Protocol

Test robot to maintain safe distance from the operator in a Hand-Guiding task

ROB-MSD-4

The purpose of this protocol is to validate the safety skill "maintain safe distance" for hand-guided robots, eventually equipped with tracking technologies and collision avoidance controllers, where a limb of a subject has a free connection point with the robot and the robot can move that point within a 3D volume while preventing collision with the operator's limbs. The minimum distance between robot internal links and subject limbs during operation must be ensured. This is validated using an instrumented limb attached to the robot end effector and a sensor system mounted on the robot.

Readiness Level	Description
7	Publication on COVR Toolkit for community testing

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CONTENTS

1 Introduction

The purpose of this protocol is to validate by measurement that a Hand Guided (HG) robot, possibly equipped with a collision avoidance controller, detecting the operator's movement, does not collide with any of its parts to the operator's body.

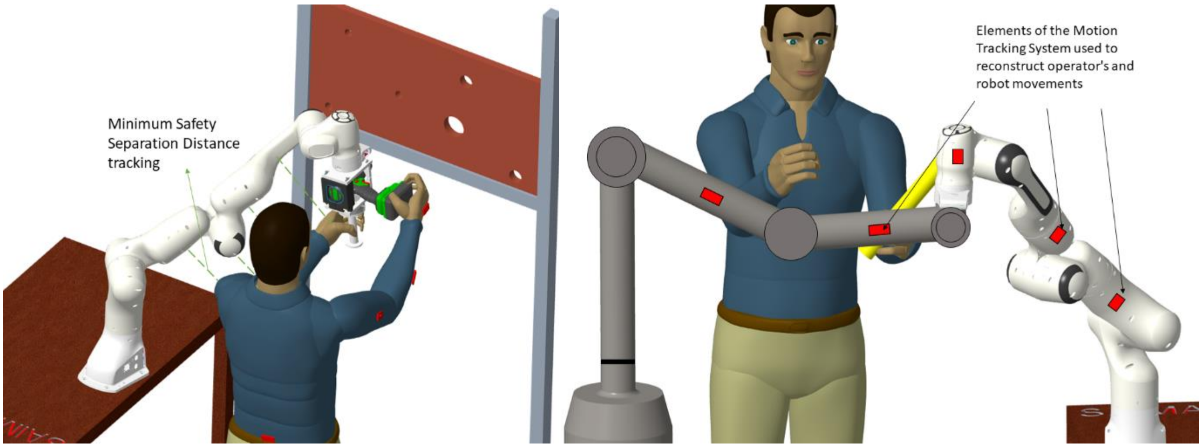

Figure 1: Example of minimum distance between robot and operator in a hand guiding robot application (left) and MSD-skill test setup (right)

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Maintain safe distance
System	Robotic arm (hand-guided robot)
Sub-System	Mounting platform for the robot arm that stabilizes the position of the robot with respect to the task environment Possible presence of a motion tracking system and a collision avoidance controller
Domain	Cross-domain
Conditions	Working environment: indoor factory Type of movement: 3D movement Control mode: Co-controlled human/robot driven (so for the human it is an active movement); optional: force amplification and virtual boundary control modalities Optional: Operator's movement may be captured with a motion tracking system and this information may be used by the robot to avoid collision with her/his limbs
Measurement Device(s)	Instrumented Limb* setup, Sensor System Mounted on the HG Robot

	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 <u>one</u> 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

Active movement (source: local to the document)
A movement of parts of a human body, produced by muscles of that human, not by external forces applied to these parts of the human body.

Collision avoidance controller (source: local to the document)
A control logic implemented in the HG robot* that uses the information provided by a motion tracking system to prevent collision between robot and subject.

Direct path (source: local to the document)
A movement trajectory between two points, where the path is depending on robot path planning (can be linear in space or not if interpolation is done on joint coordinate).

Emergency stop (source: ISO 13850)
Manually initiated interruption of operation intended to stop the HG robot* to prevent harm.

End-effector (source: ISO 8373)
Device specifically designed for attachment to the mechanical interface to enable the robot to perform its task. For HG robots* this is also described as the (actuated) applied part.

Hand guiding (source: ISO/TS 15066:2016 – clause 5.5.3)
A modality to operate a robot where an operator uses a hand-operated device to transmit motion commands to the robot system. The task is carried out by manually actuating guiding devices located at or near the robot end-effector. A robot system used in hand guiding modality may be equipped with additional features, such as force amplification, virtual safety zones or tracking technologies.

Hand guiding (HG) robot systems (source: ISO 10218-1)
Robot systems designed for collaborative operation that may use hand guiding controls for the collaborative portion of the task. These same controls may be used for "lead through teach" methods.

Hand-guided controls, HGC (source: local to the document)
Specific controls or end-effector for a hand-guiding task.

Human Tester (source: local to the document)
Qualified person who executes the test.

Instrumented Limb (source: local to the document)
Mechanical device, resembling a human limb, equipped with angle sensors (and eventually other sensors) and with known segment lengths, so joint angles and spatial distances between proximal and distal point on the device can be determined.

Monitored point (source: local to the document)
Either a point on the robot or defined as a point in space in relation to a specific point on the robot.

MSD (source: local to the document)
Maintain Safe Distance.

Overreaching (source: local to the document)
A movement that results in the Monitored point exceeding the range of motion. Can be harmful to the subject as the movement can exert an excessive strain on joints.

Passive movement (source: local to the document)
A movement resulting from an external force working on parts of a human body (e.g. limb), without any voluntary contribution to that motion by that human. So, the passive aspect is viewed from the human perspective.

Predefined path (source: local to the document)
A movement trajectory that is specified with more parameters, possibly a set of spatial coordinates.

Protective stop (source: ISO 10218-2)
Interruption of operation automatically initiated by the HG robot*, that allows a cessation of any other hazardous functions controlled by the robot system. This stop may be initiated manually or by control logic.

Range of Motion (ROM) (source: local to the document)
A combination of linear and angular distance that a defined monitored point* may move in relation to a defined reference point. The monitored point* can be either a point on the robot, or a point on the body of a human subject defined relatively to a point on the robot. The ROM can be limited to a straight line (one-dimensional ROM), a plane (two-dimensional ROM) or a space (three-dimensional ROM) in any shape. It has to be defined in relation to a reference point.

Reference point (source: local to the document)
Either a point on the robot or defined as a point in space in relation to a specific point on the robot. For example, if the reference point shall represent the expected location of the subjects' shoulder joint center, it might be set at a fixed distance from the robot surface. Please note that the reference point has to be a spatial location, which keeps a known position in relation to proximal parts of the robot.

Minimum distance (source: local to the document)
The minimum linear distance among the distances between any point of the internal robot links and any point of the human subject.

Motion tracking system (source: local to the document)
An apparatus that can be used to reconstruct the motion of the subject with respect to the robot basement.

Redundant robot (source: local to the document)
A robot that has more degrees of freedom than necessary to move the end-effector so that it can rearrange internally for a same end effector position and orientation to avoid obstacles.

S.F.C. / **Single fault condition** (source: local to the document)
A condition of a machinery in which a single means for reducing a risk is defective or a single abnormal condition is present.

Target point (source: local to the document)
Location of a point in a certain volume, relative to the reference point, the robot will be instructed to move the monitored point*.

2 Concept and Objectives

2.1 Hazardous Situations

In hand guiding mode, the specific end-effector or HGC of the robot is grasped by the human operator, who moves it in space to accomplish a specific task, such as carrying a heavy object or performing a machining operation, typically involving the bearing of loads along a path.

Based on the initiated movement by the operator, the robot will support that movement with an assistive level that can be set either during installation or by the operator to best suit the requirements of the task. As examples: force amplification of different magnitude can be implemented to relieve the effort of the operator while still providing her/him with the feeling of handling the load; static or dynamic virtual boundaries for the end-effector motion can be implemented to make task execution timely and more precise.

Based on the movements and performances required by the task as well as the dimensional and physical properties and restraints of both robot and operator, the application designer will develop the collaborative work-cell to make sure that none of the intermediate links of the robot will collide with the operator's limbs. This can be accomplished: by static approaches, which restrict the motion of the robot's links within fixed safety zones (either real obtained by hardware or virtual obtained by software) that cannot be reached by the operator's limbs; by dynamic approaches, which rely on motion tracking systems to reconstruct operator's movement and use this information to ensure that the intermediate robot links stay at a sufficient distance from the operator's limbs. The last approach, combined with a redundant robot structure, provides the most effective system with a wide ROM of the end effector.

Note: Due to the close vicinity of robot and operator, hand guiding applications significantly benefit from the adoption of redundant robot arms which, for a given end effector motion imposed by the operator, can reconfigure themselves internally so as to not interfere with the operator's body.

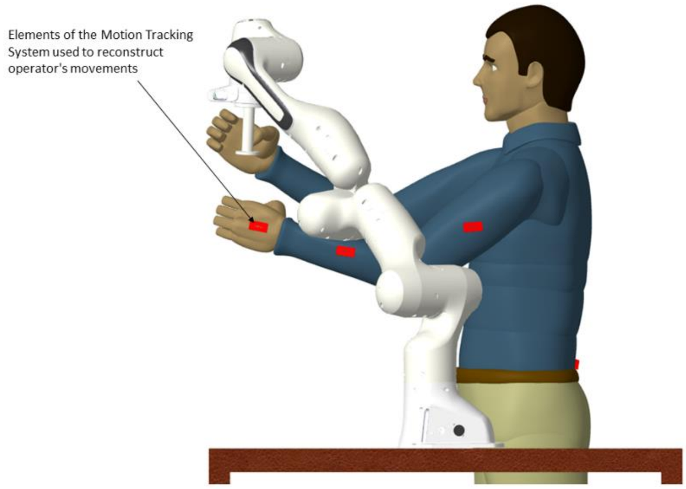

Figure 2: Example of use situation. Red boxes represent the elements of the motion tracking systems used to reconstruct operator's movements.

The hazardous situation considered in this protocol is:

- the robot arm moving through a space where a subject's body parts are located.

2.2 Target Behavior and Metric of the Safety Skill

The target behavior of the skill to be validated here is to verify whether the internal links of the HG robot do not collide with the operator's limbs while the hand guided end effector moves within the ROM specified for the application.

The movements of a HG robot with shared control are mainly defined by the input provided at the end effector by the human operator and the co-control settings for this robot; namely: the motion restrictions, possible support levels and collision avoidance strategies set for the robot controller. The hand guided movements carried out by the end-effector can usually be described by a Direct path* between 2 points or, more likely, a more variable trajectory between 2 points staying within a defined task space.

The shape of the ROM of the robot end effector for which this test needs to be performed has to be based on the task specifications of the robot, so it represents a proper normal use situation. When defining a representative ROM* description for the tests it should be considered that:

- The ROM* can take any shape and does not have to be symmetrical to the reference point.
- The shape and size of the volume will have a large impact on the validation results. Therefore, a matching ROM description of the volume used by the robot should be used during data analysis.

The target metric is based on a physical and measurable quantity. This quantity is the output variable for the validation. The value of the target metric indicates if the validated skill is effective enough to achieve the specified level of risk reduction. It represents a threshold that the output values of the test must not exceed for considering the test as passed. To assess collision avoidance, the minimum distance between robot internal links and operator's limbs is used. The values assumed by the minimum distance vary depending on the specific robot and subject motion, thus on the considered end effector ROM. The limiting value for the minimum distance may depend on the specific robot and the intended use, and may be determined by the application designer (and eventually the operator) for the specific working activity. Therefore, the system's ability to prevent collision with the operator's limbs needs to be validated using different settings for the end effector ROM* and for the limiting minimum distance.

For this validation protocol, the target metric is:

- Does any internal part of the robot maintain a minimum distance with any part of the body of the subject? [Yes/No]

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

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 listing 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 metric. Please report all conditions, represented by values, for each test using the form from Annex A.

3.1 System

The term system refers to the HG robot consisting of:

- a robot arm, whose end effector is moved by the operator within a specified workspace (ROM*).
- a base the robot is mounted on, which is also connected to the support base for the application (it is necessary to know the spatial relation between the base of the robot and the support base at any time of the application).
- optionally a motion tracking system and a collision avoidance controller that uses the captured subject movement information to prevent contact between internal robot links and the operator's body.

Apply this protocol for the complete system as it is normally used. Optionally, for a deeper analysis, and depending on the specific risk assessment, the tests can be performed even under relevant relevant S.F.C.* which may influence the safety skill, like:

- When an emergency stop* or a protective stop* is initiated.
- The S.F.C. where invalid sensor data may influence the controller behavior or the applied risk reduction measure (RRM).
- The S.F.C. where failure of an actuator may influence the behavior of the controller or the RRM.

During the risk assessment special attention should be paid to properly identify relevant S.F.C.*'s.

3.2 Environment

Environmental conditions may influence the safety skill, depending on the implementation. When applicable the validation tests should be performed under different environmental conditions, that are considered normal use conditions and that may have an influence on the performance of the safety skill. Examples of this could be:

- Presence of external obstacles that may influence the motion of the robot.
- Presence of disturbances (such as electromagnetic noise for inertial measurement systems and light interference for camera systems) that may affect the correct functioning of the motion tracking system.

3.3 Miscellaneous

The following task-related conditions shall be considered for the test:

- If applicable, the payload to be moved during the hand-guided task;
- The type of task to be performed and the loads arising in task execution.

4 Test Setup

4.1 Equipment

For validation of this safety skill, an Instrumented Limb* setup and a Sensor System Mounted on the Robot are used.

The Instrumented Limb* is equipped with angle sensors in the joints that can detect the angles of the limb segments relative to each other. The size of the Instrumented Limb* segments can be adjusted, so the tests can be performed for a variety of human sizes. These lengths should be selected in a way that they can easily reach the ROM* of the end effector of interest for the application. Since the lengths of all the used segments are known, the spatial location of all segments can be determined, including the motion of the end effector point connected to the Instrumented Limb* which can be used to verify the ROM of interest for the application.

In Figure 3 the concept of the instrumented limb is shown, where the stand is the supporting structure that keeps the Instrumented Limb* in a defined location with respect to the robot. At the top of the stand is an angular encoder that registers the rotation of the arm segments in a horizontal plane relative to the global reference frame. Above that is an angular encoder that will register rotations in the vertical frame. Two other encoders are mounted on segment A, that register the rotation around the longitudinal axis of segment A and the rotation between segment A and segment B. Segments A and B and the height of the stand can be modified to mimic different limb sizes. Segment B is connected to the HG robot via a spherical joint made by three revolute pairs with axes intersecting in a single point also instrumented with angular encoders.

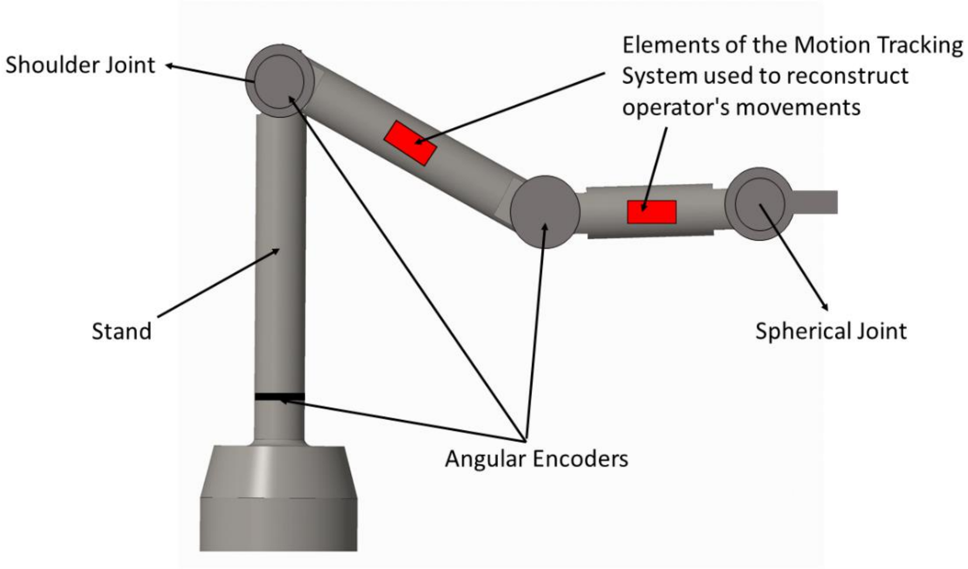

Figure 3: Conceptual image of the Instrumented Limb also mounting the Motion Tracking System for operator's movement reconstruction

⚠	**Warning**
	Make sure the length of the segments of the Instrumented Limb* as set is such a way that these freely allow movement outside of the predefined ROM*

The Sensor System Mounted on the Robot can be:

- the intrinsic sensor system the robot is equipped with (typically made by joint located encoders), in case the robot provides the resulting acquired data as outputs.
- an external tracking system, like an inertial measurement system or an optoelectronic system.

In the first case, the correctness of the measurements performed by the intrinsic system needs to be verified. This can be done previously to protocol application by using the Instrumented Limb of Figure 4 connected to appropriate points of the robot links (both end effector and internal links).

From the measurements of the Sensor System Mounted on the Robot, knowledge of the robot link lengths and the location of the sensors enable to calculate the spatial location of all the robot segments.

4.2 Method

For the assessment of the minimum distance between internal robot links and the operator's limbs (thus, for the validation of the absence of collision between robot and operator), an Instrumented Limb* and a Sensor System Mounted on the Robot will be used.

The Instrumented Limb* shall be positioned relative to the HG robot* in such a way that it resembles the human limb positioning during a normal use situation and its base has a well-defined position to the reference point, which is used to define the ROM* for the HG robot* (see Figure 3). In case the HG robot is equipped with a system to track operator's movement and a collision avoidance controller, this instrumented limb shall host the parts of this tracking systems (namely, the units of an inertial measurement system or the markers of an optoelectronic systems). The data from the Instrumented Limb* is used to reconstruct the posture of the resembled human limbs.

The Sensor System mounted on the Robot, along with the knowledge of the robot features (i.e. link lengths), is used to reconstruct the posture of the robot.

Minimum distance between internal robot links and resembled human limbs is calculated from reconstructed postures of both robot and operator during movements of the end effector within the ROM of interest for the application.

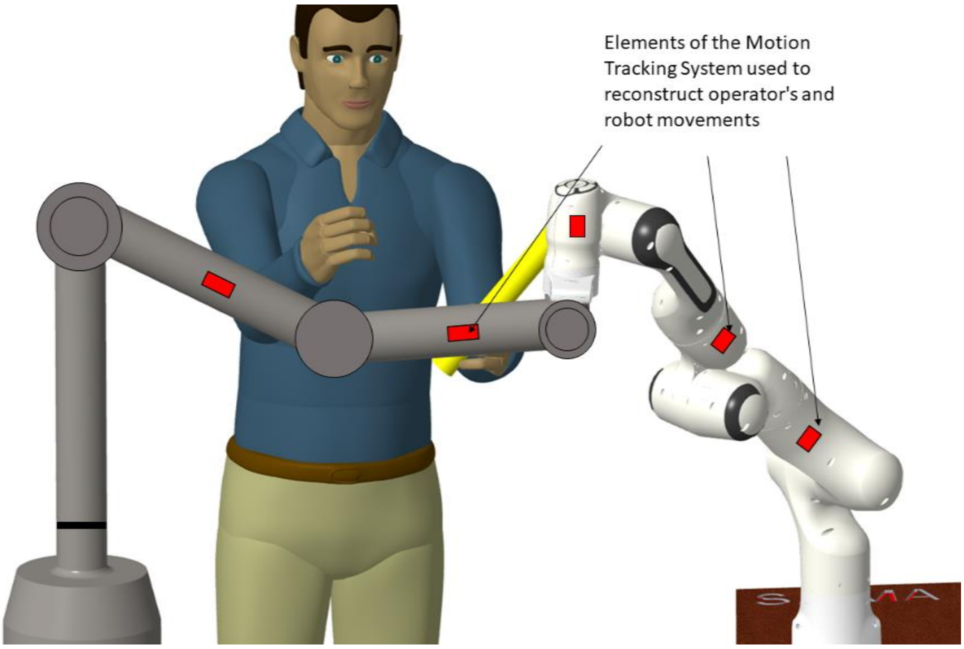

Figure 4: General structure of the test arrangement with the Instrumented Limb mounting the Motion Tracking System for operator's movement reconstruction, the Sensor System Mounted on the Robot for robot movement reconstruction and a Human Tester**

Since the robot arm uses shared control, when safely possible, the movements can be applied by a Human Tester*.

However, a proper risk analysis should be performed on the entire test setup before the decision can be made that the test movements can be performed by a Human Tester*. Main criteria will be:

- The Human Tester* should be able to remain out of reach of the robot arm during the test.

- If that is not possible, the Human Tester* should be in a position where, during the tests, contact with parts of the Instrumented Limb* is highly unlikely, but can still move freely away from potential collision by either the robot arm or the Instrumented Limb*.
- During the execution of the test, the tester should hold an end-effector or HGC including hold-to-run controls in conjunction with an enabling device , so that the robot can be stopped immediately by releasing the controls when a dangerous situation may arise.

The following considerations shall be considered for data acquisition.

- Data acquisition of the sensors of the Instrumented Limb* and of the Sensor System Mounted on the Robot should be continuous during the test, so that the entire motion trajectory of both resembled human limb and robot can be reconstructed after the test.
- The acquisition rate used for reading the sensors of the Instrumented Limb* and of the Sensor System Mounted on the Robot should be at least a factor of 10 higher than the highest expected frequency component of the movements of the robot during the test.
- The measured data may be filtered to remove high frequency measurement inaccuracies, but this filter may not use a cut-off frequency lower than 5 times the highest expected main frequency component of the robot movements during the test.
- After data acquisition the data has to be processed to determine the minimum distance between internal robot links and the resembled human limb.
- The shape and size of the volume in which the end effector is required to move in the application will have a large impact on the validation results. Therefore, a clear definition of the end effector ROM* volume used by the HG robot* during the tests should be available and used during data analysis.

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 possible collision between robot and operator, including all combinations of applicable conditions. Therefore, the test plan provides a detailed summary of the necessary tests to validate the skill for the considered application.

The test plan should at least cover the motion paths of the end-effector identified by the risk assessment as potentially hazardous.

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

- For defining the motion trajectories, consider that motions should at least cover trajectories where parts of the HG robots* may collide with parts of the subject's body.
- Tests must be run as much as possible at maximum speed with specified maximum allowed load for the HG robot* and under otherwise normal use conditions. This load should be positioned in such a way that its center of mass would be close to the end-effector of the HG robot*, unless another location is more representative of the normal use conditions.
- Repeat the tests mentioned above also under single fault conditions that may have an effect on the safety skill.

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.

- Prepare a number of test sequences and specify these in the report.

5.2.1 Test arrangement

For preparing the validation setup:

- Calibrate the sensors of the Instrumented Limb* and those of the Sensor System Mounted on the Robot (if necessary).
- Place the Instrumented Limb* in a defined position near the HG robot* in such a way that it is able to freely reach the spatial locations and motion paths required during the tests.
- If present, place the Motion Tracking System to monitor operator's movement that is part of the HG robot system at proper locations on the Instrumented Limb*.
- Attach the Instrumented Limb* to the HG robot*.
- If the intrinsic sensor system of the HG robot cannot be used, place the external Sensor System Mounted on the Robot on the HG robot under test.

5.2.2 System Conditions

Please report the system composition for each single test using the form in Annex A.

- If possible, tests should be performed with the device in "passive" mode, where the HG robot* only supports its own inertia.
    - Perform this test both without added load as well as with the maximum normal use payload which should be positioned at the end-effector* (unless another location is more usual during normal use).
- Next tests should be performed under normal use condition, with the HG robot* with typical normal use "hand guiding control" settings (e.g. force amplification, virtual boundaries on the end effector motion):
    - The tests should be performed with a payload, which should be the maximum normal use load which should be positioned at the end-effector* (unless another location is more usual during normal use).
    - Velocity during tests should be the maximum velocity that the robot can achieve.
- In both modes also test the HG robot* under the S.F.C.*('s) identified in the risk analysis that may influence the safety skill and perform these tests under these S.F.C.*('s).
- In case of an emergency stop, a system may behave differently. This situation should be validated as well.
- In case the system fails to prevent collision, the safety of these impacts should be validated, e.g. via a suitable protocol (e.g. ROB-LIE-1).

5.2.3 Environmental Conditions

The validation tests should be performed under conditions similar to the normal use conditions.

However, if environmental conditions may have an effect on the safety skill, the test should be performed under these different environmental conditions, or simulated versions of these conditions as well.

5.3 Test Execution

Activate the measurement equipment:

- Make sure the Instrumented Limb* and the Sensor System Mounted on the Robot (if present) is calibrated (if calibration is required).
- Make sure data acquisition is ready for recording the data from the sensors in the Instrumented Limb* and from the Sensor System Mounted on the Robot (if present).
- Make sure the Instrumented Limb* is attached properly to the HG robot*, especially when a previous execution of the protocol resulted in a collision or in a sudden stop of the HG robot*.

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

- Move the end effector to a predefined starting position.
- Make sure the HG robot* is stationary for at least 1 second in this starting position.
- Move the end effector either via a direct or an indirect path through the volume of interest for the application to a target position.
- After a successful motion, make sure that the HG robot* is stationary for at least 1 second in the target position before continuing.

Repeat this with various start position and target position combinations.

Repeat these tests under the conditions mentioned in §**Errore. L'origine riferimento non è stata trovata.** and §5.2.2 and those identified during the risk analysis that may affect the safety skill.

5.4 Data Analysis

To determine whether the system passed this test:

- Results from the data analysis will result in a pass or no-pass. A pass will be when the results of the validation tests show that at no instant the minimum distance between robot internal links and human limbs is above a specified threshold. During the data analysis the distance limitation settings should be known.
- A no-pass will occur when the minimum distance between robot internal links and human limbs is below the specified threshold, taking the accuracy of the measurement system into account.
- Very short "overshoots" in movement may be allowable. However, these acceptability criteria should be specified and properly documented by the manufacturer. These criteria should consist of a maximum overshoot magnitude, combined with a maximum duration of the overshoot.

5.5 Report

The following data needs to be present in the documentation:

- Description of the support settings of the HG robot*.
- Description of the used Motion Tracking System and collision avoidance controller of the robot*.
- Descriptions of the various test sequences executed.
- Start/end point + direct path / prescribed path.
- Robot speed under which the tests were performed.
- Load applied to the robot.
- System conditions (e.g. normal use, single fault, functional stop/reset, emergency stop).
- Pass or no pass result derived from analyzed data [yes/no];
- Provide logging/tracking information.

6 Annexes

6.1 Report Form

Test form - Protocol ROB-MSD-4			
Test date		**Name of tester:**	
Sequence ID (Seq#)		**Hazard ID**	
Description of HG robot* under validation			
Measurement system used:			
Measurement system Calibration date:		**Measurement accuracy:**	
Condition	Normal/S.F.C.*	**Description (S.F.C.*):**	
		Functional stop?	
		Emergency stop?	
		Max velocity (m/s)	
		Applied load (kg)	
		Inclination angle (°)	
		Total system acc (m/s^2)	
Instrumented Limb*:			
“Shoulder” height:			
proximal segment length:			
Distal segment length:			
Instrumented Limb* position (relative to HG robot* position)			
X			
Y			
Z			
Support level settings of the HG robot*			
Support level:			
Motion tracking system for operator’s motion detection			
Motion tracking system:			
Collision avoidance controller			
Collision avoidance controller:			
Minimum distance description:			
Description of the minimum distance limits:			

Test ID (Seq#-id)	Start point	Endpoint		Stayed above minimum distance (Y/N)	Collisions (Y/N)	Pass? (T/F)
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					
Seq#-ID	**Start**	**End**		**above minimum distance**	**collisions**	**Pass?**
	Motion path datafile:					

Final Information about test

Date of testing	
Name of tester	
Overall conclusion	
Signature	