Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Mobile Platform to Maintain a Separation Distance

MOB-MSD-2

The purpose of this protocol is to validate the safety skill “maintain safe distance” by measurement. Its scope is limited to Highly Automated Agricultural Machines (HAAM). In this context, the skill “maintain safe distance” is often used to protect workers from injuries caused by collisions where the HAAM collides with a part of the human. The protocol validates that the stopping distance is never exceeded in a HAAM system when using a safety skill that detect objects and triggers a stop. The validation of this protocol requires that the reader has a distance measuring system available.

	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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1 Introduction

This protocol defines how to validate the ability of a mobile robot used in an agricultural environment, called HAAM (Highly Automated Agricultural Machine) hereafter, to maintain a safety distance with respect to a fixed object, possibly a stationary human, placed on its path, by distance measurement.

It checks that the HAAM stops and that the minimal distance between an operator and the HAAM after a full stop remains above a predefined value.

This protocol is specifically for stationary human detection and collision avoidance in the HAAM's navigation space/trajectory.

Example: A small HAAM performs a navigation task in the fields of a farm eventually coupled with a task for treatments in the field (e.g. sowing, spreading, spraying, harvesting, tilling, plowing, fruit picking, etc.). It operates in a workspace with objects, humans and other robots next to the HAAM. A risk is that a coworker spontaneously crosses the HAAM's workspace. In that situation, unintended collisions between the HAAM and the coworker must be avoided. This can be tested within a test field and a standard dummy obstacle simulating a human.

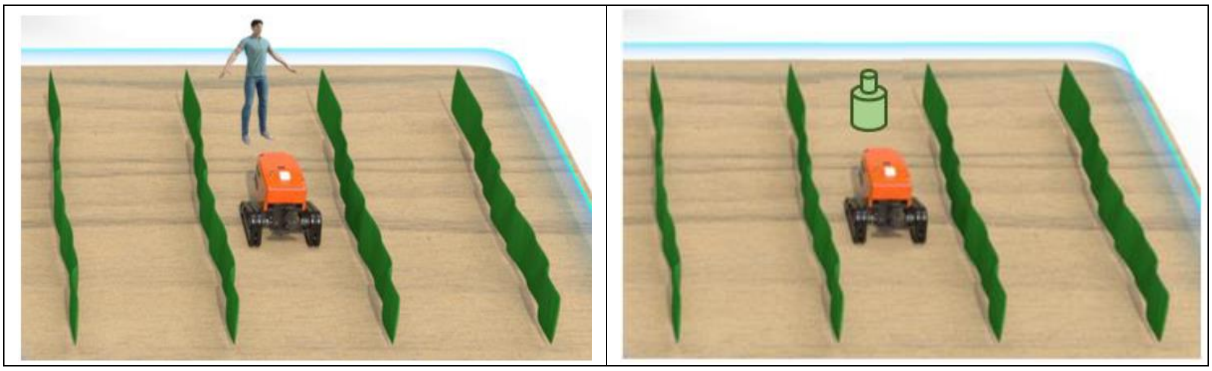


Figure 1: A stop due to a risk of collision (left) and a general test setup to analyze the stoping distance (right)

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Maintain safe distance
System	Highly Automated Agricultural Machine (HAAM)
Sub-System	Optional. Examples can be: forklift; plowing tool; lawnmower tool; tilling tool; spreading implement; spraying implement; sowing implement; trailer; robotic manipulator for specific tasks.
Domain	Agriculture
Environment	Outdoor – open fields w. crops or herbages, vineyards, orchards. Indoor - greenhouses, hay storages, agricultural warehouses etc. (safety-related) object/obstacle or human is fixed
Measurement Device(s)	A distance measuring system and ground markers for test execution. A luxmeter, a rain gauge and a dust measuring device to assess environment testing conditions.

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

1.2 Definitions and Terms

Autonomy (source: ISO 8373:2012, 22)

Ability to perform intended tasks based on current state and sensing, without human intervention.

Highly automated agricultural machine – HAAM (source: ISO 18497:2018)

Mobile vehicle or machine with or without on-board operator allowing *highly automated operation.*

Highly automated operation (source: ISO 18497:2018)

Function that is controlled by a control system without direct human input from local or *remote operator*, does not require an on-board operator for primary control, does or does not include an on-board operator station, and is subject to a *supervisory system*

Non-contact sensing (source: ISO 13482:2014)

Detection or measurement capability that does not require touching objects (including humans) in the environment.

Safety-related object (source: ISO 13482:2014)

Human, domestic animal, or property to be protected from harm.

Unintended contact situation (local)

Contact refers to a state in which the robot and static obstacle are in touch and applying mechanical forces to each other. A contact is considered as unintended if the robot touches the static obstacle accidently due to failure or misuse.

Application (source: EN ISO 10218-2)

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

2 Concept and Objectives

The verification simulates a risk of collision with a real HAAM system with a static obstacle that mimics a human body. During the test, the robot must operate under the same conditions, as it would in a real application.

The objective of the test is to measure whether the applied safety skill “maintain safe distance” prevents the robot from exceeding the applicable minimum distance limit value.

2.1 Hazardous Situation

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

The test conditions shall be as representative as possible of the operating scenario, characterized by an approach path to the obstacle, the speed of the HAAM, environmental conditions, etc. (for details see Section 3 “Conditions”).

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill to be validated is to maintain a minimal safety distance between the HAAM and the safety-related object. The distance needs to stay above a limit specified in the risk assessment.

The target metric indicates if the validated skill is effective enough to achieve the specified level of risk reduction.

For object definition, an obstacle in accordance to ISO 18497 prescriptions shall be used:

- Obstacle is a main cylinder 53 [cm] in height x 38 [cm] diameter, with a smaller cylinder on top of 27 [cm] in height x 14 [cm] diameter (see Figure 2).
- the obstacle shall be filled with water;
- the material shall be plastic with a matte (non-glossy) surface;
- the color shall be olive green with a matte (non-glossy) finish.

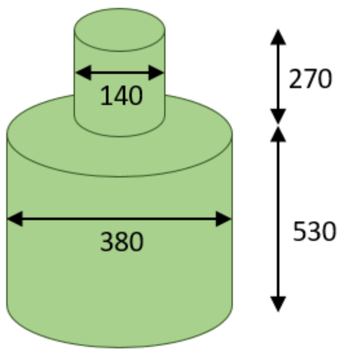


Figure 2: standard obstacle defined in ISO 18497: dimensions and example of realization

For validating the robot skill “maintain a safe distance”, the output target is:

- Minimal distance between the robot and the safety-related object [m]

The value for the target metric should be determined during the risk assessment considering the relevant operating conditions (i.e. HAAM velocity, braking distance, etc) and, if validated, represents the “safety” distance between the robot and an object or a human.

Example: Minimal resulting distance after a full stop between the HAAM and the safety-related object: 0.5 m.

The target metric may vary for different dimensions of obstacles or HAAM, so it is crucial to ensure which metric value applies to which HAAM and obstacle. Please report the values of the target metric for each test.

Example: Detection of persons in the traveling path of a HAAM

Obstacle	
Type	ISO 18497
Safety clearance [m]	0.5

3 Conditions

In case the conditions for the hazardous situation changes, the user of this protocol shall develop a test plan with all reasonable parameter combinations (some example: hill slope, with mold on the surface that would make an immediate stop of the HAAM difficult, very heavy load affecting the braking performance, presence of crops that reduce visibility, not straight path or any other condition that can reduce visibility and the minimum distance to recognize the object). The user must test the relevant skill for each combination of this list. Also, note that it is important to know the conditions with the most significant influence on the target metrics (as an example, the effects due to mold is different for tracked and wheeled HAAMs).

Being the robot working outside in the fields, the robot shall be tested at least in the listed conditions:

- With different sunlight and possibly in different seasons;
- With different visibility conditions (day, night etc.);
- With different land conditions: flat land, land with vegetation different in height;
- In harsh climatic conditions (fog, dust and rain).

The abovementioned conditions are reported as minimum set of test conditions but in case other conditions applies, it must be listed in tests conditions report.

In case of presence of vegetation, the vegetation height is a parameter for obstacle recognition so it must be reported.

As described in the ISO Standard the standardized object height is 80 cm, so for recognition systems based on vision, the vegetation height cannot exceed the object height, as there is no possibility to test such an equipped HAAM.

In the table it is reported an example of how to parametrized the test with vegetation. It could use a fixed vegetation height or it could be defined as a percentage of the sensor's height.

Testing conditions	
Illuminance level [lux]	10000
Month and hour [mmm; hh]	May; 11 am
Dust level [mg/m^3]	30
Rain level [mm]	0

Fog level [None; low; medium; high]	Low
Overall visibility [m]	>15
Ground condition	Plowed
Ground adhesion	Not slippery
Vegetation condition	Land with vegetation
Vegetation average height [cm]	50
Sensors Height [cm]	80
If relevant: sensor field of view HxV at a certain distance D [cm]	250 x 125 at 200
Observed minimum vegetation height for a successful recognition [cm]	40

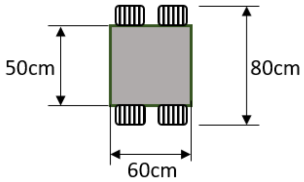
Other sensors for obstacle/human recognition could also recognize humans or obstacles with higher vegetation. Anyway, it is worth observing that it is safer to avoid robots working in vegetation whose height is comparable to that of the expected human height.

3.1 System

The term *system* refers to the HAAM itself as an autonomous mobile platform, whose type can change depending on the specific application and use. If the HAAM has a payload capability, then this must be described.

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 hazardous situations. This applies directly to the test (at least one test per hazardous situation).

Example: System Configuration

HAAM	
Type of HAAM	Four-wheeled platform
Manufacturer	The HAAM Company
Model	Mobile agriculture robot platform 10
System Configuration	Safety Package, Lidar sensor, front Bumper
Driving direction	Front direction
Control Software	FieldControl, version 3.1
Footprint on the ground and dimensions (picture or drawing)	
Payload	
Manufacturer	My Company
Model	Payload company Transport box

Description (mass, shape, etc.)	Footprint: 60 cm x 80 cm, Height: 30 cm; Mass: 10 kg

The following system- and behavior related conditions influence the target values. The HAAM shall be tested in the worst-case condition(s) (e.g. loaded, unloaded, slope, turn, forward, backward, ground slope) in combination with HAAM predetermined parameters in those case conditions (e.g. emergency braking deceleration, speed, controlled acceleration and deceleration).

- HAAM velocity (velocity during the target behavior): [insert here from risk assessment or relevant sources] mm/s
  Example: [110% of pre-determined speed] mm/s [from ISO 3691-4]
- HAAM payload: [insert here from risk assessment] kg
  Example: [110% of actual capacity] kg [from ISO 3691-4]

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

Besides the configuration of the robot system, the state of the robot in the moment when the stop due to the obstacle occurs also has a significant influence on the output values of the validation tests. The following items describe the robot state:

- Direction and magnitude of platform velocity: linear (in green in the Figure) and, if relevant, angular (in red in the Figure)

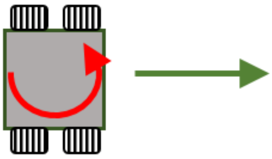


Figure 3: HAAM linear and angular velocity

These conditions are part of the robot path, which is technically a time dependent sequence of states. For a proper validation test, it is necessary to establish the same robot state as the robot will have in the moment a safety distance could be crossed, whereby the safety skill takes over control. Therefore, the point of interest for the test is the point along the robot path at which the distance to fixed object is minimum. The risk assessment should clarify the exact moment and position of this point. Therefore, the risk assessment is the primary source to identify the robot state for the test.

Please report the robot state (if available) for each single test using the form in the Annex.

Example: System State (Automated tractor)

Nominal HAAM velocity	**Absolute**	**Direction**
Linear velocity [m/s]	5,55	Forward
Angular velocity [rad/s]	0	-

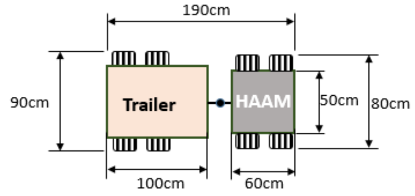
NOTE1: typical velocity of small HAAM can be usually up to 4-8 km/h (1,11-2,22 m/s). Typically, HAAMs work in fields where plants are in rows, so angular velocity is zero, except in headlands where the robot turns and reverse direction of travel.
NOTE 2: typical big tractors with automatic guidance capabilities could be equipped with sensors and become robotic tractors; in that case big tractors could spray or spread at higher speed, typically up to 15 -20 km/h.

A subsystem may be installed. The sub-system comprehends a variety of tools and additional functionalities that can be installed onto the HAAM. For example, the following subsystems could be included:

- Forklift;
- plowing tool;
- lawnmower tool;
- tilling tool;
- spreading implement;
- spraying implement;
- sowing implement;
- …

The subsystem can be mechanical, electro-mechanical or even a robotic device working in coordination with the HAAM. To this latter category belong manipulators installed on the HAAM used to carry out different tasks, mainly related to harvesting, in latest frontier applications. Also trailers eventually drawn by the HAAM are to be considered subsystems and described.

Subsystem 1	
Type of subsystem	Manipulator with 6 degrees of freedom
Manufacturer	The Robot Company
Model	cobot 10
System Configuration	Pneumatic Package Safety Package
Control Software	coControl, version 2.3.1
Footprint impact (describe)	No
Subsystem 2	
Type of system	Harvesting gripper
Manufacturer	The Harvest Company
Model	Fruit 10
System Configuration	Suction cup – large size
Control Software	None
Footprint impact (describe)	No
Subsystem 3	
Type of system	Payload trailer
Manufacturer	The Trail Company
Model	Fruits 100

System Configuration	Drawn by standard tow hook
Control Software	None
Footprint impact (describe)	

3.2 Environment

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

- Shape of the navigation area: [slope and direction of travel in respect to slope]
- Adhesion properties of the navigation area: [not slippery/wet/ mold/grass]
- unevenness of the ground [plowed/tilled/sowed terrain]
- Safety-related object dimensions: see ISO 18497 obstacle definition
- Visibility (fog or heavy rain or dust) [> 6 m]
- Plants height.

Since the environment conditions can have an influence on the target metric, we recommend running the validation tests under the same environmental conditions which the robot operator or user expects during productive operation.

3.3 Miscellaneous

Other relevant conditions are:

- Surface of the HAAM that will come the closest to the fixed object
- Endangered parts (parts of the human or fixed object which the robot can affect)
- Testing route features (length and width of the corridor, transversal position of the HAAM)
- Height of the lateral vegetation

Use the form from the Annex to record the location and shape of the contact area on the robot structure.

Example: Misc. Conditions

Closest Area to Fixed Object (on robot structure)	
Location	Lower front side of the mobile platform (bumper surface)
Photo	
Endangered parts	
Type of body (human, type of object)	Human
Part	Lower leg
Testing route features	
Length [m]	50
Width [m]	2
HAAM transversal position	Center axis misaligned by 40 cm on the left
Height of lateral vegetation [m]	2.5

4 Test Setup

4.1 Equipment

According to the target metrics, it is necessary to measure the distance between the HAAM and the test object. The following sub-section introduces a distance sensor. Please note that this protocol is specifically written for this sensor. There are variants of this protocols that make use of other distance sensors or motion tracking systems.

Laser distance sensor

The distance measuring device is designed for distance measurement.

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

Example: Sensor

Feature	**Distance Measurement Sensor**
Manufacturer and type	The Sensor Company, Model
Dimensions [mm]	110 x 50 x 30
Weight [kg]	0.2
Working Range [m]	0.05-15
Accuracy [mm]	1.5
Resolution [mm]	1

4.2 Method

The following instruments are required to measure the target metrics:

- An accurate device for distance measurement (i.e. a laser meter with error below 5% in the range of the actual distance to be measured).

This test measures the distance between a robot and a simulated safety-related object at the moment the robot finishes a protective stop in order to verify that the system “maintains a minimum required safety distances” (see ISO 18497 and ISO 3691-4).

This test is applicable to all HAAMs that have mobility capability and collision avoidance functionality realized by non-contact sensors to operate a protective stop. This test consists of three steps: (1) set-up, (2) performing the test motions with theHAAM, and (3) measuring the distance, the moment the HAAM has stopped. This test utilizes a distance measuring device, a travel path (typically along the row in a sowed field where plants are growing), and test pieces.

The test piece is an object with surface condition and dimensions like the abovementioned safety-related objects that the robot is likely to encounter under the projected conditions of use. In ISO 18487, this is accomplished by a green cylindrical test piece, placed vertically (standing) on the floor/ground and perpendicular to the direction of travel of the HAAM.

The environment should be large enough for the robot to be able to accelerate to achieve the normal operating speed (as defined in the risk analysis). If the braking distance differs according to the terrain condition in the real environment, the terrain condition that experience the longest braking distance shall be used to repeat the test in the worst conditions. The environment should also be large enough to provide for adequate space for the robot to slow down and stop after it has reached its normal travel speed. Typical measures of some rows are a length of 50 m and a width of 2 m.

The test consists in placing the test object on a test road, with the HAAM travelling at its typical speed towards the object. The HAAM must stop before the contact with the object to enable the measurement of the distance.

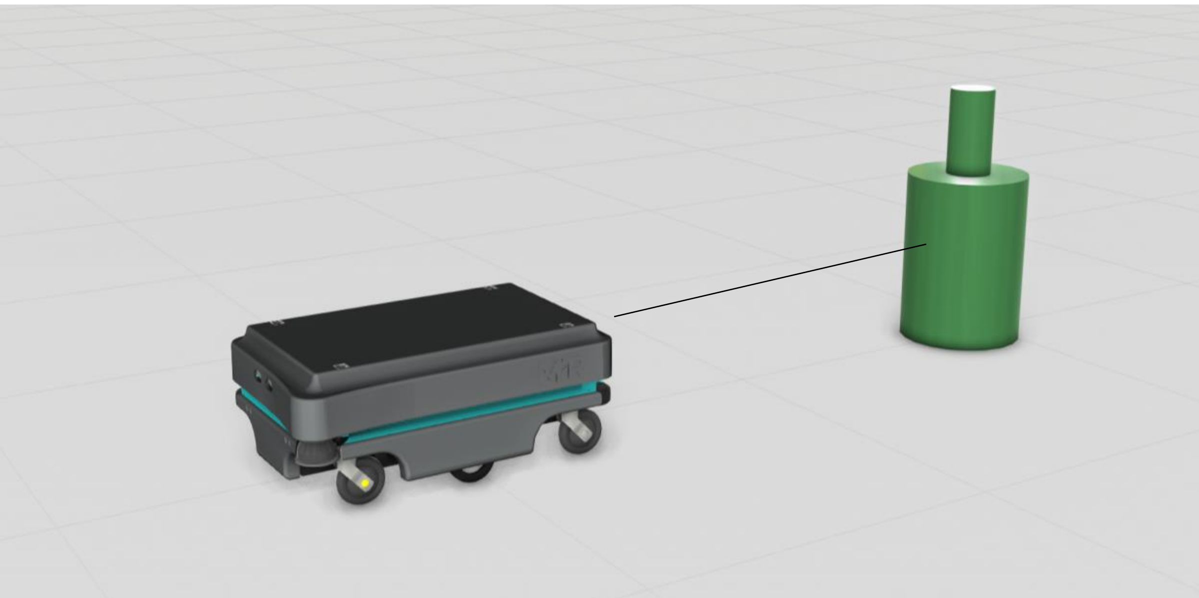


Figure 2: Test arrangement

4.3 Data Acquisition

The measurement is executed only after the HAAM fully stops. Start the laser distance sensor. Place it on the HAAM at the closest position to the object. Acquire the distance measurement.

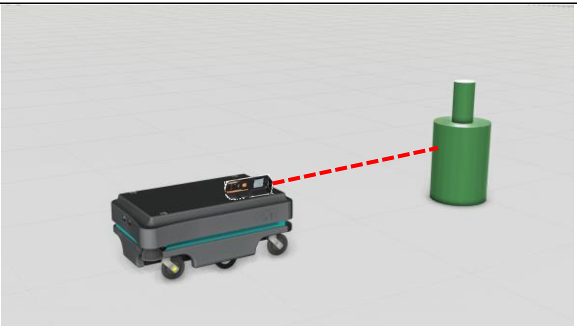


Figure 3: Left: Example of laser distance sensor (source: Magnusson). Right: Measurement on the HAAM

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 distance between robot and a fixed object along its path, included 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.

All combinations of the conditions introduced in Section 3 that are applicable and may change in the considered situation result in a list of concrete test cases.

The protocol must consider the following conditions:

- System
    - Type of system, payload if applicable
    - Direction and magnitude of velocity
    - Settings of the sensors (if applicable)
- Sub-systems
    - Subsystems installed
    - Sub-systems actually in function
    - Sub-systems configuration (if relevant)
- Environment
    - Illuminance level;
    - Month and hour;
    - Dust level
    - Rain level;
    - Fog level;
    - Overall visibility;
    - Ground condition;
    - Ground adhesion;

  - Vegetation condition;
  - Vegetation average height;
  - Sensor height;
  - Observed minimum vegetation height for a successful recognition [cm].
- Miscellaneous
  - Location and shape of the area on the robot structure the closest to the fixed object
  - Endangered parts (parts of the human or fixed object which the robot can affect)
  - Testing route features (length and width of the corridor, transversal position of the HAAM)
  - Height of the lateral vegetation

We recommend preparing this list before beginning the tests. Please apply Sections 5.2 to 5.5 for each test case and run each test at least ten times.

5.2 Preparation

Before executing a concrete 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.

5.2.1 Test Arrangement

HAAM

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

Data Acquisition

Initiate the data acquisition by using the distance measuring device.

5.2.2 System Conditions

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

- Switch on the HAAM one hour before beginning the tests (warm-up phase).
- Configure the HAAM and the sub-systems in accordance with the real working conditions to be tested.
- Install the final program that contains the motion and actions the HAAM will execute in the application.
- Configure all available safety-functions.

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

Note: If the HAAM has no safety functions to monitor its states (such as platform speed), the protocol user must perform all tests at maximum speed, even if this speed is not required for the application.

The following instructions only apply to system- or behavior-related conditions, which may change for the considered situation. Please refer to the test plan to determine which set of conditions must be prepared and tested.

HAAM velocity (velocity during the target behavior)

- Accelerate until the planned HAAM velocity.
- Tests are performed with up to 110% of pre-determined speed (if relevant).

Shape of the contact area

- The test is performed on a ground with the realistic slope condition

Adhesion properties of the contact area

- The test is performed on the usual HAAM operating environment (open filed, greenhouse, orchards, and vineyards, plowed or tilled field, sowed field, field with growing plants etc.).

Object dimensions

- Dimensions are chosen regarding objects that may be encountered during the HAAM exploitation.
- For detection test, chosen dimensions must be smaller than the smallest object that may be encountered.

HAAM payload

- Tests are performed with at least at 110% of actual capacity (if relevant).
- Make sure that no parts can fall off from the HAAM.

Parameter values of the applied safety functions

Adjust the parameters values of the applied safety functions to the values specified for the test case.

5.2.3 Environmental Conditions

The following instructions only apply to environmental conditions, which may change for the considered situation or have an impact on the target metrics. Please refer to the test plan to determine which set of conditions must be prepared and tested.

Type of object (cylindrical test piece)

Each case of the test plan is related to a particular orientation of the HAAM with regard to the object (at the center-line of the detection zone and once at each end). Select this orientation value for each new test.

Type of ground

It is recommended to perform these tests on the usual HAAM operating ground. If slopes are present in the operating area, tests with several different slope conditions must be carried out.

Weather and other environmental conditions

Depending on the intended use of the HAAM, the test must be performed in the conditions in which it will be likely to operate. This can cause the user to carry out new tests upon change of weather occur, i.e. depending on the season.

5.3 Test Execution

Apply the following test procedure for each specified test case separately. Make sure that the proper speed setpoint and proper orientation for the HAAM to the safety-related object are configured before running a test.

- Move the robot slowly to the start position and orientation point, on the proper ground with chosen slope. There shall be enough space for accelerating up to the desired speed before reaching the collision area. Pause the program with the robot in start position.
- Configure the desired speed.
- Take a photo of test situation (optional)
- Start the HAAM autonomous navigation.
- Wait for a complete HAAM stop after the safety-related object detection.
- After stopping, take another photo of the situation (optional)
- Measure the smallest distance between the HAAM and the safety-related object.
- Check if minimum distance value is lower than the limit value
  - If limit value is significantly exceeded: Decrease robot speed slightly and repeat the entire test
  - If limit value is satisfied: Keep robot speed and repeat measurement ten times.

The robot should have a security system enforcing the validated speed as its maximum speed.

5.4 Data Analysis

It is not necessary to check measurement data manually, with respect to reference minimum distance.

Example: Result from Data Analysis

	Test 1	Test 2	Test ...	Test 10	MAX
Maximum distance (mm)	500	490	...	520	520
Speed (mm/s)	1100				

If the highest maximum of all ten tests exceeds the applicable limit value, the safety skill fails the test. If not, it passes the test. In the case that the robot fails the test, it is recommended to modify the robot program (for instance reducing the speed) and to start over with the validation process. Other options could be a modification of the safety configuration or conditions.

5.5 Report

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

Example: Summary

	Test 1	**Test 2**	**Test ...**	**Test 10**	**Test Pass**
Pass	yes	yes	...	yes	yes

6 Annexes

A Report Form

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

Test ID / Test no	
Hazard ID	
Description	
Photo	

Setup

Sensors

Feature	**Distance Measurement Sensor**
Manufacturer and type	
Dimensions	
Weight	
Working Range	
Relative error (linearity)	
Resolution	

System Configuration

HAAM	
Manufacturer	
Model	
System Configuration	
Control Software	
Payload	
Manufacturer	
Model	
Description (mass, shape, etc.)	

COVER
safearoundrobots.com

Test Specifics

System State

Nominal HAAM velocity	**Absolute**	**X**	**Y**
Linear velocity (mm/s)			
Angular velocity (rad/s)			

Misc. Conditions

Closest Area to Fixed Object (on HAAMstructure)	
Location	
Photo	
Endangered parts	
Type of body (human, type of object)	
Part	
Testing route features	
Length [m]	
Width [2]	
HAAM transversal position	
Height of lateral vegetation [m]	

Testing conditions	
Illuminance level [lux]	
Month and hour [mmm; hh]	
Dust level [mg/m^3]	
Rain level [mm]	
Fog level [None; low; medium; high]	
Overall visibility [m]	
Ground condition	
Ground adhesion	
Vegetation condition	
Vegetation average height [cm]	
Sensors Height [cm]	

Observed minimum vegetation height for a successful recognition [cm]	

Test Result

Result from Data Analysis

Test	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**MIN**
Minimum distance (m)											

Summary

	Test 1	**Test 2**	**Test 3**	**ALL yes**
Pass				

Test	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**ALL yes**
Pass											