the risk assessment and should be programmed in the robot (opposite to forbidden area).

Forbidden area (local to the document)

Area outside and neighbouring the allowed area.

2 Concept and Objectives

The concept of verification process is to verify the behavior of the mobile robot in case it leaves the allowed area. In order to simulate this, a trajectory with an endpoint outside the allowed area will be programmed on the mobile robot, and its behavior will be checked.

2.1 Hazardous Situations

The risk assessment specifies for which hazardous situations the protocol user must validate by test 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. A certain state of the robot precedes always the hazardous situation. A state describes the position and velocity in the moment the hazardous situation occurs. Therefore, it is necessary to ensure that the robot is in the same state for the test as it will be in the real setting (for instance but not limited to the same position) when the skill takes over control.

In this protocol, a hazardous situation will be a situation where a part of the system {mobile robot + robotic arm + payload} is out of the allowed area.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill to be validated is to remain inside the allowed area.

In this protocol, we focus on the footprint of the whole system, in order to simplify the procedure of the tests. This way, it will be ensured that neither the mobile robot nor the robotic arm or its payload exit the allowed area, regardless of the height of the system.

The target metrics bases on physical and measurable quantities. These quantities are the output variables for the validation. The values of the target metrics indicate if the validated skill is effective enough to achieve the specified level of risk reduction. They represent a threshold that the output values of test must not exceed for considering the test as passed. For validating the robot skill “Limit Range of Motion in Space”, the output target is:

- Observation that the footprint of the robot stays at any time of the test inside the allowed area [Boolean]

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 term *system* considered here refers to the robot system consisting of:

- Type of mobile platform
- Type of robotic arm and its tool
- Type of payload

In case the application uses several payloads, the system configuration must be chosen according to the configuration involved in the hazardous situation in the risk assessment. Several system configurations may need to be considered, for instance several positioning with the largest payloads.

In case the robotic arm moves out of the footprint of the mobile robot during a trajectory close to the edge of the allowed area, the system configuration should be chosen with the arm at the most distant position from the footprint of the mobile robot. Possibly several system configurations need to be considered, depending of the trajectories of the mobile robot and its arm in the real application.

Refer to the risk assessment to identify the task-related conditions. Please report the system composition for each single test using the form in the Annex. Note that the payload may change for particular hazardous situations. This applies directly to the test (at least one test per hazardous situation).

- mobile platform velocity (velocity during the target behavior): [insert here from risk assessment] mm/s
- mobile platform payload: [insert here from risk assessment] kg

Test shall be performed without creating a hazard (e.g. tipping or sliding).

Example: System Configuration

MOBILE PLATFORM	
Manufacturer	The Robot Company
Model	Mobile robot platform 10
System Configuration	Safety Package
Control Software	MoCoControl, version 2.3.1

Robotic arm	
Manufacturer	The Robot Company
Model	Robot Arm 5
System Configuration	Safety Package
Control Software	RoCoControl, version 1.2.3
Description	Position / orientation of the robotic arm
Tool	Description (kind, shape, size, sharpness…)
Payload	
Manufacturer	My Company
Model	Transport box
Description (mass, shape, etc.)	20 cm x 50 cm long, 30 cm high, 10 kg

3.2 Environment

The following environmental conditions have an influence on the target values:

- Shape of the navigation area : [slope less than 3%] %
- Adhesion properties of the navigation area: [not slippery]

Although most of the environment conditions has almost no influence on the target metric, we recommend to run the validation tests under the same environmental conditions which the robot operator or user expects during productive operation.

4 Test Setup

4.1 Equipment

The sensing devices used in this protocol must be able to measure that the system leaves a predefined area. This protocol gives several examples of sensors that could be used for this purpose. However, the list is not complete and the user of this protocol may choose any other system able to detect the footprint of the robot with respect to the forbidden area.

In any case, make sure the location of the sensor allows the monitoring of the border(s) between the forbidden and the allowed area.

4.1.1 Camera

One option is to use a video camera placed above the scene (see Figure 2) and record the whole trajectory of the system.

Make sure the position of the camera is right above the location of the potential crossing of the border of the allowed area, as determined in the test plan (see Section 5.1). Make also sure the camera is perfectly leveled in the XY plane. It is necessary to have drawn the border of the allowed area. Be careful to have the right lens on the camera, in order to limit distortion effects.

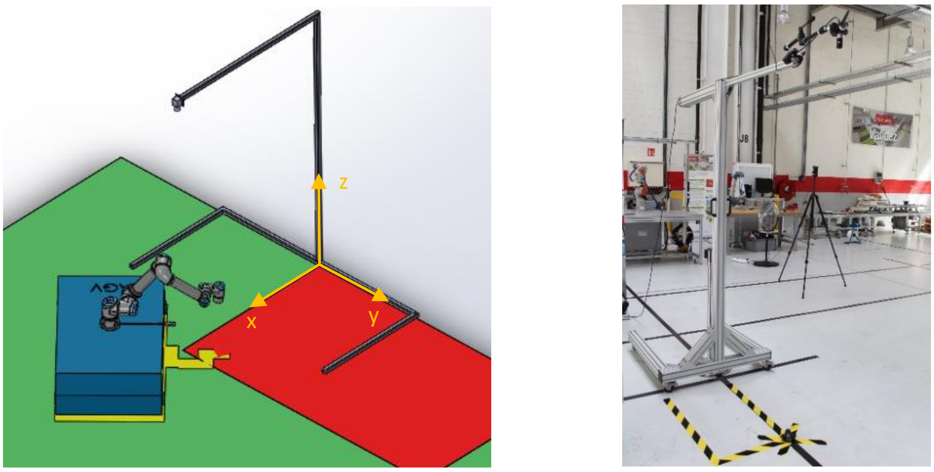

Figure 2: Video camera above the scene – a standing frame is used to suspend the camera

4.1.2 3D tracking system

Another option is the use of a 3D tracking system. The spatial position of the mobile robot will be tracked with respect to a reference frame placed at a convenient position with respect to the forbidden area.

To track the position and orientation of the mobile robot, place a rigid body tracker (Figure 3), either with a dedicated tracking device or a set of markers (3 for tracking it in space, one more is recommended). From this 'mobile tracker' you will get the position and orientation of a coordinate system for the mobile robot with its payload (with respect to the world reference system defined by your tracking system, usually from its calibration procedure).

A second rigid body tracker should be placed at a known position of the forbidden area or at its border. This way, a fixed coordinate system is defined and the mobile robot and the fixed coordinate systems are referenced to each other. Another way is to calibrate the tracking system such that the forbidden area is easily described in the world coordinate system.

The 3D position data will have to be processed to compute the footprint of the robot in the fixed coordinate system and to check if it protrudes the forbidden area. For that, the border of the forbidden area has to be described in the chosen fixed coordinate system. This processing and the required geometric modeling of the forbidden area and footprint can be implemented possibly in the 3D tracking system software or in a separate 3D geometric modelling software.

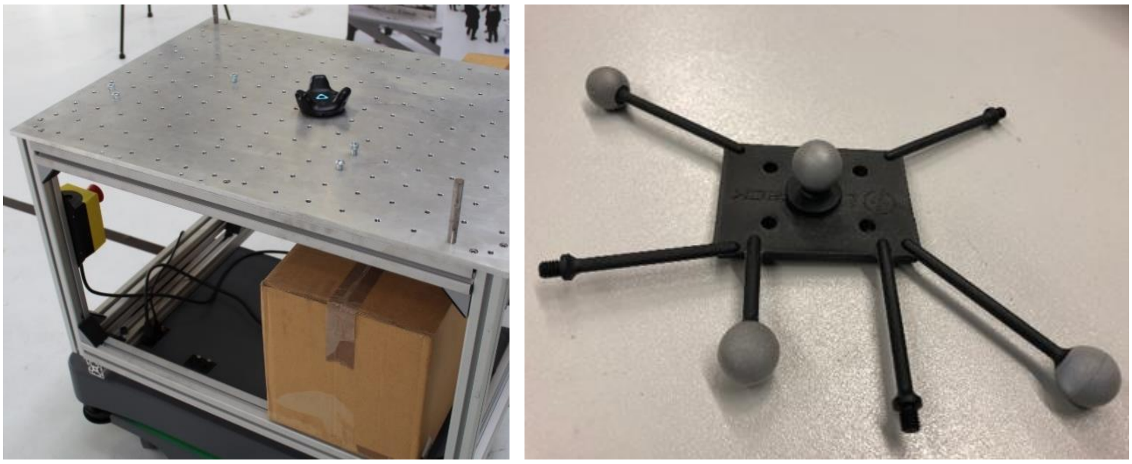

Figure 3: A rigid body marker hold on a mobile platform (left) and a marker set on a support for rigid body tracking (right)

4.1.3 Light curtain

The user can also use light curtain(s) composed of infrared light emitter and photoelectric cells to delimitate the forbidden area. The output signal of the light curtain has to be interfaced to an indicator light or a computer.

The height of the curtain and the number of beams must be adapted to the mobile system geometry. In simple configuration as a mobile platform with straight sides and no protrusion, a single beam can be used.

With this method, only straight borders between allowed and forbidden area can be checked. In addition, attention must be paid to place the columns such that the mobile system will not hit them.

4.1.4 Laser Scanner

Laser scanner could also be used to validate the described safety skill of the mobile robot.

Most scanner laser are 2D only sensing in a plane. For this protocol, it can be used with a horizontal scan plane. The height of the scan plane must then be carefully chosen according to the height of the most projecting part of the mobile system, as for instance a bulky load.

With a multilayer scanner laser, the measurement can be done on a certain height depending on the distance to the scanner head, facilitating the height adjustment.

When using a safety laser scanner, the allowed and forbidden zone will be more easily defined in the laser scanner software such that the software will compute and check the intrusion of the mobile robot in the forbidden zone.

4.2 Method

4.2.1 Frequency and accuracy of the position sensor

In either case, make sure the sensor used has a correct frequency and accuracy in regards with the test. Report the characteristics of your sensor and the way you used it in the form in the Annex.

In order to verify the characteristics of the sensor, it is necessary to get the following data:

- Maximum velocity v of the mobile robot during the test [mm/s]. It is the velocity defined in the program of the mobile robot for the tested trajectory (same velocity as in the real application). Be careful of the acceleration values, it may be possible that the mobile robot does not reach the programmed velocity if the distance between two programmed points is too short. Moreover, if the payload is very large and exceeds a significantly the mobile robot envelope, the tangential velocity should be taken into account.
- Maximum Distance *d* from which it is considered that the mobile robot has crossed the forbidden zone [mm]. For instance, it could be 5cm. It can be seen as the tolerated distance inside the forbidden area for the duration of one acquisition frame from the sensor (see Figure 4).

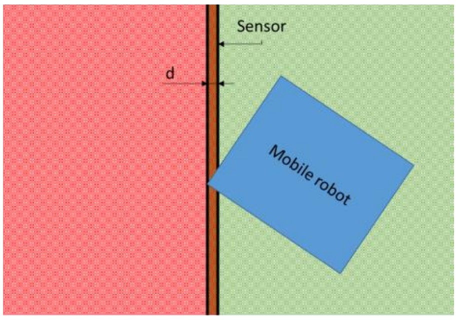

Figure 4: Distance d – tolerance to the measured robot penetration

Please make sure the sensor has the following characteristics:

- Accuracy a [mm]

The required maximum accuracy a_{req} of the sensor must fulfill the characteristics

$$a_{req} \leq \frac{d}{2} \quad ,$$

where d is the tolerance distance, as defined above and illustrated in Figure 4.

This comes from the Nyquist-Shannon sampling theorem, stipulating that the sampling frequency of a signal should be at least twice the maximum frequency of a signal. Here, the signal is the distance *d*, and the accuracy a is its sample.

With some measurement systems, like light curtains, the accuracy has no impact on the measure, so this part is optional. In this case, the sensor works by sending a signal on a receptor, and by checking the feedback of this signal. It is an on-off sensor, that's why the accuracy has no impact here, unlike the sweeping frequency.

However, the sampling frequency f must be considered for all types of sensors.

- Sampling Frequency f [Hz]

The event to capture is the robot entering the forbidden area. The mobile robot enters the area at the velocity v and must be detected within a_{req}. Then the time t to cross this distance is given by

$$t = \frac{a_{req}}{v} = \frac{d}{2\,v} \quad .$$

Then the frequency of the event to sample is

$$f_{event} = \frac{2\,v}{d} \quad .$$

The application of the Nyquist-Shannon sampling theorem leads to the minimum required sampling frequency

$$f_{req} \geq \frac{2\,v}{a_{req}} = \frac{4\,v}{d}$$

of the sensor.

Example of the calculation:

- Maximum velocity of my mobile robot: $v = 1100 \text{ mm/s}$
- Tolerated distance inside the forbidden area: $d = 5 \text{ cm}$
- Accuracy of my sensor (data found in the datasheet): a = 2 mm.
- Maximum accuracy for the sensor is $a_{req} = \frac{d}{2} =$ 25 mm.
- As $\leq\ a_{max}$, the accuracy is validated.
- Frequency of my sensor (data found in the datasheet): $f = 250 \text{ Hz}.$
- Minimum required frequency for my sensor is $f_{req} = \frac{2\,v}{a_{req}} = \frac{2*1100}{25} =$ 88 Hz.
- As $f \geq f_{req}$, the frequency is validated.

Follow the instructions manual of the manufacturer of the sensor to record, log and pre-process the data. You may report these instructions in the form in the Annex, especially if you need to pre-process the data.

Example: Sensor characteristics

Sensor type	3D Position tracking device
Sensor model	MySensor
Accuracy (mm) / Resolution (px)	2 mm
Frequency (Hz)	250 Hz
Picture	
Comments	

4.2.2 Placement of the position sensor

This test measures the fact that the footprint of the mobile system including its payload stays within the specified allowed area. Therefore, the allowed area should be made visible, with adhesive tape on the floor for instance (see Figure 5, left).

Moreover, both position sensor software and mobile robot software have to be calibrated to reflect the placement of the forbidden area. To do so, an idea could be to put a small pole (see Figure 5, right) to materialize one edge of the forbidden area, and then compute it on both software (see Figure 6). The pole will allow the mobile platform to detect the edge of the forbidden area. This way both software will reflect the same setup.

Figure 5: Tracking of the forbidden area

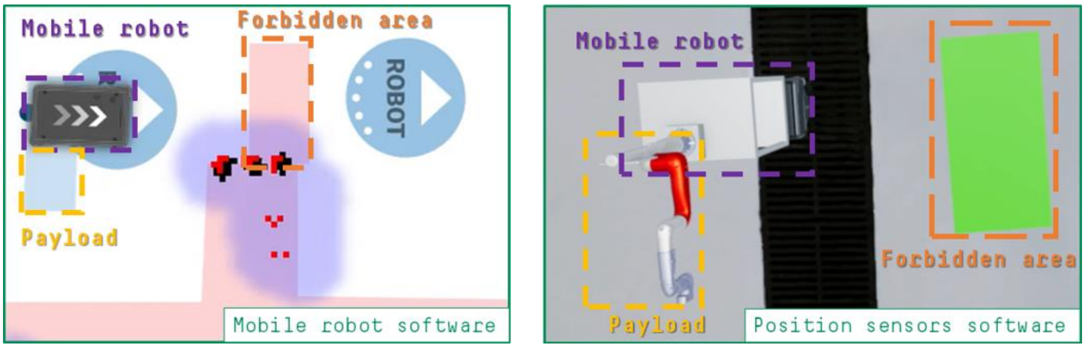

Figure 6: Representation of the forbidden area on both mobile robot software and position sensor software

5 Procedure

5.1 Test Plan

The test plan is a summary of all situations, which the risk assessment identified as hazardous due to the limit range of motion in space of the mobile robot and its payload, incl. all combinations of applicable conditions. Therefore, the test plan provides a detailed summary which tests are necessary to validate the skill for the considered application.

The test plan should at least cover the motion paths identified by the risk assessment as potentially hazardous. This means programming the mobile robot to move into or through an area that is outside the allowed area. The purpose of the test is to prove whether the mobile robot and its payload exceeds these spatial limits or not.

According to part 3, the protocol must consider the following conditions:

- The robotic arm should be positioned at its maximum length according of the real application.
- For defining the motion trajectories, consider that motions should at least cover
  - Trajectories of the mobile robot to locations in the forbidden area (see Figure 7, left)
  - Trajectories of the mobile robot to either locations inside or outside of the allowed area, where part of the robot or its payload could cross the forbidden area, should this be the shortest route (see Figure 7, right)
- If the software of the mobile robot allows it, please run the test for both kind of motions.
- If you program the endpoint at the other side of the forbidden area, keep in mind that the mobile robot may steer around it to reach the endpoint. The payload should be positioned on the mobile robot according to the worst case identified in the risk assessment for this particular motion, considering the allowed and forbidden areas.
- The velocity of the mobile robot should be set at the pre-programmed velocity of this motion.
- The straight line is the worst-case situation for this LRM test. Indeed, if the test is performed for a specific part of the path (defined in the risk assessment), it implies that the robot has to cross a forbidden area in order to go from A to B. Hence the test, verifying the correct implementation of that forbidden area in the mobile robot software, and making sure the robot takes a detour and avoids the forbidden area, even going "straight" from A to B.
- If you cannot perform the test in the real environment of the robot, you can perform it elsewhere, as long as you recreate the forbidden area with the same geometry than the real one.

In the application, if the mobile robot passes several times at the same sensitive area with different trajectories, each trajectory should be tested.

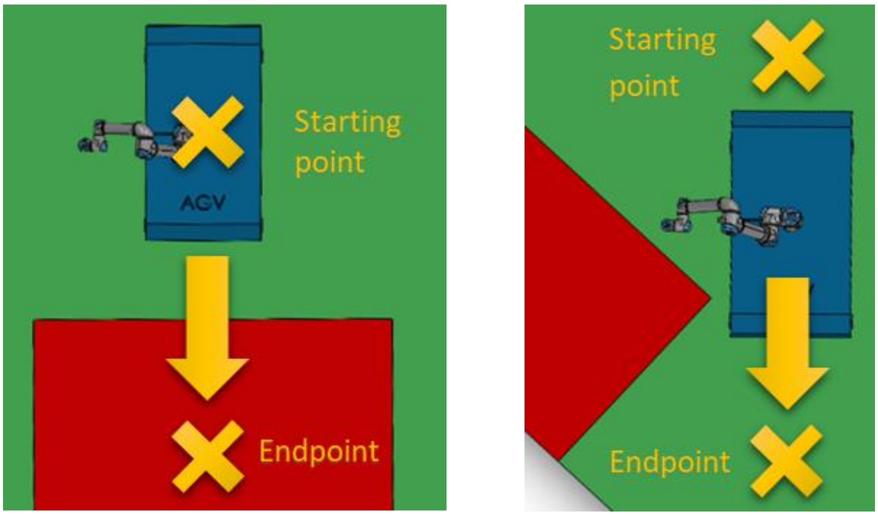

Figure 7: Trajectory of the mobile robot; The endpoint of the robots trajectory is located inside the forbidden area (left) and the footprint of the system crosses the forbidden area in case it takes the shortest path (right)

It is recommended to prepare the list of the tests to be performed before starting them. Please apply to Sections 5.2 to 5.5 for each test case, and run each test at least three times.

The endpoint should be defined as such as the path from the start point is straight-lined, and far enough as the mobile robot has enough time to reach its full velocity. Report both starting point and endpoint in the form in the Annex.

Example: Detailed test

Starting point	Description and/or coordinates in regards of border line of the allowed area
Endpoint	Description and/or coordinates in regards of border line of the allowed area
Payload	Description of the shape, of its position in the mobile robot, and weight
Velocity (mm/s)	
Configuration of the arm	Axis positions
Picture of the scene	

5.2 Preparation

Before executing a particular test from the test plan, it is necessary to prepare the setup and the conditions properly. The following sections give instructions to prepare each part of the setup and all conditions with a significant influence on the target metrics. Each test case must be documented using the form in the Annex. This also includes the identified conditions and their values.

5.2.1 Test Arrangement

Mobile robot

- Activate all available safety-functions
- Robot must be warmed up before running the tests

Data Acquisition

Initiate the data acquisition accordingly to the instructions manual. If the sensor requires it, please follow the calibration procedure of the manufacturer of the sensor.

5.2.2 System Conditions

The protocol user must configure the mobile robot (including its footprint) and the payload the exact way it will in application. The velocity must be configured as described in Section 3.1.

5.2.3 Environmental Conditions

If the application has some environmental conditions susceptible to have an influence on the result of the test, as described in Section 3.2, make sure to perform the concerned tests with the same conditions as in the application.

5.3 Test Execution

Apply the following test procedure for each specified test case separately.

- Put the mobile robot and its payload on the starting position
- Put the robotic arm at the desired position
- Program the endpoint of the mobile robot as defined in the test plan
- Verify that the sensor is set so that it reflects the programmed forbidden area
- Setup the velocity of the mobile robot according to Section **Errore. L'origine riferimento non è stata trovata.**

- Start the recording of the sensor(s)
- Start the mobile robot
- Wait for it to stop
- Stop the recording
- Move it back under manual control to its initial position

5.4 Data Analysis

The data analysis is specific when using a 3D tracking system or a laser scanner.

With the other proposed measurement system, there is no additional data analysis.

5.5 Report

Repeat each test 3 times. Process the recorded data. If the footprint of the system never crossed the border line of the allowed area, then the system passed the test. If the footprint of the system crosses at least once the border line during the test, then the test has failed. Please use the form in the Annex to report the results.

Example: Test results

	Trial #1	Trial #2	Trial #3	Test passed?
Test 1	Yes	Yes	Yes	Yes
Test 2	Yes	Yes	No	No

6 Annexes

System Configuration

MOBILE PLATFORM	
Manufacturer	The Robot Company
Model	Mobile robot platform 10
System Configuration	Safety Package
Control Software	MoCoControl, version 2.3.1
Robotic arm	
Manufacturer	The Robot Company
Model	Robot Arm 5
System Configuration	Safety Package
Control Software	RoCoControl, version 1.2.3
Description	Position / orientation of the robotic arm
Tool	Description (kind, shape, size, sharpness…)
Payload	
Manufacturer	My Company
Model	Transport box
Description (mass, shape, etc.)	20 cm x 50 cm long, 30 cm high, 10 kg

Sensor characteristics

Sensor type	
Sensor model	
Accuracy (mm) / Resolution (px)	
Frequency (Hz)	
Picture	
Comments	

Detailed test

Starting point	Description and/or coordinates in regards of border line of the allowed area
Endpoint	Description and/or coordinates in regards of border line of the allowed area
Payload	Description of the shape, of its position in the mobile robot, and weight
Velocity (mm/s)	
Configuration of the arm	Axis positions
Picture of the scene	

Test results

	Trial #1	Trial #2	Trial #3	Test passed?
Test 1				
Test 2				