
**Non-destructive testing — Robotic
ultrasonic test systems — General
requirements**

*Essais non destructifs — Systèmes robotisés de contrôle par ultrasons
— Exigences générales*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 3, *Ultrasonic testing*.

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Non-destructive testing — Robotic ultrasonic test systems — General requirements

1 Scope

This document specifies the necessary system hardware components, the characteristics, the component requirements and conditions for the application of robotic ultrasonic test systems.

This document specifies the general requirements and acceptance criteria for robotic ultrasonic test systems.

This document is applicable to robotic ultrasonic test systems composed of one or more robot(s). Some of the characteristics of a robot ultrasonic testing system can be application-specific.

This document is applicable to conventional straight-beam probes and immersion technique.

This document is also applicable for phased array equipment, but additional tests can be necessary.

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.

ISO 230-1, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

ISO 230-2, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*

ISO 5577, *Non-destructive testing — Ultrasonic testing — Vocabulary*

ISO 8373, *Robotics — Vocabulary*

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

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 22232 (all parts), *Non-destructive testing — Characterization and verification of ultrasonic test equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5577, ISO 8373, ISO 9283, ISO 22232 (all parts) and the following apply.

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

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

3.1

robotic ultrasonic test system

automatic scanning ultrasonic test system, controlled by computer program, with the scanning motion implemented by one or multiple robots

**3.2
joint robot**

robot fitted with rotary joints

Note 1 to entry: Rotary joints allow a full range of motion, as they rotate through multiple planes, and they increase the manipulating capabilities of the robot considerably. An articulated robot can have one or more rotary joints, and other types of joints may be used as well, depending on the design of the robot and its intended function.

**3.3
scan path**

motion trajectory of the probe relative to the test object when the robot is executing the ultrasonic scanning with the probe or the test object held by the *end effector* (3.5) of the robot

**3.4
Cartesian robot**

robot whose arm has three prismatic joints, whose axes are coincident with a Cartesian coordinate system

**3.5
end effector**

device specifically designed for attachment to the robot's mechanical interface to enable the robot to perform its task

**3.6
tool coordinate system**

coordinate system referenced to the tool (probe or test piece) or to the *end effector* (3.5) attached to the mechanical interface

4 Requirements for test personnel

- a) Personnel to perform verification tests using this document shall be qualified in accordance with ISO 9712 or equivalent.
- b) The personnel shall be familiar with the robotic ultrasonic scanning equipment and robot motion control technique.
- c) The personnel shall be authorized by the employer or his/her agent.

5 Test system

5.1 General

Robotic ultrasonic test systems are automated high-performance ultrasonic test systems.

They are equipped with robotic manipulating technology and ultrasonic testing technology.

A robotic ultrasonic test system is mainly composed of one or more robot(s), with one or more ultrasonic probe(s), an ultrasonic instrument and a fluid, gas or contact coupling system.

Single-pulse excitation or tone burst excitation is used.

Ultrasonic reflection or through-transmission technique may be implemented.

Two-dimensional or three-dimensional images may be used to display the test results to show the shape and the position of the detected imperfections.

5.2 Design principles

- a) The design of the test system shall meet the requirements of the application for the objects to be tested.
- b) The ambient conditions and the requirements of the test method shall be taken into account.
- c) The distance between the surface of the test objects and the probes shall be kept constant during ultrasonic scanning.
- d) Electrical or mechanical interferences shall be reduced to a minimum by design.

5.3 Test equipment

5.3.1 Instrument

- a) The ultrasonic instrument shall meet the requirements of ISO 22232-1 where applicable.
- b) The ultrasonic instrument shall be selected according to the application.
- c) The ultrasonic instrument shall support ultrasonic pulse-echo and/or ultrasonic through-transmission mode.
- d) The ultrasonic instrument shall have signal conditioning circuits for the excitation and the reception of ultrasonic pulses.
- e) The technical properties such as transmitter pulse voltage, transmitter pulse width, repetition frequency, gain range, filtering bandwidth, digitizing frequency, digitizing dynamic range (A/D converter bits) and crosstalk shall be specified in accordance with ISO 22232-1 and shall satisfy the requirements of the application.
- f) The technical properties of the ultrasonic instrument shall be determined according to the application (e.g. material characteristics and the sensitivity requirements).

5.3.2 Probes

- a) The ultrasonic probes shall be selected according to the test procedure.
- b) The ultrasonic probes shall meet the requirements of ISO 22232-2.
- c) The technical parameters of the ultrasonic probes, such as frequency, beam diameter, focal distance and relative bandwidth, shall be specified in accordance with ISO 22232-2 and shall satisfy the requirements of the application.
- d) The cable length between the probes and the instrument shall be reduced to a minimum to reduce cable attenuation and electrical noise. The housing shall be electrically grounded.

5.3.3 Robots

- a) The robots shall be selected according to the requirements of the test procedure.
- b) The robots shall conform to the requirements for the scan pattern and the scan speed.
- c) The robots may be joint robots or Cartesian robots.
- d) The technical properties such as freedom of mechanical movement, range for manipulation, maximum moving speed, motion accuracy and positioning repetition accuracy shall be specified and shall satisfy the requirements of the application.
- e) The end effector of the robots shall provide a flange for the attachment of an ultrasonic probe and/or the test object as well as a coupling supply squirter if necessary.

- f) The position and orientation of the probe’s coordinate system or the coordinate system of the test object relative to the coordinate system of the robots end effector flange or the coordinate system of the robot base shall be provided to express tested point position in different geometrical coordinate systems.

5.3.4 Couplant

- a) Dependent on the application, gas or liquid may be used as couplant with a robotic ultrasonic test system.
- b) For liquid coupling, a squirter or immersion device and a circulation system for the couplant shall be provided.

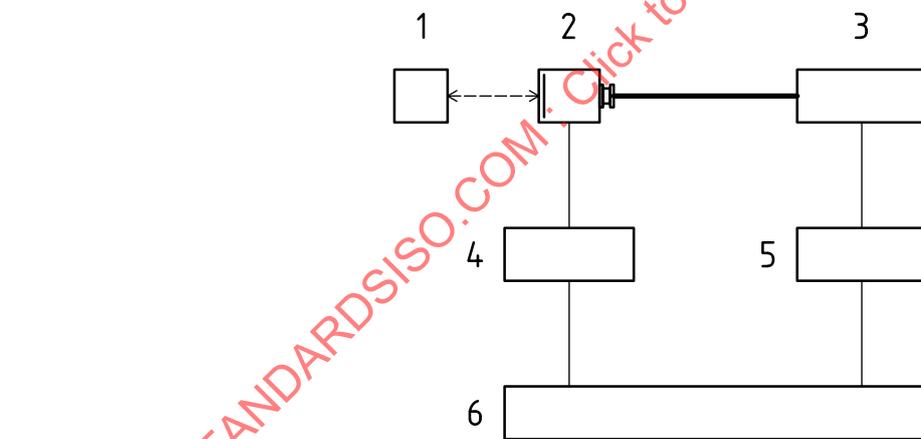
5.4 Typical test systems

5.4.1 Single-robot test system

5.4.1.1 System components

Figure 1 shows the composition of a robotic ultrasonic test system based on one robot. The system setup is mainly composed of an ultrasonic instrument, an ultrasonic probe, a robot and its control system including software and a couplant circulation system. The system shall be arranged in a way that either the probe or the test object is moved by the robot.

- a) Computer and robot controller shall be connected for control command and trajectory data transfer.
- b) Computer and ultrasonic instrument shall be connected for control command and ultrasonic data transfer.



Key

1	test object
2	probe
3	robot
4	ultrasonic instrument
5	robot controller
6	computer and software
←-----→	sound path
—————	electrical connection
—————	mechanical connection

Figure 1 — Single-robot ultrasonic test system

5.4.1.2 Scan modes

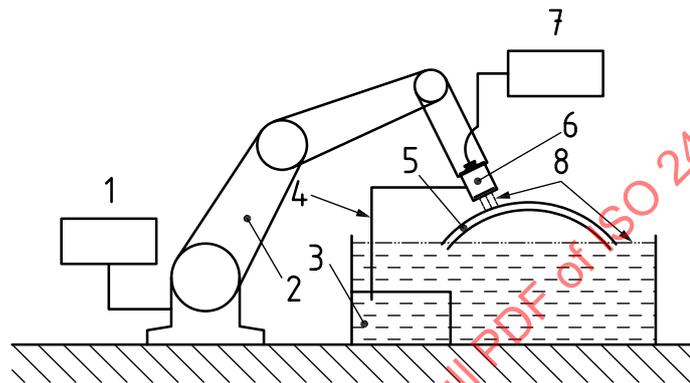
5.4.1.2.1 Scan mode with movement of the probe

The robot moves the probe while the test object is fixed, as shown in [Figure 2](#).

This mode shall be used when the test object is too large or too heavy to be held by a robot.

It is suitable when the size of the test object is large and/or the acoustic attenuation is low so that the back-wall echo can be evaluated.

Usually, the ultrasonic probe is of little weight so that the robot can hold it without overload.



Key

- 1 robot controller
- 2 robot
- 3 circulatory system for couplant
- 4 couplant supply
- 5 test object
- 6 probe
- 7 ultrasonic instrument
- 8 couplant (e.g. water)

Figure 2 — Scan mode with movement of the probe (example for squirter technique)

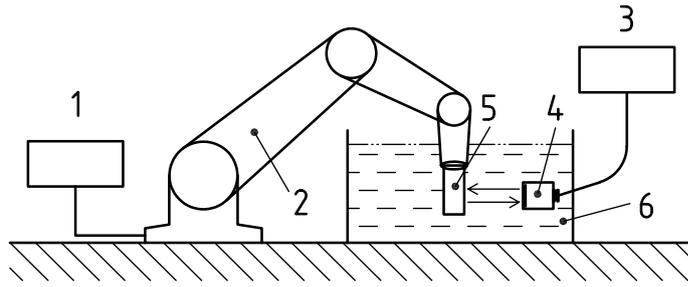
5.4.1.2.2 Scan mode with movement of the test object

The robot moves the test object while the probe is fixed, as shown in [Figure 3](#).

This scan mode shall be used when the test object has a small size and complex profile.

It is suitable for the case when the size of the test object is small and the acoustic attenuation is low so that the back-wall echo can be received.

The weight of the test object is limited by the robot's load ability.



Key

- 1 robot controller
- 2 robot
- 3 ultrasonic instrument
- 4 probe
- 5 test object
- 6 couplant (e.g. water)

Figure 3 — Scan mode with movement of the test object (example for immersion technique)

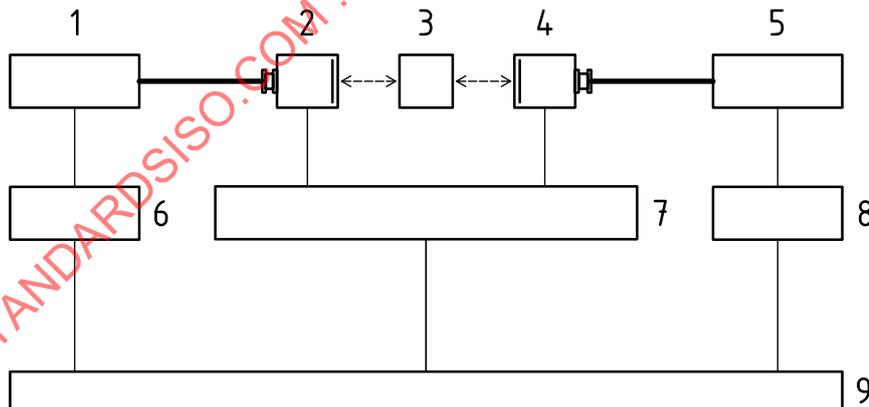
5.4.2 Twin-robot test system

5.4.2.1 System components

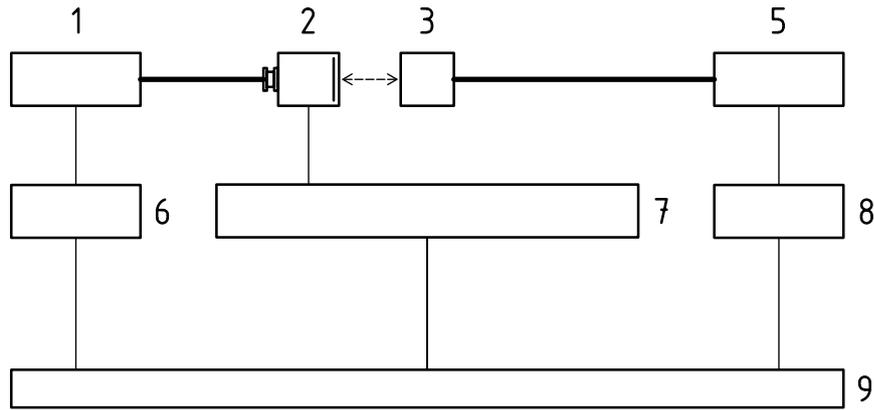
Figure 4 shows twin-robots ultrasonic test systems.

The system setup is mainly composed of one or two ultrasonic probes, one ultrasonic instrument, two robots and their control systems, including software and a couplant circulation system.

The software shall be able to send robot control commands, to transfer scan pattern data, to send commands to the ultrasonic instrument and to transfer ultrasonic signal data.



a) Setup with two robots and two probes



b) Setup with two robots and one single probe

Key

1	robot 1	7	ultrasonic instrument
2	probe 1	8	robot controller 2
3	test object	9	computer and software
4	probe 2		←-----→
5	robot 2		—————
6	robot controller 1		—————

Figure 4 — Twin-robots ultrasonic test systems

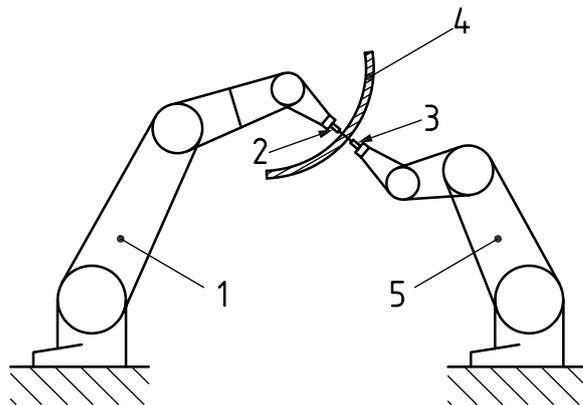
5.4.2.2 Scan modes

5.4.2.2.1 Each robot moves a probe

Each robot moves a probe simultaneously while the test object is fixed, as shown in [Figure 5](#).

This scan mode is suitable for the case when the size of the test object is large and/or the acoustic attenuation is high so that the back-wall echo cannot be received and evaluated by reflection method. Usually, the ultrasonic probes are of little weight so that the robot can hold them without overload.

The ultrasonic transmission technique requires that both beam axes be aligned to each other and be consistent with the normal vector to the surface of the test object at the test point.



Key

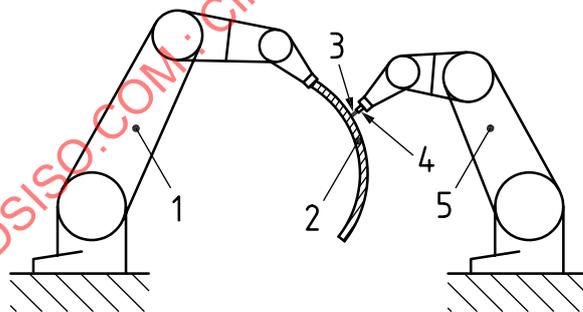
- 1 robot 1
- 2 probe 1
- 3 probe 2
- 4 test object
- 5 robot 2

Figure 5 — Each robot moves a probe (example gas couplant)

5.4.2.2.2 One robot moves the probe and another robot moves the test object

One robot moves the probe and another robot moves the test object, as shown in [Figure 6](#).

This scan mode shall be used when the size of the test object is small and/or the acoustic attenuation is low so that the back-wall echo can be evaluated. In this case, the weight of the test object is limited by the robot's load ability.



Key

- 1 robot 1
- 2 test object
- 3 couplant (e.g. water)
- 4 probe
- 5 robot 2

Figure 6 — One robot moves the probe and another robot moves the test object

6 Characteristics and requirements for robotic ultrasonic test systems

6.1 General

Robotic ultrasonic test systems are mainly used for automated scanning of test objects with complex geometries.

In order to obtain reliable test results, proper planning of the scan pattern and synchronized acquisition of ultrasonic and position data are important.

6.2 Test technique

6.2.1 General

A robotic ultrasonic test system shall be able to carry out the pulse-echo technique or the through-transmission technique.

6.2.2 Pulse-echo technique

The pulse-echo technique is an ultrasonic reflection technique with the probe or the test object being attached to the robot as shown in [Figure 2](#), [Figure 3](#) and [Figure 6](#), where the single probe transmits and receives ultrasonic pulses.

The test results may be presented as A-scan images, B-scan images or C-scan images.

Information on amplitude, time of flight and position is available for evaluation.

6.2.3 Trough-transmission technique

The through-transmission technique uses two probes, one for transmitting ultrasonic waves, the other for receiving, as shown in [Figure 5](#).

The test result may be presented as A-scan images, B-scan images or C-scan images.

Information on amplitude and position is available for evaluation.

6.3 Planning of scan pattern and programming of robot motion control

6.3.1 General

A suited scan path planning method and/or software tool shall be provided to create the robot motion control program for a robotic ultrasonic test system.

6.3.2 Path planning method

6.3.2.1 General

This subclause describes the scan path calculation and the post-processing.

The result of the scan path calculation gives the position and the orientation normal to the surface for each discrete test point on the scanning trajectory expressed in the coordinate system of the test object.

The post-processing converts the position and the orientation normal to the surface of scan points expressed in the coordinate system of the test object into the position and orientation of the robot end effector expressed in the robot base coordinate system.

Another task of the post-processing is to form the motion control program (with the converted scan point data) that the particular robot controller accepts.

The discrete scan path point is usually described by the position and the orientation normal to the surface relative to the coordinate system of the test object. It is often mathematically expressed as a vector $\mathbf{P}(p_x, p_y, p_z, I, J, K)$ in test object coordinate system. Where (p_x, p_y, p_z) gives the position of the scan point and (I, J, K) gives the cosine of the orientation normal to the surface relative to the X, Y, Z axes of the coordinate system of test object.

Normally, the movement of the robot end effector is described for robot controller by the position and orientation of a coordinate system fixed on the end effector [often called tool centre point (TCP)] relative to the base coordinate system of the robot.

The position and orientation of the tool coordinate system is often mathematically expressed as a type of vector $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$. where, (x, y, z) gives the position of the origin of the tool coordinate system, (α, β, γ) represents three angles that rotate the tool coordinate system around its axes X, Y and Z successively or the rotation of the tool coordinate system around the robot base coordinate system axes X, Y and Z successively.

In robotics the vector $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is often expressed as a homogenous matrix $\mathbf{T} = [\text{Trans}(x, y, z) \text{Rot}(x, \alpha) \text{Rot}(y, \beta) \text{Rot}(z, \gamma)]$.

Since the rotating sequence of the tool coordinate system may be different for different robots, thus the matrix \mathbf{T} may be different for different robots.

For example, if the rotation sequence is X, Y and Z successively relative to the tool coordinate system, the matrix \mathbf{T} is as given in [Formula \(1\)](#).

$$\mathbf{T} = \text{Trans}(x, y, z) \text{Rot}(x, \alpha) \text{Rot}(y, \beta) \text{Rot}(z, \gamma)$$

$$= \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 & 0 \\ \sin \gamma & \cos \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The position and orientation vector of the tool coordinate system of type $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is used to create control commands to a robot, or to create an equivalent homogenous matrix \mathbf{T} .

In order to generate the robot motion control program, path data conversion from the coordinate system of the test object with the format $\mathbf{P}(p_x, p_y, p_z, I, J, K)$ to position and orientation of the tool coordinate system relative to the base coordinate system of the robot in format $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is needed in path planning. This work is often called post-processing of scan path planning.

The conversion algorithms may be different for different scan modes (see [Annex A](#)).

All the path discrete point data with the format $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ together with the scan velocity and acceleration information will form the scan motion control program executable by the robot controller.

- a) If the CAD (computer-aided design) model of a test object can be obtained easily, method [6.3.2.3](#) or [6.3.2.4](#) shall be used.
- b) If it is too hard to obtain the CAD model of a test object, method [6.3.2.2](#) shall be used.

NOTE For CAM (computer-aided manufacturing) software, the main parameter settings are the known and constant relations between the coordinate systems. Settings are different for different scan modes.

- c) If the scan mode according to [Figure 2](#) is used, the position and orientation of the test object coordinate system relative to the base coordinate system of the robot and the position and orientation of the probes coordinate system relative to the tool coordinate system of the robot are known and constant and shall be set for the CAM software.

- d) If the scan mode according to [Figure 3](#) is used, the position and orientation of the probes coordinate system relative to the base coordinate system of the robot and the position and orientation of coordinate system of the test object relative to the tool coordinate system of the robot are known and constant and shall be set for the CAM software.

For all probes, position and orientation of the probe coordinate system always describe the probe beam origin and beam orientation.

6.3.2.2 Manual teaching method

There are two main steps to get scan path data and create the robot motion control program.

- Step 1: Teach the robot how to move and records the scan path data by physically moving the robot or moving the robot by its control panel box.
- Step 2: Create the robot motion control program using the recorded scan path data following the particular robot programming rules provided by the robot manufacturer.

6.3.2.3 Method using CAD model and CNC-oriented CAM tools

With this method a CAD model of the test object and a CNC (computer numerical control) machine-tool-oriented CAM software are applied.

There are three main steps to get the scan path data and to form the robot motion control program.

- Step 1: Get the scan path discrete point data in the format that expresses the scan point position and orientation normal to the surface in the coordinate system of the test object by the CAM software.
- Step 2: Convert each discrete point data into the format that expresses the scan point position and orientation normal to the surface in the coordinate system of the test object to the format that expresses the scan point position and Euler angles of the robot tool coordinate system in the robot base coordinate system.

This shall be done by the operator of the robot test system. [Annex A](#) gives an example of the procedure.

- Step 3: Create the robot motion control program in a way that the particular robot controller can accept the data format that expresses the scan point position and Euler angles of the robot tool coordinate system in the robot base coordinate system.

This shall be done by the robot test system operator. An example is given in [Annex A](#).

NOTE The work of step 2 and step 3 is often called post-processing of scan path planning (see [Annex A](#)).

6.3.2.4 Method using CAD model and robot-oriented CAM tool

With this method, a CAD model of the test object and robot-oriented CAM software are applied.

There are three main steps to get the scan path data and to create the robot motion control program.

- Step 1: Same as step 1 given in [6.3.2.3](#);
- Step 2: Convert each discrete point data in the format that expresses the scan point position and the orientation normal to the surface in the coordinate system of the test object into the format that expresses the scan point position and Euler angles of the robot tool coordinate system within the robot base coordinate system.

This may be done with a robot-oriented CAM software.

- Step 3: Create the robot motion control program in a way that the particular robot controller can accept the data format that expresses the scan point position and Euler angles of the robot tool coordinate system in the robot base coordinate system.

This may be done by the robot-oriented CAM software.

6.3.3 Restrictions

When implementing scan path planning, the following restrictions shall apply.

- a) The scanning point step or distance between adjacent test points shall be less than two-thirds of the diameter of the ultrasonic beam at these points.
- b) The scanning line step or distance between adjacent scan lines shall be less than two-thirds of the diameter of the ultrasonic beam at these lines.
- c) To ensure a constant ultrasonic beam incidence angle, the beam axis of the probe shall always keep a particular angle to the normal of the surface of the test object at each discrete test point of the path.

In other words, the beam axis shall be consistent with the normal vector at each discrete point along the scan path.

6.4 Synchronisation of the acquisition of ultrasonic and position data

6.4.1 Synchronisation of ultrasonic signal and robot position

In order to be able to display and evaluate mechanically recorded ultrasonic test data, the relationship between position data and ultrasonic test data shall be known.

The robot system and the ultrasonic test system shall be synchronized for the correct assignment of ultrasonic data to positional data.

The aim of synchronization is to ensure that the position information for each recorded A-scan in the data record is known and can be assigned accordingly.

If possible, the position data shall be stored together with the A-scans.

Since the ultrasonic test system and the robot system are typically two independent systems, they shall be synchronized via interfaces.

In the simplest case, this interface consists of signal lines that directly control the systems in real time.

In addition, the position and/or the cycle number can be transmitted as a value via a software interface, e.g. via a serial data connection or a network connection.

6.4.2 Synchronisation — Minimum requirements

In the simplest case, the hardware-based interface consists of two signal lines, for a trigger signal and for a reset/enable signal. These signals trigger an immediate reaction in the systems.

NOTE “reset/enable” means “reset” when logically 1, “enable” when logically 0, or vice versa.

At least one trigger signal counter shall be present in the robotic ultrasonic test system.

It is recommended to use TTL-compatible signals.

6.4.3 Synchronisation — Optional requirements

In addition to the minimum synchronization requirements, the current position data from the robot system to the ultrasonic test system and/or the current cycle number from the ultrasonic test system to the robot system can be transmitted via a serial or network connection link and a software interface.

If a trigger signal counter is implemented in the ultrasonic instrument and the robot, the data transmitted via the software interface can be uniquely assigned in the ultrasonic instrument and the robot via the reference to the trigger signal counter and encoder outputs, when used.

6.5 Conditions for the application

- a) A robotic ultrasonic test system is mostly used for automated scanning of test objects with complex geometry.
- b) Particular test techniques shall be implemented according to the type and distribution of the imperfections in the test object which shall be detected.
- c) The ultrasonic test system shall be earthed.
- d) In a laboratory environment, the following apply.

The test shall be carried out at room temperature. If water is used as the couplant, the test object can be completely immersed in water; or a water jet system at the front of the probe can be used to provide a stable water stream.

The water path shall be kept constant during ultrasonic scanning.

- e) In a workshop environment, the following apply.

The connecting cables should be insulated shielded cables.

The external interference by vibrations and electromagnetic disturbances shall be minimized.

7 Verification of the test system

7.1 General

Ultrasonic robotic test systems are typically designed for a specific task. For the verification process the planned task or application shall be taken into account. This means that in certain cases verification can be application-specific.

- a) For all components of the test system, a verification plan shall be made.
- b) It is recommended to appoint periodical checks for the instrument, probes and robots. A time interval for a periodical re-check shall be stated.
- c) The results of the verification shall be documented.
- d) The following acceptance criteria shall be defined:
 - 1) discontinuities and artificial reflectors which shall be detected;
 - 2) maximum percentage of false negative events;
 - 3) maximum percentage of false positive events.

7.2 Ultrasonic instrument and probes

7.2.1 General

- a) The functional ability and performance characteristics of the ultrasonic instrument shall be verified by tests.
- b) Characteristic parameters to be tested shall be specified by the manufacturer and the user of the robotic ultrasonic test system.
- c) Test procedures and acceptance criteria for the instrument, the probes and the combined system may refer to the ISO 22232 series.

7.2.2 Single-probe systems

- a) When single-probe systems are used, sensitivity shall be verified.
- b) Signal saturation shall be avoided.

7.2.3 Multi-probe systems

- a) Where multi-probe systems are used, a normalization of the probes shall be applied; and the homogenous sensitivity shall be verified.
- b) All probes shall be operated under the same conditions using the same test block.

7.2.4 Normalization of pulse-echo systems

- a) Prepare a test block with a thickness equal to 1/3, 1/2 and 2/3 of a reference thickness. The length and width of the test block should be 2 to 3 times larger than the probe beam diameter. Carry out a pulse-echo test on the test block with each probe channel.
- b) For the 1/2 reference thickness of the test block, the normalization of all channels shall be performed to bring the back-wall amplitudes to the same level within a tolerance of ± 1 dB.
- c) For the 1/3 and 2/3 reference thickness of the test block, the back-wall amplitudes shall not vary by more than 2 dB.
- d) Signal saturation shall be avoided.

7.2.5 Normalization of through-transmission systems

- a) At a specified sound path, the normalization of all channels shall be performed to bring the amplitudes to the same level within a tolerance of ± 1 dB.
- b) Signal saturation shall be avoided.

7.3 Robots

- a) The robots in a robotic ultrasonic test system shall be verified by tests.
- b) Characteristic parameters to be tested shall be specified by the manufacturer and the user of the robotic ultrasonic test system. At least the manipulating space and repetition positioning accuracy shall be tested.
- c) The test procedure and acceptance criteria shall be consistent with ISO 9283.
- d) When additional axes are used to extend the kinematic of the robot itself (e.g. a rail axis), the additional axes shall be verified. At least the measurement travel, motion or positioning error shall be tested.

- e) If applicable, linearity error of a linear axis and roundness error of a rotary axis shall be tested.
- f) The test procedure and acceptance criteria shall be consistent with ISO 230-1 and ISO 230-2.

7.4 Synchronization

- a) The synchronization between the ultrasonic instrument and the robots shall be checked.
- b) The achieved accuracy of the axes shall be recorded.

7.5 Complete system — Robots, instrument and probes combined

7.5.1 General

- a) The functional ability and the performance characteristics of a robotic ultrasonic test system shall be verified by tests.
- b) Characteristic parameters to be tested shall be specified by the manufacturer and the user of the robotic ultrasonic test system.
- c) At least the following aspects shall be tested for the C-scan performance of the system:
 - 1) the signal-to-noise ratio S_R for a specified reflector or discontinuity;
 - 2) the image distortion coefficient k ;
 - 3) the detection sensitivity.

7.5.2 Signal-to-noise ratio

7.5.2.1 Procedure

- a) Perform a scan of a reference object with spherical surface containing flat-bottomed holes and produce a C-scan image.
- b) The diameter of the flat-bottomed holes shall correspond to the specified sensitivity (may be frequency dependent).
- c) The increment of scanning points and increment of scan lines shall be less than half the beam diameter.
- d) Note the maximum echo amplitude A_s of the flat-bottomed holes and note the maximum noise amplitude A_n of the region without flat-bottomed holes.
- e) Calculate the signal-to-noise ratio S_R for the specified reflector or discontinuity in decibels according to [Formula \(2\)](#).

$$S_R = 20 \log \left(\frac{A_s}{A_n} \right) \quad (2)$$

7.5.2.2 Acceptance criterion

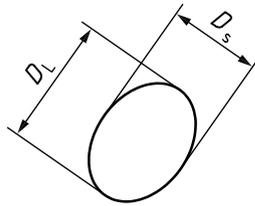
The signal-to-noise ratio S_R for the specified reflector or discontinuity shall not be less than 9 dB.

7.5.3 Image distortion coefficient

7.5.3.1 Procedure

- a) Perform a scan of a reference object with spherical surface containing flat-bottomed holes and produce a C-scan image.
- b) The diameter of the flat-bottomed-hole shall be 5 times to 10 times the diameter that corresponds to the detection sensitivity.
- c) The scan points increment and the scan lines increment shall be less than half of the beam diameter.
- d) Determine the long diameter D_L of the image of the flat-bottomed-hole and the short diameter D_s of the image of the flat-bottomed hole (see [Figure 7](#)).
- e) Calculate the image distortion coefficient according to [Formula \(3\)](#).

$$k = \frac{D_L}{D_s} \tag{3}$$



Key

D_L long diameter of the image of the flat-bottomed-hole

D_s short diameter of the image of the flat-bottomed-hole

Figure 7 — Schematic for image distortion

7.5.3.2 Acceptance criterion

The image distortion coefficient k shall not be larger than 1,2.

7.5.4 Detection sensitivity

7.5.4.1 Procedure

- a) Perform a scan of a reference object with spherical surface containing flat-bottomed holes and produce a C-scan image.
- b) The diameter of the flat-bottomed holes shall correspond to the specified sensitivity (may be frequency dependent).
- c) The increment of scanning points and increment of scan lines shall be less than half the beam diameter.
- d) Note the maximum echo amplitude A_s of the flat-bottomed holes and note the maximum noise amplitude A_n of the region without flat-bottomed holes.
- e) Calculate the signal-to-noise ratio S_R for the specified reflector or discontinuity in decibels according to [Formula \(2\)](#).
- f) Record the smallest flat-bottomed hole detected with a signal-to-noise ratio of at least 9 dB. It is specified as the test sensitivity of the robot ultrasonic test system.

7.5.4.2 Acceptance criterion

The test sensitivity given by the size of detectable flat-bottomed hole shall be better than the value stated in the performance specification of the robotic ultrasonic test system or the requirement agreed between the system manufacturer and the user.

8 Typical process of an automated test for a robotic ultrasonic test system

8.1 Preparation

- a) The test object and area to be tested shall be specified.
- b) A 3D-CAD model of the test object shall be established.

8.2 Probes

- a) The probes frequency shall be specified according to the thickness, material properties, surface shape and position of the test object.
- b) The sound beam parameters of the probes (e.g. focal distance, focal beam diameter) shall be selected according to the thickness of the test object.

8.3 Trajectory planning

Prepare the probe scan path and calculate the discrete points of the spatial trajectory of the scan path, for the particular test object and the robotic ultrasonic test system according to [6.3](#).

8.4 Setup of the scanning reference coordinate system

- a) When positioning the test object, the scanning reference coordinate system shall be checked.
- b) The relation between the coordinate system of the test object and the coordinate system of the robots shall be the same as in the trajectory plan.

8.5 Test procedure

- a) Set the signal connection.
- b) Set the following as appropriate for the test task:
 - step 1 as given in [6.3.2.3](#);
 - test mode (pulse-echo mode or separate transmitter-receiver mode);
 - excitation voltage;
 - filter cut-off frequency (low pass and high pass);
 - gain;
 - settings of imaging gate;
 - settings of scanning image (B-scan or C-scan).
- c) Prepare the robot motion control program based on the scan pattern and the trajectory plan.
- d) Load the motion control program to the robot controller.
- e) Perform the test operation by following the operation manual of the test system.

f) Record the test results, signal data and scanning images.

9 Documentation of the verification results

a) The results of the verification tests shall be recorded in a verification report.

b) The main information of the verification report shall be the characteristic performance test results of the complete ultrasonic test system and the characteristic performance test results of the main system components including ultrasonic instrument, probes and robots.

c) The content of the report shall include the following information as a minimum:

- 1) reference to this document (i.e. ISO 24647:2023);
- 2) name and location of the test entity;
- 3) objects to be tested;
- 4) reference objects used;
- 5) details on the tested robotic ultrasonic test system;
- 6) operating parameters used;
- 7) test results;
- 8) names and dated signatures of the responsible persons.

[Annex B](#) shows an example of a verification report. See [Table B.1](#).

If tests of the components (e.g. instrument, probes) cannot be performed on site, information from the datasheet provided by the manufacturer may be used.

Annex A (informative)

Trajectory planning

A.1 Overview

The scan path planning includes three steps.

- Step 1: Calculate the discrete points of the scan path in the format that expresses the scan point position and the orientation normal to the surface in the coordinate system of the test object by a CAM software.
- Step 2: Convert each discrete point data obtained in step 1 into the format that expresses the scan point position and the Euler angles of the robot tool coordinate system in the robot base coordinate system.
- Step 3: Create the robot motion control program that the particular robot controller can accept with the data format that expresses the scan point position and the Euler angles of the robot tool coordinate system in the robot base coordinate system.

Steps 2 and 3 are called post-processing of path planning.

The post-processing may be easily carried out by robot-oriented CAM software.

If there is no robot-oriented CAM software, the post-processing may be done manually by the test system operator.

The method shown here gives an example of an extrinsic rotation sequence method. Alternatively, intrinsic rotation sequence methods may be used

A discrete point on the scan path calculated by a CAM software is usually described by the position and vector normal to the surface at the scan point relative to the test object coordinate system.

It is often mathematically expressed as a vector $\mathbf{P}(px, py, pz, I, J, K)$ in coordinate system of the test object.

Where (px, py, pz) is the position vector of the scan point and (I, J, K) gives the cosines of the vector normal to the surface relative to the X, Y, Z axes of the coordinate system of the test object.

Normally the robot tool movement for the robot controller is described by the position and orientation of a coordinate system fixed on the end effector (often called tool coordinate system) relative to the base coordinate system of the robot.

The position and orientation of the tool coordinate system are often mathematically expressed as a type of a vector $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ where (x, y, z) is the position of the origin of the tool coordinate system and (α, β, γ) represents three angles that the tool coordinate system rotate around its axes X, Y and Z or the tool coordinate system rotate around the robot base coordinate system axes X, Y and Z successively.

In robotics the vector $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is often expressed as a homogenous matrix $T = [Trans(x, y, z)Rot(x, \alpha)Rot(y, \beta)Rot(z, \gamma)]$.

Since the rotation sequence of the tool coordinate system may be different for different robots, thus the matrices T may be different.

For example, if the rotation sequence is X, Y and Z successively relative to the tool coordinate system, the matrix T is given by [Formula \(A.1\)](#):

$$T = \text{Trans}(x, y, z) \text{Rot}(x, \alpha) \text{Rot}(y, \beta) \text{Rot}(z, \gamma)$$

$$= \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 & 0 \\ \sin \gamma & \cos \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (\text{A.1})$$

The position and orientation vector of the tool coordinate system of type $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is used to create the control commands to a robot or to form an equivalent homogenous matrix T or matrix transformation inside the robot controller.

In order to generate the robot motion control program, conversion of scan path data from points in the coordinate system of the test object into the format $\mathbf{P}(p_x, p_y, p_z, I, J, K)$ to position and orientation of the tool coordinate system relative to the base coordinate system of the robot into format $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is needed for scan path planning.

This work is often called post-processing of scan path planning. The conversion algorithms may be different for different scan modes.

All discrete point data of the scan path in format $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$, together with the scan velocity and acceleration information, create the scan motion control program executable by the robot controller.

A.2 Coordinate system and homogenous matrix

A.2.1 General

A vector in format $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$ is sufficient for describing the robot tool coordinate system movement (scan movement), so it is used in robot movement commands.

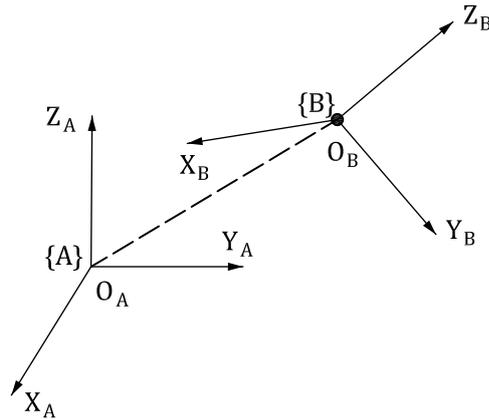
The tool coordinate system is related to many other coordinate systems, as is shown in [A.3](#) and [A.4](#).

To avoid the descriptions of the relations between different coordinate systems by vector $\mathbf{P}(x, y, z, \alpha, \beta, \gamma)$, its equivalent homogenous matrix T can be used to express relations between different coordinate systems.

A.2.2 Coordinate system

When a coordinate system is attached to a test block, it may be used to express the position and orientation of the test block.

The position and orientation of a coordinate system is usually expressed relative to a fixed reference coordinate system, as shown in [Figure A.1](#).



Key

{A}	coordinate system {A}	{B}	coordinate system {B}
O _A	origin of coordinate system {A}	O _B	origin of coordinate system {B}
X _A	X axis of coordinate system {A}	X _B	X axis of coordinate system {B}
Y _A	Y axis of coordinate system {A}	Y _B	Y axis of coordinate system {B}
Z _A	Z axis of coordinate system {A}	Z _B	Z axis of coordinate system {B}

Figure A.1 — Coordinate system {A} and coordinate system {B}

The origin of coordinate system {B} relative to coordinate system {A} represents its position, it is expressed by a vector as given by [Formula \(A.2\)](#):

$${}^A P_{BORG} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{A.2}$$

The orientation of {B} relative to {A} is expressed by three unit axis vectors ${}^A x_B, {}^A y_B, {}^A z_B$, where ${}^A x_B$ means that unit vector x_B is expressed in {A}, so as for ${}^A y_B$ and ${}^A z_B$, as given in [Formula \(A.3\)](#)

$${}^A_B R = \begin{bmatrix} {}^A x_B & {}^A y_B & {}^A z_B \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{A.3}$$

where ${}^A_B R$ is the orientation matrix or rotation matrix because it can be realized by rotating {B} around the axis of {A}.

Note that ${}^A_B R = ({}^B_A R)^{-1}$.

A.2.3 Homogenous matrix

A homogenous matrix may be constructed by combining [Formulae \(A.2\)](#) and [\(A.3\)](#) and then be marked as ${}^A_B T$; it also describes the position and orientation of {B} relative to {A} according to [Formula \(A.4\)](#).

$${}^A_B T = \left[\begin{array}{ccc|c} {}^A_B R & & & {}^A P_{BORG} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \tag{A.4}$$

Note that

$${}^A_B T = ({}^B_A T)^{-1} \tag{A.5}$$

As shown in [Figure A.2](#), mathematically, a spatial point **P** may be expressed as a position vector in a coordinate system.

If there are more than two coordinate systems, the position of point **P** may be expressed as different position vectors in different coordinate systems.

Homogenous matrices may be used to transfer a position vector from one coordinate system to another as given by [Formulae \(A.6\)](#) to [\(A.8\)](#).

$${}^B P = {}^B_C T {}^C P \tag{A.6}$$

$${}^A P = {}^A_B T {}^B P \tag{A.7}$$

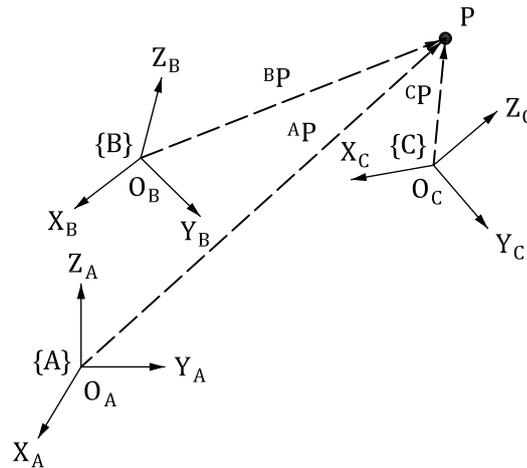
$${}^A P = {}^A_B T {}^B_C T {}^C P = {}^A_C T {}^C P \tag{A.8}$$

So, [Formula \(A.9\)](#) results.

$$\begin{aligned} {}^A_C T &= {}^A_B T {}^B_C T = \left[\begin{array}{ccc|c} {}^A_B R & & & {}^A P_{BORG} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \left[\begin{array}{ccc|c} {}^B_C R & & & {}^B P_{CORG} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \\ &= \left[\begin{array}{ccc|c} {}^A_B R {}^B_C R & & & {}^A_B R {}^B P_{CORG} + {}^A P_{BORG} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \end{aligned} \tag{A.9}$$

$$\begin{aligned} &= \left[\begin{array}{ccc|c} {}^A_C R & & & {}^A P_{CORG} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \\ {}^A_C R &= {}^A_B R {}^B_C R \end{aligned} \tag{A.10}$$

[Formula \(A.10\)](#) means that the homogenous orientation matrix of a new coordinate system can be compound by homogenous orientation matrices of other coordinate systems, so as the rotation matrix.

**Key**

{A}	coordinate system {A}	Z_B	Z axis of coordinate system {B}
O_A	origin of coordinate system {A}	O_C	origin of coordinate system {C}
X_A	X axis of coordinate system {A}	X_C	X axis of coordinate system {C}
Y_A	Y axis of coordinate system {A}	Y_C	Y axis of coordinate system {C}
Z_A	Z axis of coordinate system {A}	Z_C	Z axis of coordinate system {C}
{B}	coordinate system {B}	P	spatial point
O_B	origin of coordinate system {B}	AP	position vector of point P in a coordinate system {A}
X_B	X axis of coordinate system {B}	BP	position vector of point P in a coordinate system {B}
Y_B	Y axis of coordinate system {B}	CP	position vector of point P in a coordinate system {C}

Figure A.2 — Compound coordinate system

Among the ${}^A_B R$ of a homogenous matrix ${}^A_B T$, vectors ${}^A x_B, {}^A y_B, {}^A z_B$ are mutually perpendicular to each other and the length of ${}^A x_B, {}^A y_B, {}^A z_B$ equals 1, since there are only three independent degrees of freedom (DOF) in ${}^A_B R$, which may be expressed by three continues rotations around the axes x, y and z.

The rotation sequences and relative coordinate systems may be different for different robots.

For example, the rotation sequence may be x-y-z or z-y-x, or x-z-y, the only constraint is that the two adjacent axes are not the same.

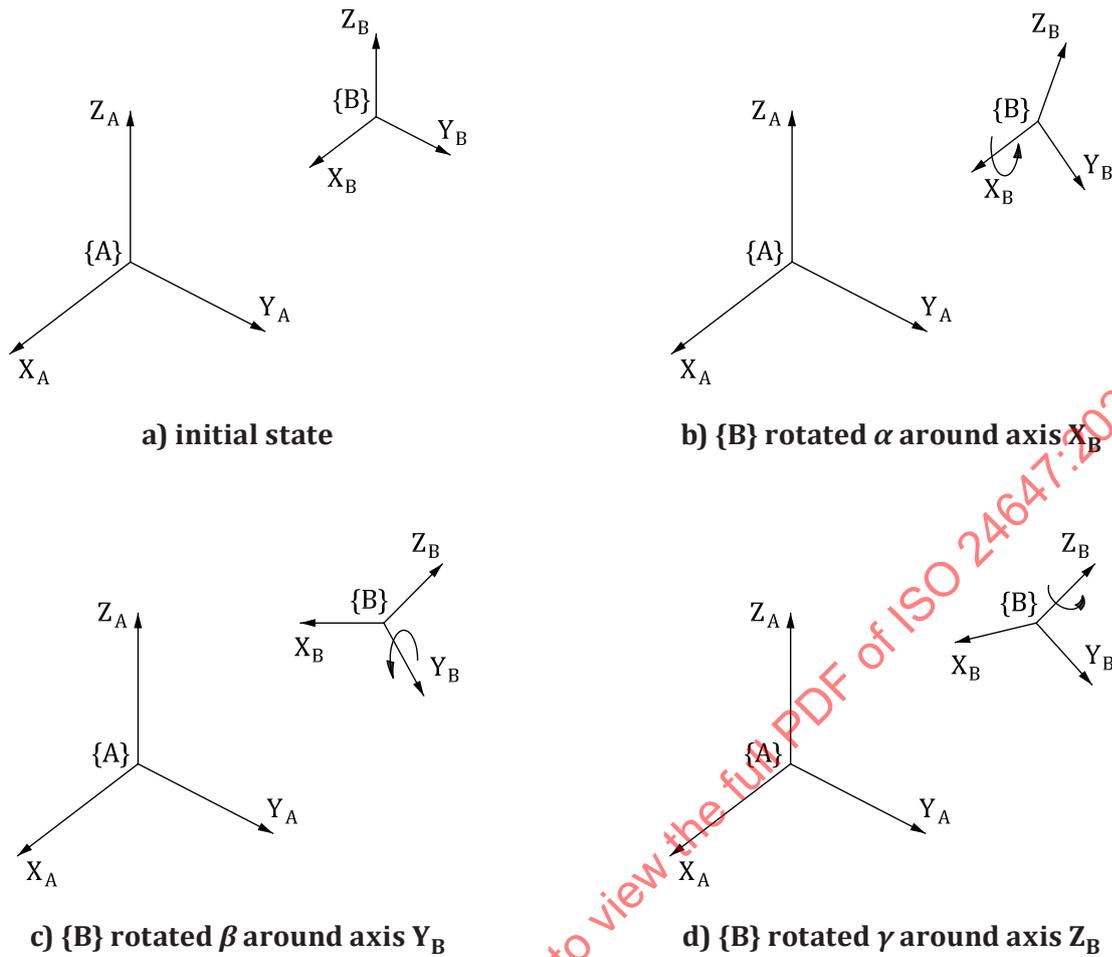
The rotation axis can be either the axis of a fixed coordinate system or the axis of a moving coordinate system.

As for the robot kinematics, usually the axes of the moving coordinate system are selected as rotation axes and these rotation angles are called Euler angles.

That means a coordinate system may be expressed by six independent variables ($p_x, p_y, p_z, \alpha, \beta, \gamma$) or by an equivalent homogenous matrix.

For example, take a robot whose rotation sequence is x-y-z relative to the moving coordinate system (tool coordinate system), assume that {B} is the tool coordinate system and {A} is the base coordinate system of this robot.

In initial state, {A} and {B} have the same orientation the rotation process is shown in [Figure A.3](#).



Key

{A}	coordinate system {A}	{B}	coordinate system {B}
X _A	X axis of coordinate system {A}	X _B	X axis of coordinate system {B}
Y _A	Y axis of coordinate system {A}	Y _B	Y axis of coordinate system {B}
Z _A	Z axis of coordinate system {A}	Z _B	Z axis of coordinate system {B}

Figure A.3 — Euler rotations with sequence x-y-z

According to the coordinate system compound rule, orientation of {B} relative to {A} after three successive rotations can be expressed according to [Formula \(A.11\)](#):

$$\begin{aligned}
 {}^A_B \mathbf{R} &= \text{Rot}(x, \alpha) \text{Rot}(y, \beta) \text{Rot}(z, \gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta \\ s\alpha s\beta c\gamma + c\alpha s\gamma & -s\alpha s\beta s\gamma + c\alpha c\gamma & -s\alpha c\beta \\ -c\alpha s\beta c\gamma + s\alpha s\gamma & c\alpha s\beta s\gamma + s\alpha c\gamma & c\alpha c\beta \end{bmatrix} \tag{A.11}
 \end{aligned}$$

Where $\cos \alpha$ and $\sin \alpha$ can be abbreviated as $c\alpha$ and $s\alpha$ respectively for observation.

If $(x, y, z, \alpha, \beta, \gamma)$ is known, ${}^A_B T$ can be obtained by [Formulae \(A.2\), \(A.4\) and \(A.11\)](#); If ${}^A_B T$ is known, $(x, y, z, \alpha, \beta, \gamma)$ may also be obtained by [Formulae \(A.2\), \(A.3\), \(A.4\) and \(A.13\), \(A.14\), \(A.15\)](#).

$${}^A_B \mathbf{R} = \begin{bmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta \\ s\alpha s\beta c\gamma + c\alpha s\gamma & -s\alpha s\beta s\gamma + c\alpha c\gamma & -s\alpha c\beta \\ -c\alpha s\beta c\gamma + s\alpha s\gamma & c\alpha s\beta s\gamma + s\alpha c\gamma & c\alpha c\beta \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \quad (\text{A.12})$$

So,

$$\beta = a \tan 2(r_{13}, \sqrt{r_{11}^2 + r_{12}^2}) \quad (\text{A.13})$$

$$\alpha = a \tan 2(-r_{23}/\cos \beta, r_{33}/\cos \beta) \quad (\text{A.14})$$

$$\gamma = a \tan 2(-r_{12}/\cos \beta, r_{11}/\cos \beta) \quad (\text{A.15})$$

[A.3](#) and [A.4](#) show how to calculate the tool coordinate system ${}^W_M T$ depending on different scan modes.

After ${}^W_M T$ is obtained, the position vectors of the tool coordinate system and Euler angles corresponding to all scan points of the scan path shall be solved.

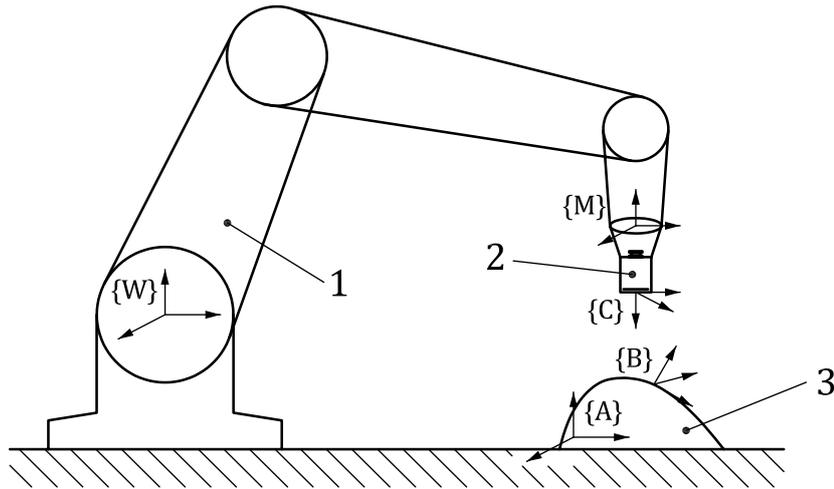
A.3 Calculation of the homogenous matrix of the tool coordinate system when the robot holds the probe and the test object is fixed

According to [Figure A.4](#), the reference coordinate system of the robot is marked as {W}, the tool coordinate system is marked as {M}, the coordinate system attached with the ultrasonic probe is expressed as {C}.

The coordinate system attached with test object is marked as {A}.

An auxiliary coordinate system {B} is built on a point of the scanning path.

The position and orientation of {B} relative to {A} is confirmed by CAM software.



Key

- | | | | |
|-----|-----------------------------------|-----|---|
| 1 | robot | {M} | tool coordinate system |
| 2 | probe | {C} | probe coordinate system |
| 3 | test object | {A} | coordinate system attached with test object |
| {W} | robot reference coordinate system | {B} | auxiliary coordinate system |

Figure A.4 — Calculation of the tool coordinate system when the robot holds the ultrasonic probe

According to the coordinate system compound principle, the homogenous matrix of coordinate system {M} relative to coordinate system {W} can be expressed by [Formula \(A.16\)](#):

$${}^W_M\mathbf{T} = {}^W_A\mathbf{T} \begin{matrix} A \\ B \end{matrix} \mathbf{T} \begin{matrix} B \\ C \end{matrix} \mathbf{T} \begin{matrix} C \\ M \end{matrix} \mathbf{T} \tag{A.16}$$

where

${}^W_A\mathbf{T}$ is determined by test object fixture;

${}^W_M\mathbf{T}$ expresses the position and orientation of the tool coordinate system {M};

${}^C_M\mathbf{T}$ is determined by probe fixture;

${}^B_C\mathbf{T}$ is constrained by ultrasonic testing requirements;

${}^A_B\mathbf{T}$ is acquired from scan path planning software.

In order to calculate ${}^W_M\mathbf{T}$, ${}^W_A\mathbf{T}$ and ${}^C_M\mathbf{T}$, the terms ${}^B_C\mathbf{T}$ and ${}^A_B\mathbf{T}$ shall be prepared before.

After the test system is set up and ultrasonic testing requirements are given, ${}^W_A\mathbf{T}$, ${}^C_M\mathbf{T}$ and ${}^B_C\mathbf{T}$ can be determined.

A method to calculate ${}^A_B\mathbf{T}$ is given in [A.5](#).

A.4 Calculation of the homogenous matrix of the tool coordinate system when the robot holds the test object and the probe is fixed

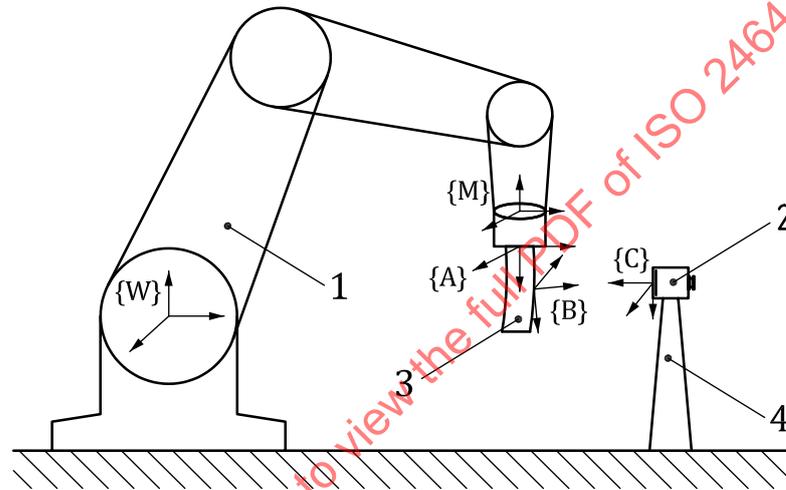
The CAM software shall be used to collect position coordinates and the normal vector of scanning points on the tested object under a Cartesian coordinate system based on a CAD mathematical model of the test block.

According to [Figure A.5](#), the reference coordinate system of the robot is marked as {W}, tool coordinate system is marked as {M}, the coordinate system attached with the ultrasonic probe is expressed as {C}.

The coordinate system attached with the test object is marked as {A}.

An auxiliary coordinate system {B} is built on a point of the scanning path.

The position and orientation of {B} relative to {A} is confirmed by the CAM software.



Key

1	robot	{W}	robot reference coordinate system
2	probe	{M}	tool coordinate system
3	test object	{C}	probe coordinate system
4	probe support	{A}	coordinate system attached with test object
		{B}	auxiliary coordinate system

Figure A.5 — Tool coordinate system when the robot holds the test object

According to the coordinate system compound principle, the homogenous matrix of coordinate system {M} relative to coordinate system {W} may be expressed by [Formula \(A.17\)](#):

$${}^W_M\mathbf{T} = {}^W_C\mathbf{T} \begin{matrix} C \\ B \end{matrix} \mathbf{T} \begin{matrix} B \\ A \end{matrix} \mathbf{T} \begin{matrix} A \\ M \end{matrix} \mathbf{T} \quad (\text{A.17})$$

where

${}^W_M\mathbf{T}$ expresses the position and orientation of the tool coordinate system {M};

${}^W_C\mathbf{T}$ is determined by probe fixture;

${}^C_B\mathbf{T}$ is constrained by ultrasonic testing requirements;

${}^B_A\mathbf{T}$ is acquired from scan path planning software;