Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Mobile Robot Arm for Dynamic Stability

MRO-DYS-1

The purpose of this protocol is to test the skill dynamic stability of mobile robot arms by measurement. Its scope is limited to robot arms with a mobile base used in industrial indoor applications. For the stability scenarios studied it is assumed that the mobile base is at a standstill with only the mobile robot arm moving. The objective is to protect workers from injuries caused by collisions where the mobile base tilts. The validation of this protocol requires that the reader has access to an inclinometer.

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 test the stability of a mobile robot arm mounted on a mobile base.

The protocol relies on the following assumptions:

1. A robot arm is mounted on a mobile base
2. The mobile base is at standstill – only the robot arm is moving

The goal of the protocol is to validate the mechanical stability so that foreseeable events do not lead to a dynamic instability. Dynamic instability can cause the robot to trip over and cause injury to surrounding personnel.

The dynamic stability along the roll and pitch axis of the mobile platform are tested:

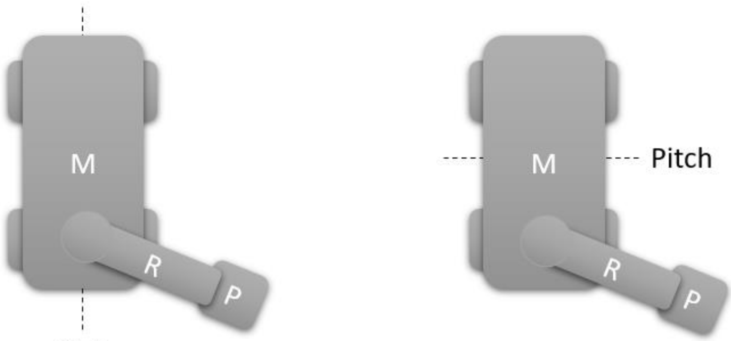

Figure 1: Roll and pitch rotation axis. M is a mobile platform; R is a robotic arm and P is a payload

The idea of the protocol is to determine roll and pitch values of the mobile platform while the robot arm moves. The values will be captured in a real-world scenario. Experiments starts with low speeds, accelerations, payloads, motions, floor tilts, and center of gravity slowly progressing to more demanding scenarios – depending on the application.

The platform is not expected to tilt over at any time. The idea of the protocol is to verify that the measured dynamic values stay within the selected stability limits to a tolerance of a safety factor.

Figure 2: Example of a robot arm on a mobile platform moving in such a way that it may cause the base to become unstable

Example: A mobile platform with a mobile arm carries parts inside a factory. The robot arm performs a rapid movement with a high payload. This causes the mobile platform to lose its stability. The shift of the weight distribution by moving the robot arm outside of the mobile platform is a contributing factor to the instability shown in this example.

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Dynamic Stability
System	Mobile robot arm on a mobile platform
Sub-System	n/a (no subsystem)
Domain	Indoor/outdoor, factory, humans
Conditions	Inclination of the floor, floor surface material
Measurement Device(s)	Inclinometer

⚠	**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 Normative reference

Prior to using this protocol, please make yourself familiar with the following regulations and standards referenced by this protocol:

EN1525 Safety of industrial trucks – Driverless trucks and their systems

ISO 3691-4:2020 Industrial trucks — Safety requirements and verification — Part 4: Driverless industrial trucks and their systems

ISO 18646-1:2016 Robotics — Performance criteria and related test methods for service robots — Part 1: Locomotion for wheeled robots

Consider the following regulations and standards, even if this protocol does not specifically refer to them:

EN ISO 10218-2 - Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robot Systems and Integration

EN ISO 10218-1 - Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots

Directive 2006/42/EC on Machinery

Consider the following regulations and standards, even if they are out of scope:

EN ISO 12100 - Safety of machinery — General principles for design — Risk assessment and risk reduction

1.3 Definitions and Terms

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).

Category 0 Stop (source: EN/ISO 13850:2015)

Stopping by immediate removal of power to the machine actuators (i.e. an uncontrolled stop – stopping of machine motion by removing electrical power to the machine actuators)

Category 1 Stop (source: EN/ISO 13850:2015)

A controlled stop (stopping of machine motion with electrical power to the machine actuators maintained during the stopping process) with power available to the machine actuators to achieve the stop and then removal of power when the stop is achieved

Category 2 Stop (source: EN/ISO 13850:2015)

A controlled stop with power left available to the machine actuators

Collaborative Workspace (source: ISO/TS 15066)

Space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

Mobile robot (source: ISO 13842:2014)

Robot able to travel under its own control

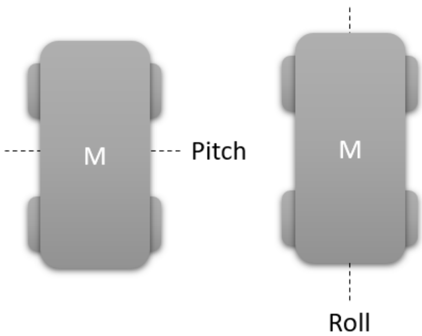

Figure 3: Definition of the terms pitch and roll with respect to the geometry of the robot.

Pitch

Rotation along an axis running from side to side of the platform as shown in Figure 3. We assume positive angle value for clockwise rotations and negative otherwise. An angle value of 0 means no rotation.

Roll

Rotation along an axis running from front to the back of the platform as shown in Figure 3. We assume positive angle value for clockwise rotations and negative otherwise. An angle value of 0 means no rotation.

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 risk assessment specifies which hazardous situations the protocol user must validate by test and whether the applied safety skill mitigates the risk effectively. The mobile robot is assumed to be in certain state before the hazardous situation can occur (see section 3.1).

The verification process consists of creating a movement with the robotic arm and to validate by measurements that stability is maintained.

2.1 Hazardous Situations

In the following a hazardous situation refers to that the robot loses its stability and tips over.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill "dynamic stability" to be validated is to maintain a roll and a pitch angle which stays within certain stability bounds.

For validating the robots skill dynamic stability, the *output target* (dynamic measurements) are the values

- $roll(t)$ where $-60\,^{\circ} < roll(t) < 60\,^{\circ}$
- $pitch(t)$ where $-60\,^{\circ} < pitch(t) < 60\,^{\circ}$,

where t denotes the time parameter. In other words, a timeseries of roll and pitch inclinations is captured. Notice that positive values denotes clockwise rotations and negative counterclockwise rotations. The evaluation criteria given later will ignore the sign.

The values for the *target metric* (static measurements - expected limits) should be selected through the risk assessment and technical specification of the mobile platform. For this validation protocol, the target metric is:

- $roll_{stability}$ where $0\,^{\circ} < roll_{stability} < 10\,^{\circ}$
- $pitch_{stability}$ where $0\,^{\circ} < pitch_{stability} < 10\,^{\circ}$.

Pass criteria

The test is passed if

$$SF \max(\,|roll(t)|) < roll_{stability} \;\; and$$
$$SF \max(\,|pitch(t)|) < \, pitch_{stability}$$

where a safety factor of $SF \geq 1$ according to Table 1 is selected and $\max(|\ldots|)$ denotes the maximum absolute of the roll and pitch angles measured over time. In other words, the system passes the test in case the measured dynamic values stay within the static stability limits to a tolerance of a safety factor.

Table 1 gives suggestions for how to select the safety factor. Notice that the suggested safety factors are only suggestions that should be validated through testing where relevant combination of conditions are included.

The "Robot Impulse" part has two categories where "low" means systems running with low impulses (low speeds/low payloads) and "high" means high impulse (high speed/high payload). To quantify these categories one may multiply maximal speed and total weight for a given robot arm and use this as an equivalent for "high" and define "low" as the multiple of slow speed (250 mm/s) with the weight of the robot arm with no additional payload.

The "Environmental uncertainty" part has two categories where "low" means the factors contributing to behavior of the system are known. Examples of the factors are: the required reach of the robot arm, the loads carried by the robot arm, ramps connecting areas, etc. "high" means high uncertainty which applies to more demanding environments where the robot runs in environments with more variation to factors that influences it's stability.

Table 1: Guideline to choose safety factors

Robot impulse / **Environ-mental uncertainty**	Low	High
Low	1.2	1.8
High	1.8	2.5

The system state described in 3.1 and its system state metrics forms the situation description. You may report the values of these system state metric for each test using the form in the Annex A.

3 Conditions

Since the conditions under which the hazardous situation can occur vary, the user of this protocol shall develop a test plan that contains all relevant combinations. The user must test the applied skill for each combination.

It is therefore important to know the conditions with the most significant influence on the target metrics. Factors like the robot reach, high velocity, high payload, inclination of the floor, and center of gravity can significantly influence on the target metrics. See section 3.2 for more significant factors. Notice that factors may be combined to create scenarios in which the platform is more unstable for example combining a floor inclination with a sudden de-acceleration of the arm "downhill".

Please report all conditions, represented by values, for each test using the forms in Annex A.

3.1 System

The term *system* refers to a robot system that consists of the:

- Type of mobile platform
- Type of robot arm
- Payload handled by the arm (if any)
- Payload carried by the platform (if any)

System

Mobile platform	
Manufacturer	The Mobile Platform Company
Model	Mobile robot platform 10
Control Software Version	Safety Package v 3.2
Robot arm	
Manufacturer	The Robot Arm Company
Model	Robot Arm 5
Control Software Version	Safety Package v 8
Payload	
Description	Box
Mass [kg]	5 kg
Picture of the payload	…insert picture…
Entire system	
Picture of the complete robot system	…insert picture…

The term *system states* refer to the movement characteristics and the test conditions. Relevant parameters are

- Joint configuration of the robot
- Velocity of the robot
- Acceleration/jerks of the robot
- Sudden positive or negative accelerations, either programmatically or by emergency stop
- Emergency braking/category 0, 1 and 2 stops while moving
- Choice of trajectory: Movements along trajectories with a stretched arm
- A displaced center of gravity

Example: System State

Metric	Symbol	Value
Maximal velocity of the robot arm $[\mathrm{mm/s}]$, $[°/\mathrm{s}]$	v	$30\ °/s$
Movement from pose with joint angles	q_{start}	$[60, 0, 0, 0, 0, 0]\ °$

Movement to pose with joint angles	q_{stop}	$[-180, 0\ ,0\ ,0\ ,0\ ,0]\ °$
Type of stop resulting in braking of the robot arm: category 0, 1 or 2	c	1
Inclination [degrees] of the floor (value is 0 if the floor is leveled, ramps will have a value different from 0)	α	$0\ °$

3.2 Environment

The environment in which the experiments take place will have influencing factors like:

1. Inclination of the floor
2. Surface of the floor

4 Setup

4.1 Test Arrangement

The robot arm travels along a trajectory with velocity v placed at a mobile base at an inclination (which may be $0\ °$). The robot carries the intended payload. An inclinometer is attached to the unit. The brakes of the robot arm are engaged at a stage and the inclinometer measures the resulting tilt angles.

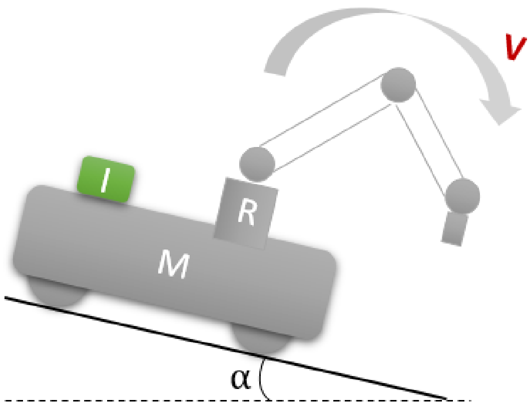

Figure 4: Side view of the test scenario: The mobile robot M, robot arm R, inclinometer I, and a floor tilt angle α

The mobile base is assumed to be at a standstill prior to the tests.

4.2 Sensing devices

The inclinometer must support recording of roll and pitch axis over time.

Table 2: Requirements for the inclinometer

	Minimum	Recommended
Number of axes	2 (roll and pitch)	2 (roll and pitch)
Calibrated range	$-60 \ldots 60\,°$	$-60 \ldots 60\,°$
Accuracy	$\pm 1\,°$	$\pm 0.5\,°$
Sampling rate	$800\ \mathrm{Hz}$	$800\ \mathrm{Hz}$

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

Example: Sensors

Feature	Inclinometer
Manufacturer and type	Sensor Company, PE 1000
Number of axis	2
Calibrated range	$\pm 60\,°$
Accuracy	$\pm 1\,°$
Sampling rate	$1000\ \mathrm{Hz}$

4.3 Data Acquisition

The inclinometer should be mounted to the robot prior to the tests and be initialized on a leveled surface.

5 Procedure

5.1 Test Plan

The protocol must describe how the system and the corresponding system state relate that to the risk assessment for the given scenario. If there are multiple scenarios and they differ significantly then there must be formulated multiple test plans.

5.2 Preparation

Before executing a test from the test plan, it is necessary to prepare the setup and the conditions properly. Be mindful of the following:

- Identify the scenarios of the risk assessment where instability may lead to the greatest risks.
- Identify the contribution factors of these risks
- Select the safety settings of the robot arm so that the tests can be conducted with the required robot arm velocities and payload
- If the test involves an inclination, make sure that the robot has the right gravity vector configured
- Prepare the robot program of the robot arm to perform the motion

- If an emergency stop should be issued while moving prepare the emergency stop button / sensors (light curtain to be triggered)

The following section gives 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 Annex A.

5.2.1 Setup

Install the inclinometer, position the mobile robot and initialize the robot arm.

5.2.2 Environmental Conditions

Describe the following:

- Inclination of floor if any
- See section 3.2 for more environmental conditions

5.2.3 System Conditions

Describe the system state in detail and observe the following:

Floor inclination

- Adjust the inclination of the test floor (test facility) or use the floor from a use case
- Depending on the maximally inclination, consider starting from small inclinations progressing to steeper ones.

Payload

- If the scenario includes a payload besides the robot arm itself:
- Mount the payload to the robot arm, so that it is fixed and cannot fall off

Robot trajectories

- Start from low velocities and small radius displacements of the robot arm with payload. This will make it possible to conduct tests without making the platform trip over.

Robot velocity (velocity during the target behavior)

- Accelerate until the planned mobile target robot velocity, v, has been reached.
- Depending on the risk analysis consider whether tests should be performed with at least at 110 % of pre-determined speed to describe a worst-case scenario.

Robot braking

- If relevant, make it possible issue a stop of the category listed in the system state.

Mobile base

- Ensure the mobile base it at rest prior to the test

Inclinometer

- Place the inclinometer on the mobile platform and mount it firmly.

5.3 Test Execution

Apply the following test procedure for each specified test case separately. Make sure that the proper program and payload are configured for the robot arm before running a test.

- Ensure the environment is as expected (either directly use case on-site or in reproduced test lab)
- Ensure the system is configured properly
- Move the robot slowly to the initial start position and orientation point
- Take a photo of test situation (optional)
- Start the inclinometer data acquisition, acquiring roll and pitch values
- Run the program with the desired trajectory
- Trigger stops if needed
- Stop the inclinometer and save the time series with:
    - a description,
    - date,
    - test name and
    - test number
- Repeat the procedure five times.

Notice: It may be a good idea to form a progression of speeds, velocity etc. for the tests of stability. This will lower the probability for the platform to trip over.

5.4 Data Analysis

For the data analysis an example is introduced for which a safety factor of $SF = 2$, $roll_{stability} = 30\,°$ and $pitch_{stability} = 15\,°$ is assumed. The mobile platform stands on an inclined floor with $\alpha = 5\,°$. The robot performs a Point-to-Point movement at a maximum velocity of $v = 15\,°/\mathrm{s}$ in a radius of $r = 300\ \mathrm{mm}$ with respect to its base frame. The payload of the robot is $5\ \mathrm{kg}$.

To guarantee valid test results the tests must be repeated at least five times. For every repetition all systems states (r, v, α) remain identical.

Data analysis for one Configuration

	Test 1	Test 2	Test 3	Test 4	Test 5
$roll_{max} = max(\lvert roll(t)\rvert)$	1.5	1.3	1.1	1.2	1.3
$SF\ \ roll_{max}$	3	2.6	2.2	2.4	2.6
ROLL PASS $SF\ roll_{max} < roll_{stability}$	TRUE	TRUE	TRUE	TRUE	TRUE
$pitch_{max} = max(\lvert pitch(t)\rvert)$	5.2	4.1	6.2	4.4	5.5
$SF\ \ pitch_{max}$	10.4	8.2	12.4	8.8	11
PITCH PASS $SF\ pitch_{max} < pitch_{stability}$	TRUE	TRUE	TRUE	TRUE	TRUE
TEST PASS I.E. ROLL AND PITCH PASS	**TRUE**	**TRUE**	**TRUE**	**TRUE**	**TRUE**

In case the robot passes all tests the validation criteria is fulfilled. In case of a failure the system states must be adjusted. Lowering the speed, reducing the payload or minimizing the workspace of the robot can be helpful steps. Note that the actions are dependent on the functionality from the project requirements of the application.

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 evidence 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).

In the example for the summary different joint configurations of the robots are assumed while the rest of the parameters stay identical. In configuration 2 and 3 the robot reaches out for a radius of $r = 450\ \mathrm{mm}$ and $r = 700\ \mathrm{mm}$ respectively. The test criteria show, that the system does not pass the test in case of configuration 3. Consequently the user has to limit the working radius of the robot to $r = 450\ \mathrm{mm}$ or reduce its speed / lower the payload and repeat the test.

Summary

	Test pass
Configuration 1	TRUE
Configuration 2	TRUE
Configuration 3	FALSE

6 Annexes

6.1 Annex A – Report Form Protocol MRO-DYS-1

Test Mobile Robot Arm for Dynamic Stability

System

Mobile platform	
Manufacturer	
Model	
Control Software Version	
Robot arm	
Manufacturer	
Model	
Control Software Version	
Payload	
Description	
Mass [kg]	
Picture of the payload	
Entire system	
Picture of the complete robot system	

System State

Metric	Symbol	Value
Maximal velocity of the robot arm [mm/s]	v	
Movement from pose with joint angles	q_{start}	
Movement to pose with joint angles	q_{stop}	
Type of stop resulting in braking of the robot arm: category 0, 1 or 2	c	
Inclination [degrees] of the floor (value is 0 if the floor is leveled, ramps will have a value different from 0)	α	

Sensor system

Feature	**Inclination sensor**
Manufacturer and type	
Number of axis	
Calibrated range	
Accuracy	
Sampling rate	
Miscellaneous	

Measurement results

Test ID / Test no	
Hazard ID	
Description (motion, significant factors, see section **Fehler! Verweisquelle konnte nicht gefunden werden.**)	
Maximal ROLL measured	
Maximal PITCH measured	
Photo	

Result from Data analysis

	Test 1 Config x	**Test 2 Config x**	**Test 3 Config x**	**Test 4 Config x**	**Test 5 Config x**
$roll_{max} = max(\|roll(t)\|)$					
$SF\ \ roll_{max}$					
ROLL PASS $SF\ roll_{max} < roll_{stability}$					
$pitch_{max} = max(\|pitch(t)\|)$					
$SF\ \ pitch_{max}$					
PITCH PASS $SF\ pitch_{max} < pitch_{stability}$					
TEST PASS I.E. ROLL AND PITCH PASS					

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Summary

	Test pass
Configuration x	
Configuration y	
Configuration z	