CEN

WORKSHOP

AGREEMENT

CWA 17384

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English version

Articulated industrial robots - Elastostatic compliance calibration

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European foreword

CWA 17384 was developed in accordance with CEN-CENELEC Guide 29 'CEN/CENELEC Workshop Agreements – The way to rapid agreement' and with the relevant provision of CEN/CENELEC Internal Regulations – Part 2. It was agreed on 2018-10-30 in a workshop by representatives of interested parties, approved and supported by CEN following a public call for participation made on 2018-09-28. It does not necessarily reflect the views of all stakeholders that might have an interest in its subject matter.

Results incorporated in this CEN Workshop Agreement (CWA) received funding from the European Union's HORIZON 2020 research and innovation programme under the grant agreement number 723853. This CWA is based on the results of the COROMA research project.

The final text of CWA 17384 was submitted to CEN for publication on 2019-06-14. It was developed and approved by:

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Introduction

Industrial robots progressively complement value streams as they can realize numerous applications while providing the flexibility required in modern manufacturing environments. This can be observed across important industries for a wide variety of commodities such as consumer electronics, industrial machinery or vehicles.

The most significant disadvantages of industrial robots, when compared to specialized machinery, are their comparably lower accuracy as well as their comparably higher complexity. The lower accuracy is a result of kinematic and non-kinematic inaccuracies. Kinematic inaccuracies are a result of the imperfect geometries and dimensions of the links as well as the configurations of the joints. Non-kinematic inaccuracies can be due to several sources:

- joint and link compliance;
- thermo-mechanical errors;
- gear backlash;
- controller errors;
- wear;
- environmental influences; and
- installation errors.

One approach to partly compensate for these inaccuracies lies in manipulator calibration as described by Mooring et al. in 1991 [1]. This CWA focuses on the calibration of elastostatic compliance, i.e. the compensation of the deformation of components due to their finite stiffness under external static loads.

The information from the elastostatic compliance calibration can be implemented in industrial manipulators to reduce inaccuracies using on-line, off-line or combined compensation and control strategies. It is useful to standardize an elastostatic compliance calibration procedure to save time and cost and create the following advantages across different groups of share- and stakeholders:

- customers could benefit from a broadened range of potential applications with their existing robotic systems and subsequently an easier adaptable production system due to the flexibility of industrial robots; and
- researchers could benefit from a common understanding of the calibration procedure for the compliance of industrial robots, which facilitates the dissemination of research results and the application by researchers of other fields in synergetic projects.

Currently, it is possible to employ a wide range of methods, instruments and models to test the compliance of industrial robots. These methods have their own potential strengths and weaknesses in terms of time, cost and their ease of use. This CWA intends to provide an international mutual understanding of robotic compliance amongst customers, developers, manufacturers and researchers.

1 Scope

This CEN Workshop Agreement (CWA) intends to define one good practice elastostatic compliance calibration for articulated industrial robots using an enhanced stiffness formulation for the robot model, a pragmatic measurement approach inspired by the application and an identification of the model parameters based on position data.

The CWA compliance for industrial robots describes how it can be specified, recommends how it should be tested and outlines the potential usage of the information for industry applications. This document is intended to be used by customers, developers, manufacturers and researchers of industrial robotic systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN ISO 9283:1998, *Manipulating industrial robots — Performance criteria and related test methods*

EN ISO 10218-1:2011, *Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots (ISO 10218-1:2011)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
articulated robot
robot (3.14) whose arm has three or more **rotary joints** (3.15)

[SOURCE: ISO 8373:2012, definition 3.15.5]

3.2
autonomy
ability to perform intended tasks based on current state and sensing, without human intervention

[SOURCE: ISO 8373:2012, definition 2.2]

3.3
base coordinate system
BCS
coordinate system referenced to the base mounting surface

[SOURCE: ISO 8373:2012, definition 4.7.2]

3.4
degree of freedom
DOF
one of the variables (maximum number of six) required to define the motion of a body in space

[SOURCE: ISO 8373:2012, definition 4.4]

3.5
denavit hartenberg
DH
formalism to assign coordinate frames to the joints of manipulators to describe their kinematics

3.6
end effector
EE
device specifically designed for attachment to the mechanical interface to enable the **robot** (3.14) to perform its task

[SOURCE: ISO 8373:2012, definition 3.11]

3.7
industrial robot
automatically controlled, **reprogrammable** (3.13), **multipurpose** (3.11) **manipulator** (3.9), programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications

[SOURCE: ISO 8373:2012, definition 2.9, modified: Notes 1 and 2 removed]

3.8
jacobian matrix
matrix of the first order partial derivates of the robot's degree of freedom

[SOURCE: EN ISO 13482:2014, definition 3.28, Note 2]

3.9
manipulator
machine in which the mechanism usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several **degrees of freedom** (3.4)

[SOURCE: ISO 8373:2012, definition 2.1, modified: Notes 1 and 2 removed]

3.10
measurement point
MP
translational transformation of the point in which the measurement is taken with respect to the manipulator’s mechanical interface

3.11
multipurpose
capable of being adapted to a different application with **physical alteration** (3.12)

[SOURCE: ISO 8373:2012, definition 2.5]

3.12
physical alteration
alteration of the mechanical system

[SOURCE: ISO 8373:2012, definition 2.3, modified: Note removed]

3.13
reprogrammable
designed so that the programmed motions or auxiliary functions can be changed without **physical alteration** (3.12)

[SOURCE: ISO 8373:2012, definition 2.4]

3.14
robot
actuated mechanism programmable in two or more axes with a degree of **autonomy** (3.2) moving within its environment, to perform intended tasks

[SOURCE: ISO 8373:2012, definition 2.6]

3.15
rotary joints
assembly connecting two links which enables one to rotate relative to the other about a fixed axis

[SOURCE: ISO 8373:2012, definition 3.7.2]

3.16
static compliance
linear (or angular) displacement per unit static force (or moment) between two objects, specified with respect to the structural loop, the location and direction of the applied forces, and the location and direction of the displacement of interest

[SOURCE: ISO 230-1:2012, definition 3.3.2, modified: Notes 1 and 2 removed]

3.17
operating space
Cartesian space that is actually used while performing all motions commanded by the task program

3.18
working space
space which can be swept by the wrist centre point increased by the range of rotation or translation of each joint in the wrist

[SOURCE: ISO 8373:2012, definition 4.8.4, modified: Note removed]

3.19
wrench point
translational transformation of the point in which the wrench is applied with respect to the manipulator's mechanical interface

3.20
wrist centre point
WCP
point of intersection of joints 4, 5 and 6

4 Elastostatic compliance calibration procedure

Manipulator calibration is the procedure of defining a mathematical model (modelling phase) with model parameters that are characteristic for the capabilities of the robot, then the actual robot is measured (measurement phase) and its model parameters are identified (identification phase). The information can be used to optimize the capabilities of the robot (implementation phase) [1].

Elastostatic compliance calibration is the procedure of defining a mathematical model for the compliance of the structural members of the manipulator, which relates the loaded to the unloaded configuration, then measuring the difference between a loaded and unloaded robot and identifying the model parameters. The procedure is depicted in Figure 1 and it considers the preparation, modelling as well as the measurement and identification phase. It omits the implementation phase.

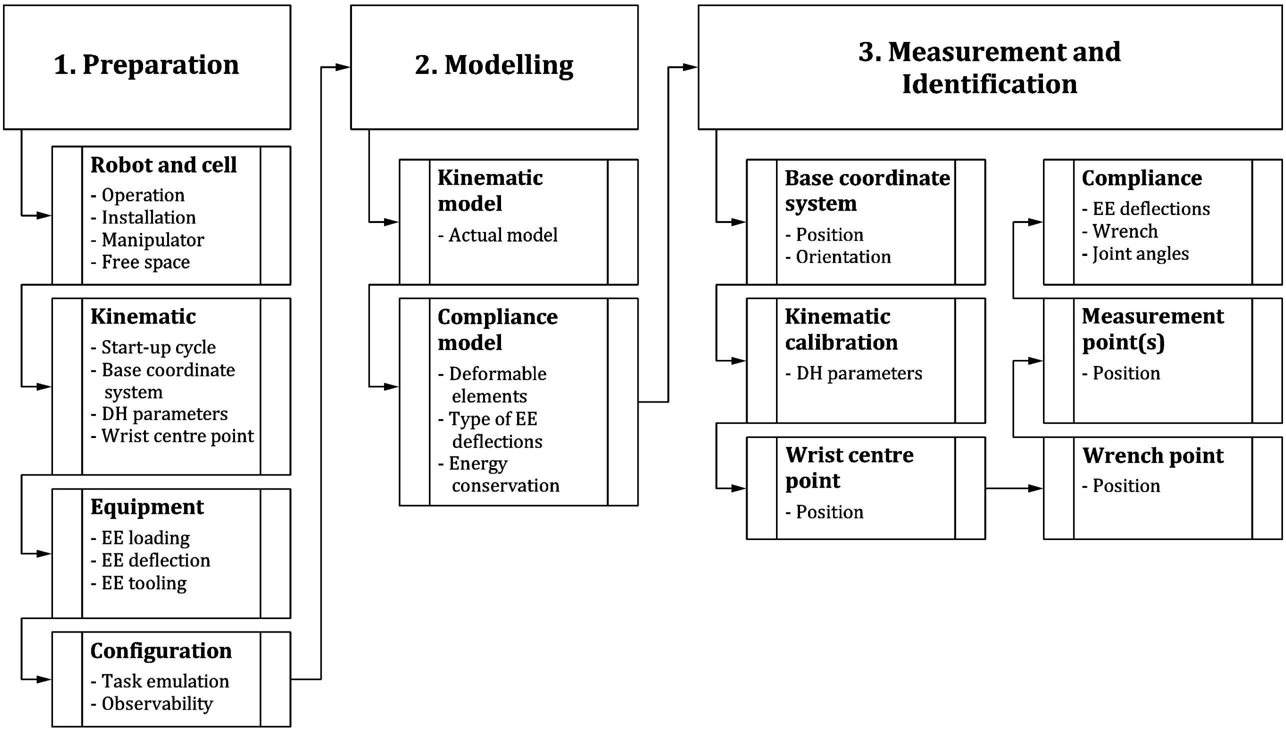

Figure 1 — Elastostatic compliance calibration procedure

Elastostatic means that the manipulator is deformable by static forces in a linear stress strain region, i.e. the stiffness is linear. The latter aspect is also referred to as linear-elastic deformation, which is commonly abbreviated to elastic. This document uses an elastostatic compliance model based on the Virtual Joint Method (VJM). The VJM is based on the extension of the rigid kinematic model by adding virtual degrees of freedom in terms of translational and or rotational springs to the structural loop components that are considered deformable. The model considers only one rotary degree of freedom for each link [2]. The joints can be represented as linear elastic torsional springs. This is schematically presented in Figure 2. Each spring has a linear rotary stiffness, also termed joint stiffness. The model parameter to be identified is the joint stiffness matrix, K_θ.

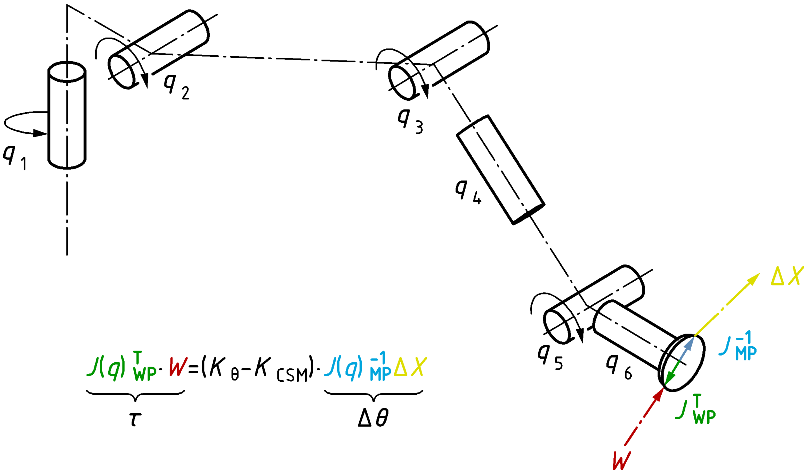

Figure 2 — Schematic representation of a compliance calibration

5 Preparation

5.1 Robot and cell

Operation

The robot shall be completely assembled and fully functional in the automatic and manual operating mode. Levelling operations, alignment procedures and functional tests shall be completed according to the specifications of the robot manufacturer.

The ambient and test temperature shall conform to the temperature specified by EN ISO 9283:1998. The ambient temperature of the testing environment should be 20 °C. The test temperature shall be maintained in a range of ±2 °C.

Manipulator and the measuring instruments should be in a thermally stable condition before testing. They should be placed in the test environment before testing.

The speed shall conform to the safety-rated reduced speed specified by EN ISO 10218-1:2011. Throughout all phases of the calibration procedure the maximum Cartesian speed shall not exceed the safety-rated reduced speed of 250 mm/s for the test.

The robot shall be operated with its servos activated and brakes deactivated.

The measurements of the manipulator configurations for the identification of the manipulator compliance shall be conducted in manual mode.

Installation

The robot shall be mounted in accordance with the manufacturer’s recommendations.

All other equipment and devices, such as end effectors, which are used in the calibration procedure and are in the flow of forces shall be considerably stiffer than the anticipated stiffness of the manipulator.

Manipulator

Tests shall conform to the loads specified by EN ISO 9283:1998. All tests shall be executed with loads equal to or lower than 100 % of the rated load conditions. The rated load conditions depend on the mass, the centre of gravity as well as moments of inertia and are specified by the robot manufacturer.

Tests can be conducted on a manipulator with a customized end effector (EE), if the EE can be considered much stiffer than the robot or if the stiffness is known, i.e. when it can be modelled as a rigid link or its deflections can be accounted for.

Free space

The position of the measurement instrument should be selected such that its instrument uncertainty is considered low, it does not obstruct the measurement procedure and it allows a measurement of the operating space.

The the position of the measurement instruments for measurements that take longer than a working day should be considered using invariant robot cell references to validate. Additionally, these references can be used to cover a bigger operating space or the working space.

At least 12 manipulator configurations for the identification of the compliance parameters of the robot model shall be measured. The manipulator measurement configurations shall be evenly spaced in the operating space. The selection of the manipulator measurement configurations should be derived from the application or in accordance with ISO 9283:1998.

50 % or more manipulator measurement configurations than intended to measure to compensate for potential obstruction of the measurement points (MPs) should be prepared.

5.2 Kinematic

Start-up cycle

Tests shall be preceded by a start-up cycle. If no such start-up cycle is available, one has to be defined which is as close as possible to the task program of the robot or moves all joints as much as possible. The start-up cycle shall be repeated periodically to maintain the operational conditions.

Base coordinate system

The measured position data (x_j, y_j, z_j) shall be expressed in the base coordinate system or in a coordinate system with the orientation of the base coordinate system.

Denavit Hartenberg (DH) paramters

Prior to the elastostatic compliance calibration, a kinematic calibration relying on the circle point method to identify the actual DH parameters of the manipulator should be conducted. The information is used to decrease the model uncertainty.

Wrist centre point (WCP)

Prior to the elastostatic compliance calibration the WCP should be measured and identified. The information can be used to decouple the identification procedure into the arm and the wrist. For more information see [3].

The identification of the WCP is based on trilateration. Trilateration requires three MPs. The placement of the MPs is important for the identification of the WCP. The MPs should be placed at the corners of a triangle with equal side length.

5.3 Equipment

The measuring instruments used for the tests shall be calibrated and the uncertainty of measurement shall be estimated and stated in the test report. The following parameters have to be taken into account:

- instrumentation uncertainty;
- systematic errors associated with the measurement method.
- the test uncertainty ratio should not be lower than 1:5.

5.4 Configuration

Task emulation

The measurement should be conducted in the operating space to improve the implementation of the identified model parameters.

Observability

Within the operating space the manipulator measurement configurations should be selected considering the following three points:

1) Condition number of the Jacobian matrices;

2) Observability values of the model parameters;

3) Trace of the sensitivity matrix.

For more information refer to [4].

The manipulator measurement configurations shall be stated as depicted in Table 1. The three dots indicate the fields to be filled out.

Table 1 —Manipulator measurement configuration template

No	θ_1 [°]	$\theta_2\left[°\right]$	θ_3 [°]	θ_4 [°]	θ_5 [°]	θ_6 [°]
1	...	...	...	...	...	...
⋮	...	...	...	...	...	...
18	...	...	...	...	...	...

6 Modelling

6.1 Kinematic model

The kinematic model relates the joint and Cartesian space.

The geometric Jacobian $J\left(\theta\right) \in \mathbb{R}^{6\times6}$ relates the joint velocity to the Cartesian velocity of a point on the manipulator:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = J\left(q\right) \cdot \dot{\theta} \tag{1}$$

where

$v\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T \in \mathbb{R}^3$	is the translation speed of the EE expressed in the base coordinate system (BCS);
$\omega\begin{bmatrix} \omega_1 & \omega_2 & \omega_3 \end{bmatrix}^T \in \mathbb{R}^3$	is the rotational speed of the EE expressed in the BCS;
$q\ [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5 \quad \theta_6]^T \in \mathbb{R}^6$	is the actuated joint angle vector.

The geometric Jacobian of the robot can be calculated from the robot's DH parameters.

The Jacobian matrix also relates the wrench applied to a point on the manipulator to the torques in each joint:

$$\tau = J\left(q\right)^{T} \cdot W \tag{2}$$

where

$\tau\ [\tau_1 \quad \tau_2 \quad \tau_3 \quad \tau_4 \quad \tau_5 \quad \tau_6]^T \in \mathbb{R}^6$	is the joint torques;
$W\ [F_x \quad F_y \quad F_z \quad \tau_x \quad \tau_y \quad \tau_z]^T \in \mathbb{R}^6$	is the wrench expressed in the BCS.

For more information refer to [4].

6.2 Compliance model

The elastostatic compliance model relates the loaded to the unloaded static configuration of the robot under the consideration that a static external force is applied in a linear stress strain region of the robot. In general, these models consider joint or joint and link compliance. This work uses an elastostatic compliance model based on the Virtual Joint Method. The VJM method is based on the extension of the rigid kinematic model by adding virtual degrees of freedom in terms of translational and or rotational springs to the structural loop components that are considered deformable. The model considers only one rotary degree of freedom for each link [2]. The joints can be represented as linear elastic torsional springs.

The links of the robot are assumed to be rigid. The spatial Cartesian stiffness of a serial robot can be defined by Hooke's law for rigid bodies:

$$W = K_x \cdot \Delta x \tag{3}$$

where

$W\ [F_x \quad F_y \quad F_z \quad \tau_x \quad \tau_y \quad \tau_z]^T \in \mathbb{R}^6$	is the wrench expressed in the BCS;
$K_x \in \mathbb{R}^{6\times6}$	is the Cartesian stiffness matrix;
$\Delta x \left[\delta_x \quad \delta_y \quad \delta_z \quad \delta_{\varphi_x} \quad \delta_{\varphi_y} \quad \delta_{\varphi_z}\right] \in \mathbb{R}^6$	is the displacement vector.

In joint space this is expressed by:

$$J\left(q\right)_{WP}^{T} \cdot W = \left(K_\theta - K_{CSM}\right) J\left(q\right)_{MP}^{-1} \cdot \Delta x \tag{4}$$

where

$J\left(q\right)_{WP} \in \mathbb{R}^{6\times6}$	is the geometric Jacobian at the wrench point;
$W = [F_x \quad F_y \quad F_z \quad \tau_x \quad \tau_y \quad \tau_z]^T \in \mathbb{R}^6$	is the wrench expressed in the BCS;
$K_\theta \in \mathbb{R}^{6\times6}$	is the joint stiffness matrix

$$K_\theta = \begin{bmatrix} k_{\theta_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_{\theta_6} \end{bmatrix};$$

$K_{CSM} \in \mathbb{R}^{6\times 6}$ is the complementary stiffness matrix;

$J\left(q\right)_{MP} \in \mathbb{R}^{6\times 6}$ is the geometric Jacobian at the measurement point;

Δx is the translational deflections in the direction of the x, y and z axes of the BCS.

This can be simplified by conducting the measurements in configurations which are far from kinematic singularities to, such that the K_{CSM} is negligible:

$$J\left(q\right)_{WP}^{T} \cdot W = K_\theta \cdot J\left(q\right)_{MP}^{-1} \cdot \Delta x \tag{5}$$

7 Measurement and identification

7.1 Base coordinate system

The base coordinate system should be measured and identified using the circle point method for:

a) the operating space under investigation; or

b) for a sufficiently big portion to enable a good identification of axis of rotation.

The Cartesian speed of the MP shall not exceed the safety-rated reduced speed of 250 mm/s during the measurement.

The circle point method measures the individual movement of one joint for an otherwise invariant configuration, e.g. each joint describes a circle as in Figure 3. Circles can be fitted to the measurement data. The centre points of the circles and their normal vectors describe the position and orientation of the BCS in the Coordinate system of the measurement instrument.

The position of the base coordinate system is given by the *x* and *y* coordinates of the circle inscribed by joint 1 and the *z* coordinate of the circle inscribed by joint 2.

The orientation is the cross product of the normal vectors of the circles inscribed by joints 1 and 2.

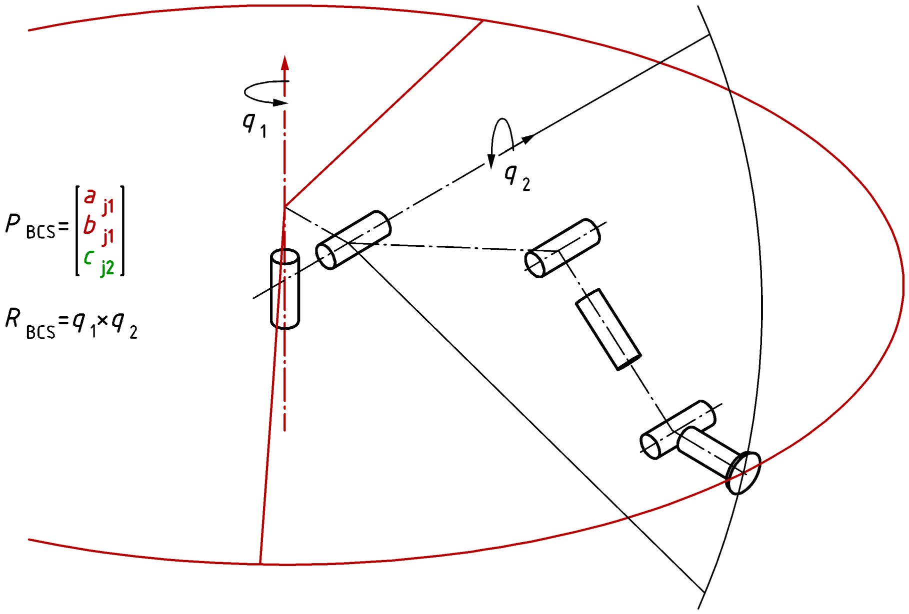

Figure 3 — Conceptual idea of the circle point method

7.2 Kinematic calibration

The actual DH parameters should be measured and identified using the circle point method for:

a) the operating space under investigation; or

b) for a sufficiently big portion to enable a good identification of axis of rotation.

The Cartesian speed of the MP shall not exceed the safety-rated reduced speed of 250 mm/s during the measurement.

Circles can be fitted to the measurement data. For each axis, the position of the axis (one point) and the orientation of the axis (one vector) can be identified. Based on the method and the preconditions, not all DH parameters will be observable. For these parameters the nominal DH parameters shall be used.

For more information, refer to [4].

7.3 Wrist centre point

The WCP shall be measured and identified using trilateration. This requires three measurement points. Joints 4, 5 and 6 need to be moved simultaneously for a sufficiently big portion to enable a good identification of their pivot point; i.e. the WCP. The Cartesian speed of the MPs shall not exceed the safety-rated reduced speed of 250 mm/s during the measurement.

A sphere can be fitted to the movement data of each MP. The resulting three spheres have two points of intersection. The intersections points can be found using trilateration. One of the intersection points of the three spheres is the WCP. The concept is depicted in Figure 4.

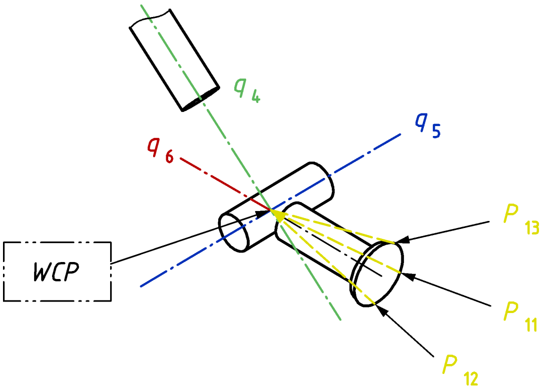

Figure 4 — Concept to measure and identify the wrist centre point

7.4 Wrench point

The measurement points should be measured in known configurations in combination with the actual kinematic robot model and identified as position transformations from the mechanical interface of the manipulator to the measurement point. The concept is depicted in Figure 5.

For more information, refer to [4].

7.5 Measurement point(s)

The measurement points should be measured in known configurations in combination with the actual kinematic robot model and identified as position transformations from the mechanical interface of the manipulator to the measurement point. The concept is depicted in Figure 5.

For more information, refer to [4].

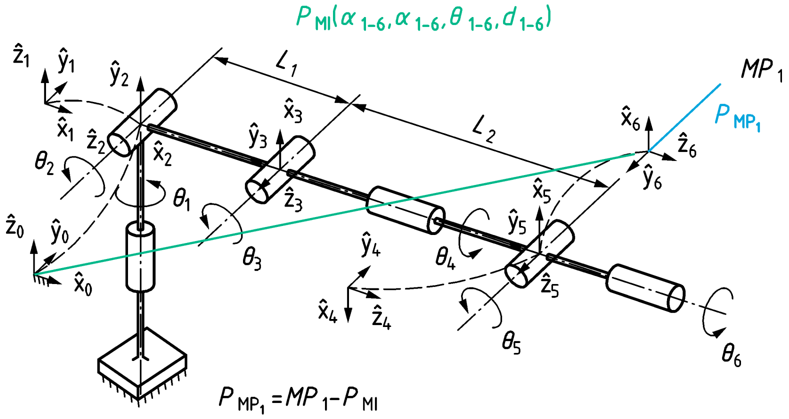

Figure 5 — Concept to measure and identify the MPs and WP

7.6 Compliance

For the measurement of the compliance parameters, i.e. the joint stiffness matrix, the following procedure shall be repeated for the number of selected manipulator measurement configurations i:

1) Move the manipulator to a static configuration i;
2) Measure the unloaded position of the MP;
3) Apply a static load;
4) Measure the wrench of the static load;
5) Measure the loaded position of the MP.

For the identification of the joint stiffness matrix, the EE deflections Δx shall be calculated as the difference between the loaded and unloaded position of the MP, as well as the wrench W and record the actuated joint angles q.

The joint stiffness matrix for the selected manipulator measurement configurations i shall be obtained using a linear least squares mapping:

$$\| J\left(q\right)_{MP,i} K_{\theta}^{-1} J\left(q\right)_{WP,i}^{T} \cdot W_i - \Delta x_i \|_2^2 \tag{6}$$

$$\| A_i K_{\theta}^{-1} - \Delta x_i \|_2^2 \tag{7}$$

where

$A \in \mathbb{R}^{6\times 6}$ is the observation matrix;

$$A = \begin{bmatrix} J_{11}\cdot\tau_1 & \cdots & J_{16}\cdot\tau_6 \\ \vdots & \ddots & \vdots \\ J_{61}\cdot\tau_1 & \cdots & J_{66}\cdot\tau_6 \end{bmatrix};$$

$$J(q)_{MP,i}\cdot K_{\theta}^{-1}\cdot\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix} = \begin{bmatrix} J_{11} & \cdots & J_{16} \\ \vdots & \ddots & \vdots \\ J_{61} & \cdots & J_{66} \end{bmatrix}\cdot\begin{bmatrix} k_{\theta_1}^{-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_{\theta_6}^{-1} \end{bmatrix}\cdot\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix} = \begin{matrix} J_{11}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{16}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{21}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{26}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{31}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{36}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{41}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{46}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{51}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{56}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{61}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \cdots + J_{66}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \end{matrix}$$

If only position deflections are considered in Δx_i, then the system of equations reduces to:

$$\begin{bmatrix}\delta_x\\ \delta_y\\ \delta_z\end{bmatrix} = \begin{matrix} J_{11}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \ldots + J_{16}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{21}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \ldots + J_{26}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \\ J_{31}\cdot k_{\theta_1}^{-1}\cdot\tau_1 + \ldots + J_{36}\cdot k_{\theta_6}^{-1}\cdot\tau_6 \end{matrix}$$

8 Presentation of results

The test results for each joint shall be specified numerically in terms of the measure and of the joint stiffness values according to Table 2.

Table 2 — Template for test results

Joint	Stiffness $\left[10^5 \frac{\text{Nm}}{\text{rad}}\right]$
k_{θ_1}	To be filled out.
k_{θ_2}	To be filled out.
k_{θ_3}	To be filled out.
k_{θ_4}	To be filled out.
k_{θ_5}	To be filled out.
k_{θ_6}	To be filled out.

The test report shall give the following information:

a) reference to this document (CWA 17384);

b) date of the test;

c) name of the industrial robot;

d) measurement configurations;

e) measuring equipment;

f) test parameters; and

g) a visualization of the investigated operating space, in Cartesian representation.

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