Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Mobile Platform for Dynamic Stability

MOB-DYS-1

The purpose of this protocol is to test the skill "dynamic stability" of mobile platforms by measurement. Its scope is limited to mobile platforms used in industrial indoor applications. In this context, the objective is to protect workers from injuries caused by collisions where the mobile platform 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 dynamic stability of mobile platforms. We assume a scenario where the platform is mounted with a fixed payload. Under certain circumstances the robot may trip over and cause injury to surrounding personnel. The goal of the protocol is to validate that foreseeable events does not lead to a dynamic instability both in production and while testing the stability.

We study the *static* and *dynamic* roll and pitch of the platform.

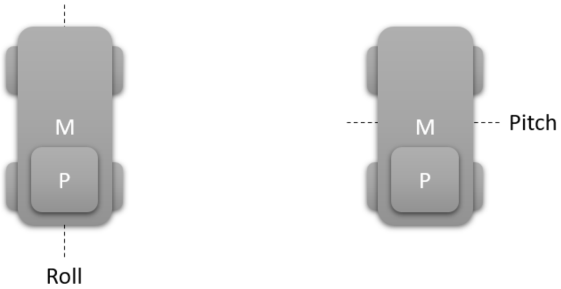


Figure 1 Roll and pitch rotation axis. M is a mobile platform and P is a payload

The verification process consists of two phases:

Phase 1) Static roll and pitch stability of the mobile platform

Here experiments are performed to establish safe (not necessarily maximal – safe may be good enough) roll and pitch rotations for which the mobile platform will return to a stable equilibrium with the wheels on the floor.

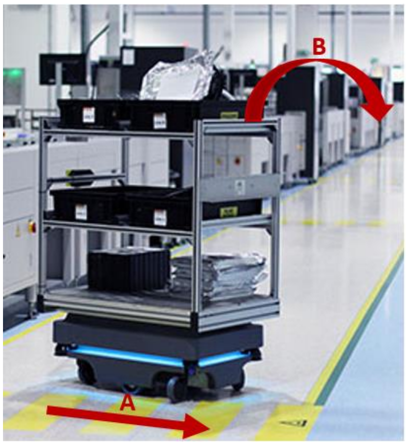
Phase 2) Dynamic roll and pitch stability of the platform

In this experiment roll and pitch values of the mobile platform are captured in a real-world scenario. Experiments starts with low speeds, accelerations, payload, motions, floor tilt, and center of gravity slowly progressing to more demanding scenarios.

The platform is not expected to tilt over at any time during Phase 1 and Phase 2. The idea of the protocol is to verify that the measured dynamic values stay within the static stability limits to a tolerance of a safety factor.

Example

A mobile platform carries parts inside a factory. The robot runs at full speed until a sudden brake occurs. The weight distribution causes the robot to tilt and trip over.



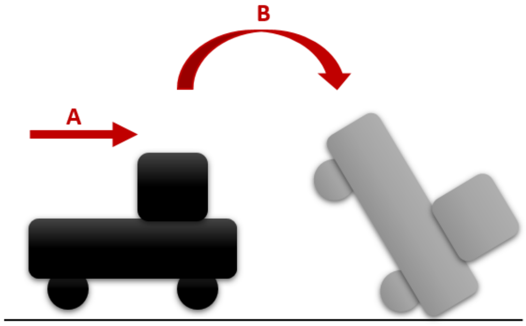


Figure 2: Braking along A causes a dynamic instability along B and a danger

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Dynamic Stability
System	Mobile platform
Sub-System	No subsystem i.e. no actuators besides the mobile platform
Domain	cross-domain
Conditions	The environment is indoor factory
Measurement Device(s)	Video camera Inclinometer, in case floor is not level

⚠	**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

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)

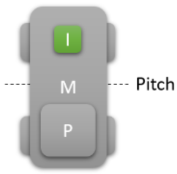
Space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

Mobile robot (source: ISO 13842:2014)

Robot able to travel under its own control

Pitch

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

Unintended contact

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

2 Concept and Objectives

2.1 Hazardous Situations

In the following a hazardous situation refers to a mobile robot that tilts.

	Suggestion
	The intended use and the foreseeable misuse as identified by the risk assessment can support to clarify the potentially hazardous events. Typically, pushing the mobile platform or malicious mischief/vandalism are not foreseeable misuse.

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).

2.2 Target Behavior and Metrics of the Safety Skill

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

For validating the robot skill dynamic stability, the *output target* (dynamic measurements) are two values:

- ROLL(t) WHERE $-60° < \text{ROLL}(t) < 60°$
- PITCH(t) WHERE $-60° < \text{PITCH}(t) < 60°$

Where t denotes a time parameter.

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 determined through the risk assessment and the phase 1 experiments. For this validation protocol, the target metric is:

- $\text{ROLL}_{\text{STABILITY}}$ WHERE $0° < \text{ROLL}_{\text{STABILITY}} < 60°$
- $\text{PITCH}_{\text{STABILITY}}$ WHERE $0° < \text{PITCH}_{\text{STABILITY}} < 60°$

Notice that roll and pitch stability not necessarily are maximal. They may be roll and pitch rotations for which the mobile platform will return to a stable equilibrium with the wheels on the floor when released.

Pass criteria

The test is *passed* if for all moments t:

$$\text{SF} \cdot |\text{ROLL}(t)| < \text{ROLL}_{\text{STABILITY}}$$

and

$$\text{SF} \cdot |\text{PITCH}(t)| < \text{PITCH}_{\text{STABILITY}}$$

where SF is a *safety factor* SF, SF ≥ 1 is selected (see Table 1 below) and |…| denotes the absolute function (i.e. |x| = x for x >= 0 and |x| = -x for x < 0).

In other words, the measured dynamic values stay within the static stability limits to a tolerance of a safety factor.

The table below (Table 1) gives suggestions for how to select a 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 “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 mobile platform and use this as an equivalent for “high” and define “low” as the multiple of slow speed (250 mm/s) and weight of the platform 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 are: the floor type are the same, ramps connecting areas are the same, the robots are loaded the same way etc. “high” means high uncertainty which applies to more chaotic environments where the robot runs in environments with more variation to factors that influences it’s stability.

Impulse / **Environ-mental uncertainty**	Low	High
Low	1.2	1.8
High	1.8	2.5

Table 1 Safety factors. Horizontally: impulse of a collision, vertically: uncertainty of the environment the robot runs in

The system state described in 3.1 and its system state metrics forms the situation description.

Please report the values of these system state metric for each test using the form in the Annex.

3 Conditions

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

Therefore, it is important to know the conditions with the most significant influence on the target metrics, see examples below.

Please report all conditions, represented by values, for each test using the forms in section 6.

Example

Factors like the velocity, payload, the floor material type, and center of gravity can significantly influence on the target metrics. See section 3.3 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 negative acceleration “downhill”.

3.1 System

The term *system* refers to a robot system consisting of:

- Type of mobile platform
- Payload handled by the platform if any

Mobile platform	
Manufacturer	The Robot Company
Model	Mobile robot platform 10
Control Software Version	Safety Package v. 3.2
Payload	
Description	Boxed with screws
Mass [kg]	10 kg
Picture of the payload	n/a
Entire system	
Picture of the complete robot system	n/a

Example: System State

Metric	Symbol	Value
Initial velocity [mm/s]	v	1500 mm/s
Radius of turn [mm]	r	520 mm
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 Sub-System

We assume a mobile platform with a payload and no further actuators.

3.3 Environment

The test environment shall represent the production environment faithfully. That applies to important factors like:

- The velocity of the platform
- Sudden positive or negative accelerations, either programmatically or by emergency stop
- Emergency braking/category 0, 1 and 2 stops
- High payload
- Choice of trajectory: Turning with a small radius
- A displaced center of gravity
- Obstacles on the floor
- Inclination of the floor
- Floor material type

4 Setup

4.1 Test Arrangement

4.1.1 Phase 1 Static roll and pitch stability of the mobile platform

A test setup is chosen considering important factors from section 3.3. The mobile unit is loaded with the intended payload at a floor with the wanted inclination. An inclinometer is attached to the unit.

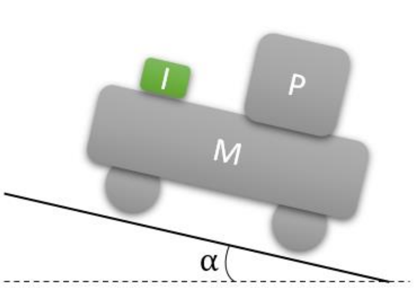


Figure 3: Left (side view): The mobile robot M, payload P, inclinometer I, floor tilt angle α, Right (top view)

The mobile base is then tilted to determine safe roll and pitch angles, i.e. $ROLL_{STABILITY}$ and $PITCH_{STABILITY}$. Notice that it is often not necessary to find the maximal values for roll and pitch stability. The mobile unit must be moved around (yaw directions) and tilted along different axis (see below) to discover the worst scenario for which the platform is unstable – yet is capable of regaining stability when released.

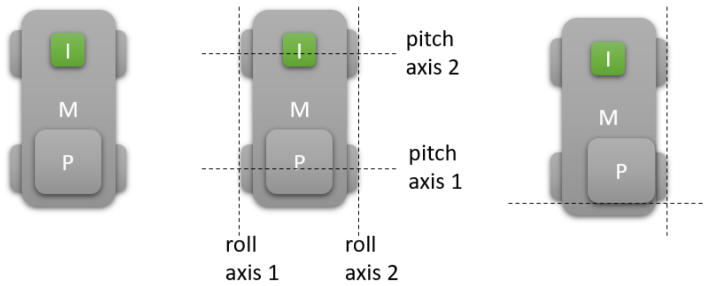


Figure 4 Possible tilt axis. Left (top view) The mobile robot M, payload P and inclinometer I. Middle (top view): Roll and pitch axis, Right: displaced payload and critical roll and pitch axis

In the figure above it is assumed that the mobile robot has a uniform mass distribution and that the displaced payload is the only factor the moves the center of gravity. The inclinometer is assumed to have an insignificant mass relatively to that of the mobile robot.

Notice that these values may also be possible to obtain from the manufacturer of the concrete robot, which makes the above obsolete. There may however be reasons for validating the given numbers, if any.

4.1.2 Phase 2 Dynamic roll and pitch stability of the mobile platform

A test setup is chosen considering important factors from section 3.3. The mobile unit either:

- moves around at constant velocity or
- positive or negative accelerations are imposed programmatically or by emergency stops.

An inclinometer is attached to the unit which reads a timeseries of roll and pitch angles.

4.2 Sensing devices

The inclinometer must support recording of roll and pitch axis in timeseries.

	Minimum	Recommended
Number of axes	2 (roll and pitch)	2 (roll and pitch)
Calibrated range	-60° - 60°	-60° - 60°
Accuracy	± 1°	± 0.5°
Sampling rate	800Hz	800Hz

Table 2. Requirements for the inclinometer

Use the form in section **Fehler! Verweisquelle konnte nicht gefunden werden.** 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	± 60°
Accuracy	± 1°
Sampling rate	1000 Hz

4.3 Data Acquisition

The inclinometer should be mounted to the robot prior to the tests and be initialized.

5 Procedure

5.1 Test Plan

The protocol must describe the system and the corresponding system state and 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, prepare the setup and the conditions properly. The following sections give instruction to prepare the setup and all conditions with a significant influence on the target metrics. Each test case must be documented using the form in the section 0.

5.2.1 Setup

Initialize the mobile robot and install the inclinometer.

5.2.2 Environmental Conditions

Describe the following:

- Floor material type
- Inclination of floor if any
- The presence/absence of obstacles on the floor
- See section 3.3 for more environmental conditions

5.2.3 System Conditions

Describe the system state in detail and observe the following:

Payload

- Mount the payload to the mobile robot, so that it is fixed and cannot fall off
- A total mass of 110 % from the manufacturer specification, can be considered as a worst-case scenario.

Floor inclination

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

Robot trajectories

- Start from low velocities, accelerations, displacements of payload (if possible). This will make it possible to conduct tests without making the platform trip over.

5.3 Test Execution

5.3.1 Phase 1 Static roll and pitch stability of the mobile platform

Either obtain data on maximal roll and pitch in the used configuration from the robot manufacturer.

Use the following test execution to obtain / validate the values $ROLL_{STABILITY}$ and $PITCH_{STABILITY}$:

- Move the robot slowly to the initial start position and orientation point, on the proper ground with chosen slope.
- Determine the worst orientation for measuring roll
- Position robot to that position
- Measure roll by tilting (push or pull) the platform along the axis – while not tripping over – release the platform and inspect that it returns to stability. Let rollSTABILITY equal the maximum angle measured
- Determine the worst orientation for measuring pitch
- Position robot to that position
- Measure the pitch by tilting (push or pull) the platform along the axis – while not tripping over – release the platform and inspect that it returns to stability. Let PITCHMax equal the maximum angle measured

5.3.2 Phase 2 Dynamic roll and pitch stability of the mobile platform

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

Make sure that the proper speed setpoint and proper orientation for the mobile robot to the breaking point are configured 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.

Note: 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

Here is an example of the data analysis for tests, assuming a safety factor of 2, SF = 2, and $ROLL_{STABILITY}$ = 30° and $PITCH_{STABILITY}$ = 15°. We use the following definitions: ROLL is the maximum of the function $t \mapsto |ROLL(t)|$ and PITCH is the maximum of the function $t \mapsto |PITCH(t)|$.

Data analysis

	Test 1 Configuration 1	**Test 2 Configuration 1**	**Test 3 Configuration 1**	**Test 4 Configuration 1**	**Test 5 Configuration 1**
ROLL	1.5	1.3	1.1	1.2	1.3
SF · ROLL	3	2.6	2.2	2.4	2.6
ROLL PASS SF · ROLL < $ROLL_{STABILITY}$	TRUE	TRUE	TRUE	TRUE	TRUE
PITCH	5.2	4.1	6.2	4.4	5.5
SF · PITCH	10.4	8.2	12.4	8.8	11
PITCH PASS SF · PITCH < $PITCH_{STABILITY}$	TRUE	TRUE	TRUE	TRUE	TRUE
TEST PASS I.E. ROLL AND PITCH PASS	**TRUE**	**TRUE**	**TRUE**	**TRUE**	**TRUE**

Here we assume the five tests are performed with the same underlying Configuration 1. That could for example refer to a mobile robot performing a 360° closed trajectory on an inclined floor with α = 5° and a turning radius of 600mm running at a constant speed of 0.4 m/s with a payload of 40 kg at a displacement of [x,y,z] = [250mm, 300mm, 500mm].

In this case all the tests show that the validation criteria were fulfilled. In case of a failure perform a root cause analysis and check if factors as mentioned in section 3.3 can be modified while still maintaining the functionality from the project requirements of the finished integration.

5.5 Report

Use the form in Annex 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).

Here is an example where we assume configuration is as mentioned in the above section and configuration 2 and 3 is like configuration 1 but with v = 0.8 m/s and v = 1.2 m/s respectively.

Summary

	Test pass
Configuration 1	TRUE
Configuration 2	TRUE
Configuration 3	FALSE

We see that the test does not pass for configuration 3, i.e. v = 1.2m/s why we will recommend the speed limit of 0.8 m/s in configuration 2.

6 Annexes

A Report Form

System state

System

Mobile platform	
Manufacturer	...insert..
Model	...insert...
Control Software Version	...insert...
Payload	
Description	...insert...
Mass [kg]	...insert...
Center of gravity [x,y,z]	...insert...
Picture of the payload	...insert picture...
Entire system	
Picture of the complete robot system	...insert picture...

System State

Metric	**Value**
Velocity [mm/s]	
Maximal acceleration / de-acceleration, if any	
Stops occurring, category 0,1, 2, if any	
Description of the trajectory	
Inclination [degrees] of the floor (value is 0 if the floor is leveled, ramps will have a value different from 0)	

Test setup

Sensor system

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

Measurement results

Static roll and pitch stability of the mobile platform

Test ID / Test no	
Axis to be tested (Roll 1, Roll 2 or Pitch 1, Pitch 2) (see Figure 4, page 8)	
Maximal angle measured	
Description	
Photo	

Dynamic roll and pitch stability of the mobile platform

Test ID / Test no	
Hazard ID	
Description (motion, significant factors, see section 3.3)	
Maximal ROLL measured	
Maximal PITCH measured	
Photo	

Test Result

Data analysis

	Test 1 Configuration x	**Test 2 Configuration x**	**Test 3 Configuration x**	**Test 4 Configuration x**	**Test 5 Configuration x**
ROLL					
SF · ROLL					
ROLL PASS SF · ROLL < $ROLL_{STABILITY}$					

PITCH					
SF · PITCH					
PITCH PASS SF · PITCH < $PITCH_{STABILITY}$					
TEST PASS I.E. ROLL AND PITCH PASS					

Summary

	Test pass
Configuration x	
Configuration y	
Configuration z	