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Road vehicles — Multidimensional measurement and coordinate systems definition

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Foreword

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This document was prepared by Technical Committee ISO/TC 22, *Road Vehicles*, Subcommittee SC 36, *Safety aspects and impact testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides a unified method to handle and process various types of multidimensional displacement sensors for use in crash dummies and automotive crash testing. The content covers existing sensors and dummies, but the document also offers a generic method to handle future new dummies and/or sensors.

Multidimensional measurement systems are used in crash dummies (ATD, or anthropomorphic test device) to monitor the position of dummy features (e.g. ribs, abdomen, etc.) for injury assessment. The dummy feature position is typically expressed in an orthogonal coordinate system which is fixed to the thoracic spine of the dummy, see Annex A. The systems covered in this document are an assembly of one distance sensor and one or two angle sensors, the axes of which are organised in a (rotating) spherical coordinate system, see Figure C.1. Other 2- and 3-dimensional position measurement systems are outside the scope of this document. Although in this document a suit of ATD's and their features are discussed to explain the methodology, its scope is not limited to these examples and can be applied to any other ATD and its features.

Road vehicles — Multidimensional measurement and coordinate systems definition

1 Scope

This document defines the measurement coordinate systems and presents the protocol to determine the sensor offsets to the chosen coordinate system. Finally, the method is presented how to process the sensor spherical coordinate system data to calculate the position of a dummy feature in three-dimensional space in the defined local orthogonal coordinate system.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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
multidimensional measurement system
system that measures spatial position of a crash dummy feature (e.g. rib, abdomen, etc.) with respect to a defined reference feature (e.g. dummy spine) and its local coordinate system origin.

Note 1 to entry: Examples of multidimensional sensors and applications are given in the NOTES of Figure 1, Figure 2 and Figure 3.

3.2
radius
distance between the centre of rotation at spine interface and centre of rotation at feature interface (e.g. dummy rib).

Note 1 to entry: The parameter radius (*R*) is associated with the ISO MME Code DC for Distance, ISO/TS 13499[2].

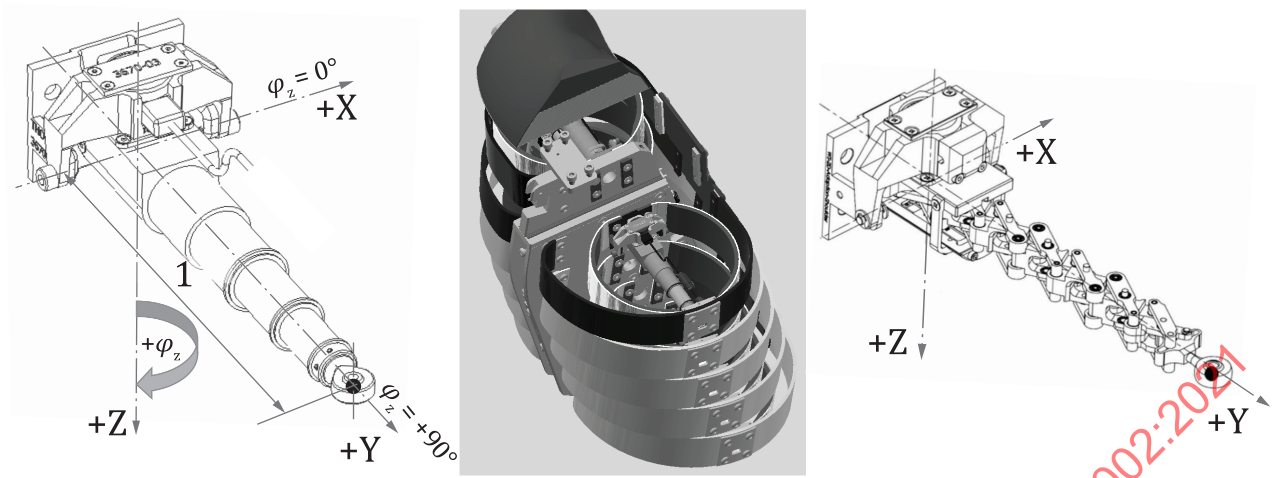
3.3
sensor Y-angle
angle of the multidimensional sensor along Y-axis with respect to local orthogonal coordinate system

Note 1 to entry: The positive rotation direction is defined following SAE sign convention right hand rule.

3.4
sensor Z-angle
angle of the multidimensional sensor along Z-axis with respect to local orthogonal coordinate system

Note 1 to entry: The positive rotation direction is defined following SAE sign convention right hand rule.

Note 2 to entry: Examples of the angle definitions are given in the NOTES of Figure 1, Figure 2 and Figure 3.

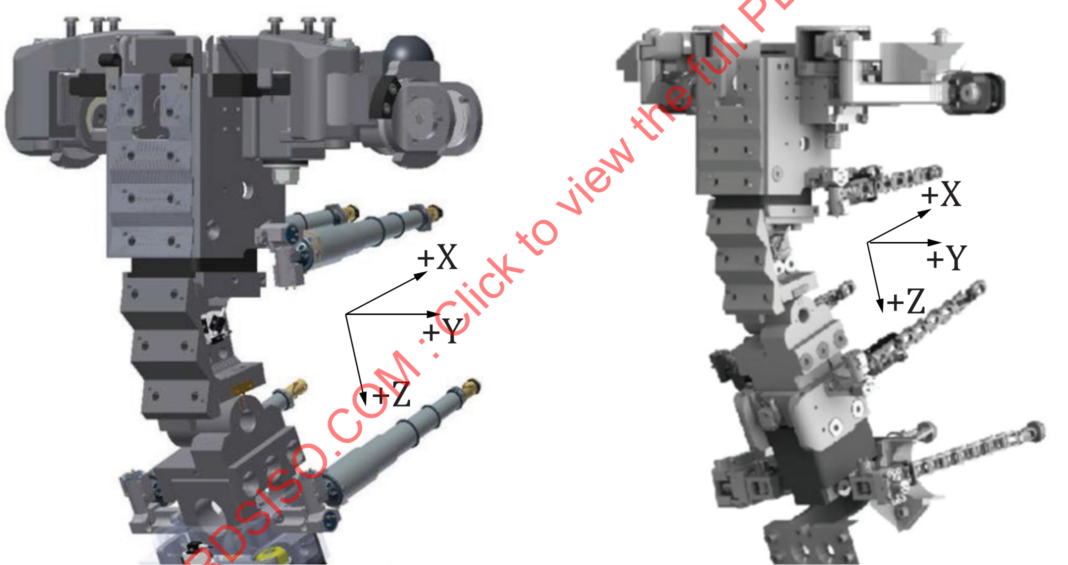


Key

1 radius, R_i

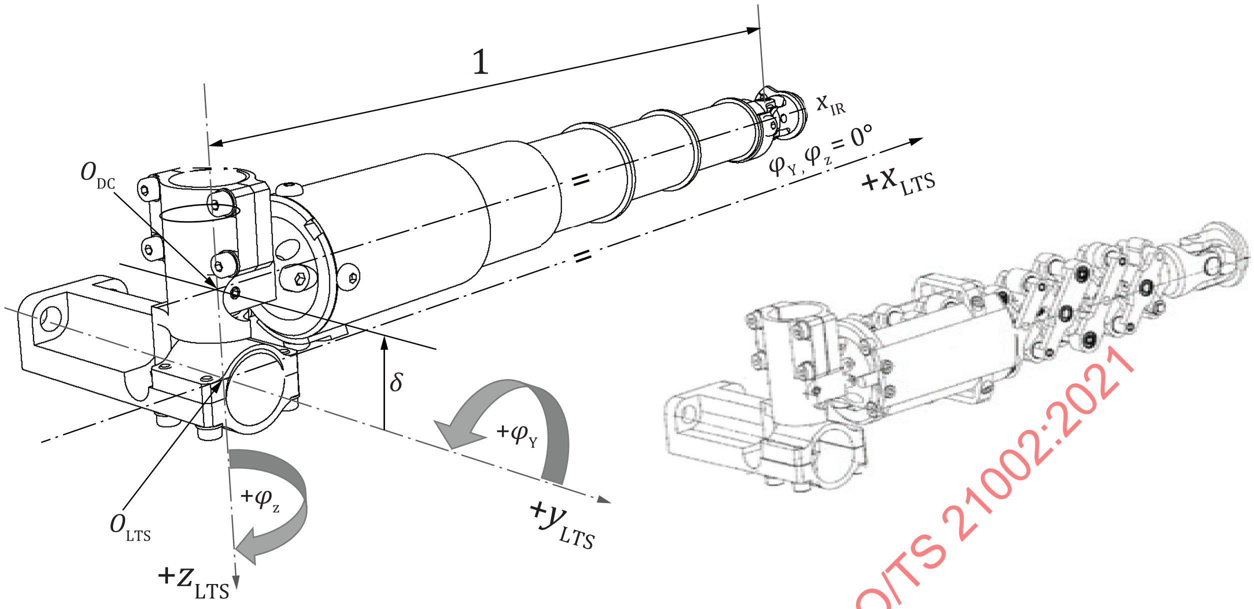
NOTE Two examples for WorldSID application are shown: left image 2D IR-TRACC, right image S-Track.

Figure 1 — Two-dimensional sensor mounted in right-hand side WorldSID 50M dummy



NOTE Two examples for THOR application are show: left image IR-TRACC, right image S-Track.

Figure 2 — Three-dimensional sensors mounted in THOR 50M right-hand view and global coordinate system.



Key

1 radius, R_i

NOTE Two informative examples for THOR application are shown: left image 3D IR-TRACC, right image 3D S-Track).

Figure 3 — Three-dimensional sensors for THOR lower right-hand thorax and their local orthogonal coordinate system

3.5
zero-position
condition of multidimensional sensor when mounted by the spine interface and the distance sensor is aligned with (parallel to) the local orthogonal coordinate system axes and the feature interface is fixed at an accurately defined distance from the coordinate system origin

Note 1 to entry: By definition the angles of the multidimensional position sensor are zero.

3.6
zero-position fixture
tool to set up a multidimensional position sensor in its *zero-position* (3.5)

Note 1 to entry: A zero-position fixture has accurately machined reproducible mountings to simulate the dummy spine and the feature mountings. These sensor mountings of the fixture are accurately positioned in (2D- and 3D) space such that the sensor is in its zero-position condition, called position 0 (position zero). The fixture has additional mounting positions for the feature interface, which are translated from zero position over a defined distance in a direction perpendicular to the distance sensor axis and parallel to at least one of the local orthogonal coordinate system axes.

Note 2 to entry: The fixture is considered adequately accurate if the overall dimensional tolerance stack ups of the sensor mountings are within ±0,3mm in all directions.

Note 3 to entry: Examples of 2D and 3D zero-position fixtures are given in Annex B.

Note 4 to entry: The zero-position fixtures are used in subsequent steps of the zero-position verification procedure:

a) to find the offset of the sensors with respect to the local orthogonal coordinate system;

b) to remove offsets (by adjustment or compensation in a data acquisition system);

c) to check if sensor offsets are removed with a live data acquisition system;

d) to check sensor polarities with respect to global orthogonal coordinate system;

e) to check if calculations for coordinate system transformation are reproducing the design positions of the fixture in 2D or 3D space. See paragraph 7 and Annex B.

3.7
offset angle
output in degrees of the angle sensor(s) when the multidimensional position sensor is in its *zero-position* (3.5) condition

Note 1 to entry: If the angle sensor has a positive offset according to the local orthogonal coordinate system, the offset angle is defined positive.

3.8
orientation angle
correction angle for multidimensional sensors that can be mounted in sensor orientation for left hand and right-hand side impact operation, as well as for frontal impact operation

Note 1 to entry: Typically the two-dimensional sensors can be mounted in various orientations inside the dummy. In side impact dummies the sensors can be set up for left hand and right-hand impact (even simultaneously), and the Q10 child dummies can be set up for both frontal and lateral impacts.

Note 2 to entry: The two-dimensional sensors can be oriented inside the dummy with a rotated coordinate system about the Z-axis. The orientation angle can be implemented in Data Acquisition Systems Z-angle data channels as a fixed offset to correct for a rotated coordinate system, see Table 1.

Table 1 — Orientation angle definition per orientation in the dummy

	Sensor orientation for impact operation		
	Left Lateral	Frontal	Right Lateral
Orientation angle	-90°	0°	+90°

3.9
reference angle
orientation angle minus the *offset angle* (3.7)

Note 1 to entry: Calculate the reference angle with Formula (1).

$$\varphi_{\mathrm{REF}} = \varphi_{\mathrm{ORIENT}} - \varphi_{\mathrm{OSZ}} \tag{1}$$

Note 2 to entry: The reference angle can be used with data acquisition systems that can handle only one fixed offset parameter, see example in Figure 4.

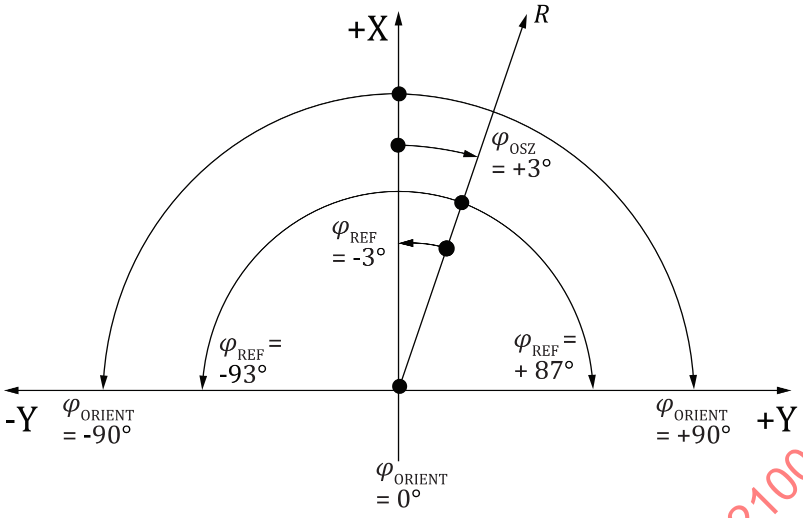


Figure 4 — Angle sensor parameter examples seen from top of dummy (looking over dummy shoulder)

Table 2 — Examples for φ_{REF} and φ_{ORIENT} when offset angle is +3°, for left side, frontal and right-side impact dummy set up, see Figure 4

	Left lateral impact	Frontal impact	Right lateral impact
φ_{ORIENT}	-90	0	+90
φ_{OSZ}	+3	+3	+3
φ_{REF}	-93	-3	+87

3.10
angle sensor polarity
direction of rotation of the sensor shaft with reference to its fixed body in relation to its electrical (digital) signal output and sensor body and shaft orientation to the relevant coordinate system

Note 1 to entry: The polarity is defined positive when the far end of the shaft points in the positive orthogonal direction and the shaft (or internal wiper) is rotated in the positive rotation direction according to the relevant coordinate system, see example Figure 5.

Note 2 to entry: The value of the polarity can only be +1 or -1.

Note 3 to entry: Depending of the sensor assembly orientation in the dummy some sensors need to change the polarity sign to get a positive output in accordance with the relevant coordinate system.

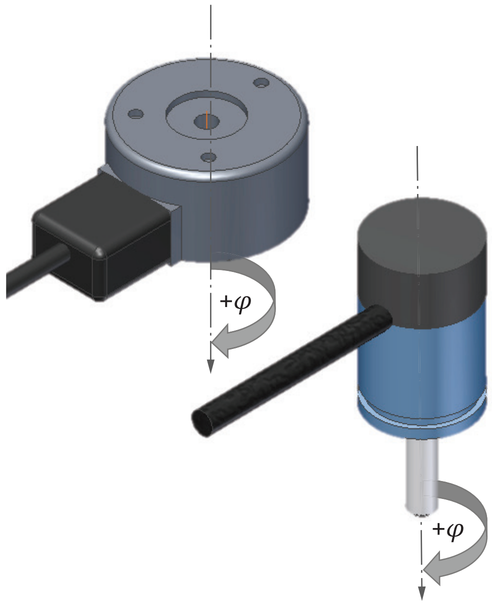


Figure 5 — Positive polarity for angle sensors

4 Symbols

Table 3 — List of symbols

Parameter	Symbol	Unit	Definition/description	Application
X-axis	x	-	Global orthogonal coordinate system X-axis	
Y-axis	y	-	Global orthogonal coordinate system Y-axis	
Z-axis	z	-	Global orthogonal coordinate system Z-axis	
Origin of local orthogonal coordinate systems	O_{UTS} O_{LTS} O_{LS} O_{DC}	-	Origin upper thoracic spine Origin lower thoracic spine Origin lumbar spine Origin distance sensor	
	x_{UTS}	-	Local X-axis upper thoracic spine	3D-THOR
	y_{UTS}	-	Local Y-axis upper thoracic spine	3D-THOR
	z_{UTS}	-	Local Z-axis upper thoracic spine	3D-THOR
	x_{DC}	-	Distance sensor axis	3D-THOR
	y_{DC}		Position sensor Y-pivot axis	3D-THOR
	z_{DC}	-	Position sensor Z-pivot axis	3D-THOR
	x_{LTS}	-	Local X-axis lower thoracic spine	3D-THOR
	y_{LTS}	-	Local Y-axis lower thoracic spine	3D-THOR
	z_{LTS}	-	Local Z-axis lower thoracic spine	3D-THOR
	x_{LS}	-	Local X-axis lumbar spine	3D-THOR
	y_{LS}	-	Local Y-axis lumbar spine	3D-THOR
	z_{LS}	-	Local Z-axis lumbar spine	3D-THOR

Table 3 *(continued)*

Parameter	Symbol	Unit	Definition/description	Application
Distance Distance position 0 Distance position 1 Distance position 2	D D_{ZERO} D_{P1} D_{P2}	mm	Design distance on zero-position fixture from 2D sensor origin to rib interface centre in position-0, position-1, position-2	2D
Distance positions ZERO-L, ZERO-R, PZL, PZR, PYL, PYR PYZL, PYZR	 D_{ZERO} D_{PZ} D_{PY} D_{PYZ}	mm	Design distance on zero-position fixture from origin O_{UTS}, O_{LTS}, or O_{LS} to rib interface centre in position ZERO, position PZ (L and R), position PY (L and R), position PYZ (L and R)	3D
Z-angle Angle position 0 Angle position 1 Angle position 2	Θ_Z $\Theta_{Z\ ZERO}$ Θ_{Z1} Θ_{Z2}	degrees	Design Z-angles on zero-position fixture 2D sensor origin to rib interface centre in zero-position, position-1, position-2	2D
Y-angle positions ZERO-L, ZERO-R, PZL PZR, PYL, PYR PYZL, PYZR	Θ_Y $\Theta_{Y\ ZERO}$ $\Theta_{Y\ PZ}$ $\Theta_{Y\ PY}$ $\Theta_{Y\ PYZ}$	degrees	Design Y-angles on zero-position fixture origin O_{UTS}, O_{LTS}, or O_{LS} to rib interface centre in position ZERO, position PZ (L and R) , position PY (L and R), position PYZ (L and R)	3D
Z-angle positions ZERO-L, ZERO-R, PZL PZR, PYL, PYR PYZL, PYZR	Θ_Z $\Theta_{Z\ ZERO}$ $\Theta_{Z\ PZ}$ $\Theta_{Z\ PY}$ $\Theta_{Z\ PYZ}$	degrees	Design Z-angles on zero-position fixture origin O_{UTS}, O_{LTS}, or O_{LS} to rib interface centre in position ZERO, position +Z, position +Y, position PYZ (L and R)	3D
Calibration range	d_E	mm	Distance between starting and end point of displacement calibration	
Distance sensor output	U_{DC}	V, LSB	Distance sensor output	
Tubes-IN output	$U_{DC\ IN}$	V, LSB	Output at certain displacement with all floating tubes pushed IN	IR-TRACC only
Tubes-OUT output	$U_{DC\ OUT}$	V, LSB	Output at certain displacement with all floating tubes pushed OUT	IR-TRACC only
Linearization exponent	*EXP*	[-]	Optimized linearization exponent	IR-TRACC only
Linearized voltage	U_{LIN}	V_{LIN} LSB_{LIN}	IR-TRACC output to power of exponent; calculated parameter	IR-TRACC only
Distance sensor calibration factor	C_{DC}	mm/V and mm/LSB mm/ V_{LIN} mm/LSB_{LIN}	linear sensor mm displacement per output IR-TRACC mm displacement per linearized output	Ratiometric sensor IR-TRACC
Distance sensor sensitivity	S_{DC}	V/mm and LSB/mm V_{LIN} /mm and LSB_{LIN} /mm	linear sensor output per mm displacement IR-TRACC linearized output per mm displacement	Ratiometric sensor IR-TRACC
Angle sensor calibration factor	C_{ANY} C_{ANZ}	degrees/V/V degrees/LSB	Angle sensor degrees rotation at 1V output per 1V excitation or degree rotation per digital output	

Table 3 *(continued)*

Parameter	Symbol	Unit	Definition/description	Application
Angle sensor sensitivity	S_{ANY} S_{ANZ}	V/V/degrees LSB/degrees	Angle sensor output per degree rotation at 1V excitation or digital output per degree	
Angle sensor polarity	P	[-]	The value can be either +1 or -1	2D-3D
Distance sensor Pos0 output	U_{DC0}	V, LSB	Distance sensor average output at zero position on Zeroing Fixture	2D-3D
Distance sensor Pos0 output tubes-IN	$U_{DC0\ IN}$	V, LSB	Distance sensor output at zero position tubes IN	IR-TRACC
Distance sensor Pos0 output tubes-OUT	$U_{DC0\ OUT}$	V, LSB	Distance sensor output at zero position tubes OUT	IR-TRACC
Distance sensor Pos1 output	U_{DC1}	V, LSB	Distance sensor output at position 1	2D
Distance Sensor Pos2 output	U_{DC2}	V, LSB	Distance sensor output at position 2	2D
Distance sensor output position PY	$U_{DC\ PY}$	V, LSB	Distance sensor output at position PY	3D
Distance sensor output position PZ	$U_{DC\ PZ}$	V, LSB	Distance sensor output at position PZ	3D
Distance sensor output position PYZ	$U_{DC\ PYZ}$	V, LSB	Distance sensor output at position PYZ	3D
Radius	R R_0 R_i	mm	Distance from O_{DC} to rib interface rotation centre, see Figure 3. Distance sensor output in mm at t_0, at t_i.	2D 3D
Radius Pos0	R_{IO}	mm	Radius at zero position on zeroing fixture calculated using average IN-OUT output	2D-3D
Radius Pos0 tubes-IN	R_{IN}	mm	Radius at zero position calculated using tubes IN output	IR-TRACC
Radius Pos0 tubes-OUT	R_{OUT}	mm	Radius at zero position calculated using tubes OUT output	IR-TRACC
Radius Pos0	R_{ZERO}	mm	Radius at zero-position	2D-3D
Radius Pos1	R_1		Radius at position-1	2D
Radius Pos2	R_2		Radius at position-2	2D
Radius PY	R_{PY}		Radius at position PY	3D
Radius PZ	R_{PZ}		Radius at position PZ	3D
Radius PYZ	R_{PYZ}		Radius at position PYZ	3D
Excitation	U_{EX}	V	Excitation voltage angle sensor during zero-position verification	
Y-angle sensor output	U_{ANY}	V, LSB	Y-axis angle sensor voltage	3D
Z-angle sensor output	U_{ANZ}	V, LSB	Z-axis angle sensor voltage	
Z-Angle output 0 (ZERO)	U_{ANZ0}	V, LSB	Z-Angle sensor average output at position-0 (ZERO)	2D & 3D
Z-Angle output 0-Near	$U_{ANZ\ NEAR}$	V, LSB	Z-Angle sensor output at position-0 pull Near (3D away from spine)	2D & 3D
Z-Angle output 0-Far	$U_{ANZ\ FAR}$	V, LSB	Z-Angle sensor output at position-0 pull Far (3D towards spine)	2D & 3D

Table 3 *(continued)*

Parameter	Symbol	Unit	Definition/description	Application
Z-Angle output 1	U_{ANZ1}	V, LSB	Z-axis angle sensor output at position-1	2D
Z-Angle output 2	U_{ANZ2}	V, LSB	Z-axis angle sensor output at position-2	2D
Z-Angle output PZR	$U_{ANZ\ PZ}$	V, LSB	Z-Angle sensor output at position PZ	3D
Y-Angle output zero	U_{ANY0}	V, LSB	Y- Angle sensor average output at position-zero	3D
Y-Angle output zero-Down	$U_{ANY\ DOWN}$	V, LSB	Y- Angle sensor output at position-zero pull Down	3D
Y-Angle output zero-Up	$U_{ANY\ UP}$	V, LSB	Y- Angle sensor output at position-0 pull Up	3D
Y-Angle output PY	$U_{ANY\ PY}$	V, LSB	Y-Angle sensor output at position PY	3D
Y-Offset Angle	φ_{OSY}	degrees	Y-angle sensor average offset between extremes (Up-Down) when at fixture zero-position	
Z-Offset Angle	φ_{OSZ}	degrees	Z-angle sensor average offset between extremes (Near-Far) when at fixture zero-position	
Sensor Y-angle	φ_Y φ_{Y0} φ_{Yi}	degrees	Distance sensor angle along y-axis with respect to local orthogonal coordinate system, see Figure 3, and at t_0 and at t_i.	
Sensor Z-angle	φ_Z φ_{Z0} φ_{Zi}	degrees	Distance sensor angle along z-axis with respect to local orthogonal coordinate system, see Figure 3, and, at t_0 and at t_i.	
Distance intercept	I_{DC}	mm	Distance sensor offset in mm from coordinate system origin.	
Distance intercept voltage	I_{DCV}	V, V_{LIN} LSB_{LIN}	Calculated (linearized) output at 0mm radius	
Axis offset	δ	mm	Mechanical offset distance between O_{DC} distance sensor origin and coordinate system origin, see Figure 3.	3D thoracic
Orientation angle	φ_{ORIENT}	degrees	Orientation angle of 2D position sensor assembled inside dummy. For definition see also Figure 4 and Table 1.	2D
Reference angle	φ_{REF}	degrees	Orientation angle minus offset angle. For definition see also Figure 4 and Table 1.	2D
Time	t t_0 t_i	s	time time zero, start of the test time i	
x coordinate	x, x_0, x_i	mm	Feature interface rotation centre x-coordinate, x at t_0, x at t_i, see NOTES of Figure 1, Figure 2 and Figure 3.	
y coordinate	y, y_0, y_i	mm	Feature interface rotation centre y-coordinate, y at t_0, y at t_i , see NOTES of Figure 1, Figure 2 and Figure 3.	
z coordinate	z, z_0, z_i	mm	Feature interface rotation centre z-coordinate, z at t_0, z at t_i , see NOTES of Figure 1, Figure 2 and Figure 3.	

Table 3 *(continued)*

Parameter	Symbol	Unit	Definition/description	Application
x deflection	Dx_i	mm	Feature deflection in *x* direction at t_i	
y deflection	Dy_i	mm	Feature deflection in *y* direction at t_i	
z deflection	Dz_i	mm	Feature deflection in *z* direction at t_i	
Resultant deflection	D_i	mm	Resultant deflection of the feature interface centre at t_i	

5 Sensor calibration

Individual angle and displacement or distance sensors are calibrated according to accepted standards before conducting the zero-position verification procedure. (Recommended: calibrate non-linear Infrared distance sensor IR-TRACC[3] according to ISO/TS 21476[4] and calibrate ratio metric distance sensor according to ISO/TS 23521[5]).

6 Procedures zero-position verification

6.1 General

This clause describes procedures to obtain reproducible data from multidimensional position sensors on zero-position fixtures. Example sensors and fixtures are used in the procedures to describe the method, but the procedures should also be applicable to other sensors and fixtures. The sequences for 2D and 3D zero-position verification are generally following the same principle.

6.2 Verification acceptance limits

The acceptance limits of the zero-position verification procedure are based on an uncertainty analysis conducted according to procedures outlined in JCGM_100_2008[6] applying four components of variation. The components identified are

a) variation introduced by the operator (assembly of the sensor on the fixture, system play in the mountings),

b) imperfection of the sensor, like system play, friction and non-linearity,

c) voltage measurement uncertainty, and

d) manufacturing tolerances of fixtures.

To quantify the operator component of variation a round robin was conducted in 2018-2019, involving one 2D sensor and fixture and one 3D sensor and fixture. The round robin included eleven qualified test labs on three continents. The other three components of uncertainty, b), c), and d), were accounted for in the uncertainty analysis based on the specifications of the equipment used. The total uncertainty was calculated from the square root of the sum of squares of standard deviation, σ, of the four components, and a multiplier of three was applied to define acceptance limits ($3\sigma \equiv 99{,}7$ % confidence limits). The verification acceptance limits are defined based on these studies as follows:

— For angles: ±3 % of mechanical range of ±45°: ±1,35°. (Example max error: with distance sensor at 140mm radius, 1,35° corresponds to 1,35π/180 × 140 = 3,3mm).

— For distance: ±3 % of calibration range of distance sensor. (Example max error: calibration range 80mm, 3 % corresponds to 2,4mm).

6.3 Zero-position data collection

Zero-position verification data collection sequences are given in Table 4 for 2D sensors and Table 5 for 3D sensors. The sensors are connected to measurement systems according adequate and accepted laboratory practise standards to measure the sensor outputs.

The zero-position verification procedure are conducted in a temperature controlled environment between 20 °C to 25 °C.

A 120 s warm up time after powering the sensors is observed before data collection starts.

The sensor assembly are setup on the zero position fixture in its zero position. Measurements and calculations are conducted according to the sequences given in Table 4 and Table 5 and formulae given in 6.4. Measurements taken under conditions of controlled lateral loading to find the extreme sensor offsets are conducted with a ballast 0,44 kg to 0,47kg; finally the rib interface are manipulated in multiple positions to verify the sensor polarities and pass criteria are applied for the expected sensor outputs in these positions. See also Annex B for example fixtures and data collection examples.

Table 4 — 2D zero-position verification sequence; formulae can be found in 6.4

Rib interface position	Tubes	Ballast	Distance V or LSB	Z-angle V or LSB	Design parameter mm or deg	Actual mm or deg	Pass-fail
0	In	No	Collect $U_{DC0\ IN}$	-	-	-	-
0	Out	No	Collect $U_{DC0\ OUT}$	-	-	-	-
0	Random	Near	-	Collect data $U_{ANZ\ NEAR}$	-	-	-
0	Random	Far	-	Collect data $U_{ANZ\ FAR}$	-	-	-
0	-	-	Calculate U_{DC0} Formula 2	Calculate U_{ANZ0} Formula 5	-	-	-
0	-	-	Calculate I_{DC} Formula 3	Calculate φ_{OSZ} Formula 7	-	-	-
1	Random	No	Collect data U_{DC1}	-	D_{P1}	Calculate R Formula 8	Formula 12
1	Random	No	-	Collect data U_{ANZ1}	Θ_{Z1}	Calculate φ_Z Formula 9	Formula 13
2	Random	No	Collect data U_{DC2}	-	D_{P2}	Calculate R Formula 8	Formula 12
2	Random	No	-	Collect data U_{ANZ2}	Θ_{Z2}	Calculate φ_Z Formula 9	Formula 13

Table 5 — 3D zero-position verification sequence; formulae can be found in 6.4

Fixture face up	Figure	Rib interface position	Tubes	Ballast	Distance V or LSB	Y-angle V or LSB	Z-angle V or LSB	Design parameter[a] mm or deg	Actual mm or deg	Pass-fail
A or C[a]	a.	Zero-L[a] or Zero-R	In	No	Collect $U_{DC0\text{-}IN}$	-	-	-	-	-
A or C[a]	b.	Zero-L or Zero-R[a]	Out	No	Collect $U_{DC0\text{-}OUT}$	—	—	—	—	—
A or C[a]	c.	Zero-L or Zero-R[a]	Out	Yes	—	Collect $U_{ANY\text{-}DOWN}$	—	—	—	—
C or A[a]	d.	Zero-L or Zero-R[a]	Out	Yes	—	Collect $U_{ANY\text{-}UP}$	—	—	—	—
B	e.	Zero-L or Zero-R[a]	Out	Yes	—	—	Collect $U_{ANZ\text{-}NEAR}$	—	—	—
D	f.	Zero-L or Zero-R[a]	Out	Yes	—	—	Collect $U_{ANZ\text{-}FAR}$	—	—	—
—	—	Zero-L or Zero-R[a]	—	—	Calculate U_{DC0} Formula 2	Calculate U_{ANY0} Formula 4	Calculate U_{ANZ0} Formula 5	—	—	—
—	—	Zero-L or Zero-R[a]	—	—	Calculate I_{DC} Formula 3	Calculate φ_{OSY} Formula 6	Calculate φ_{OSZ} Formula 7	—	—	—
A or C[a]	g.	PY (L or R)[a]	Random	No	Collect data U_{DC}	—	—	D_{PY}	Calculate R Formula 8	Formula 12
A or C[a]	g.	PY (L or R)[a]	Random	No	—	Collect data U_{ANY}	—	$\Theta_{Y\ PY}$	Calculate φ_Y Formula 10	Formula 13
A or C[a]	g.	PY (L or R)[a]	Random	No	—	—	Collect data U_{ANZ}	$\Theta_{Z\ PY}$	Calculate φ_Z Formula 11	Formula 13
A or C[a]	h.	PZ (L or R)[a]	Random	No	Collect data U_{DC}	—	—	$D_{Z\ PZ}$	Calculate R Formula 8	Formula 12
A or C[a]	h.	PZ (L or R)[a]	Random	No	—	Collect data U_{ANY}	—	$\Theta_{Y\ PZ}$	Calculate φ_Y Formula 10	Formula 13
A or C[a]	h.	PZ (L or R)[a]	Random	No	—	—	Collect data U_{ANZ}	$\Theta_{Z\ PZ}$	Calculate φ_Z Formula 11	Formula 13

Table 5 *(continued)*

Fixture face up	Figure	Rib interface position	Tubes	Ballast	Distance V or LSB	Y-angle V or LSB	Z-angle V or LSB	Design parameter[a] mm or deg	Actual mm or deg	Pass-fail
A or C[a]	i.	PYZ (L or R)[a]	Random	No	Collect data U_{DC}	—	—	$D_{Z\ PYZ}$	Calculate R Formula 8	Formula 12
A or C[a]	i.	PYZ (L or R)[a]	Random	No	—	Collect data U_{ANY}	—	$\Theta_{Y\ PYZ}$	Calculate φ_Y Formula 10	Formula 13
A or C[a]	i.	PYZ (L or R)[a]	Random	No	—	—	Collect data U_{ANZ}	$\Theta_{Z\ PYZ}$	Calculate φ_Z Formula 11	Formula 13

[a] Depending dummy application and position, see B.1, Table 2.

6.4 Calculations

Calculate average in-out voltage U_{IR0} with Formula (2).

$$U_{DC0} = (U_{DC\,0IN} + U_{DC0\,OUT})/2 \qquad (2)$$

Calculate the displacement intercept I_{DC} with Formula (3).

$$I_{DC} = D_{ZERO} - C_{DC} \cdot U_{DC0}{}^{EXP} \qquad (3)$$

NOTE For ratio metric sensors, EXP = 1 is applied.

Calculate average up-down voltage, U_{ANY0} and average near-far voltage, U_{ANZ0} with Formulae (4) and (5).

$$U_{ANY0} = (U_{ANY\,UP} + U_{ANY\,DOWN})/2 \qquad (4)$$

$$U_{ANZ0} = (U_{ANZ\,NEAR} + U_{ANZ\,FAR})/2 \qquad (5)$$

Calculate the angle sensor offset, φ_{OSY} and φ_{OSZ} using Formulae (6) and (7).

$$\varphi_{OSY} = P_Y \cdot C_{ANY} \cdot U_{ANY0}/U_{EX} \qquad (6)$$

$$\varphi_{OSZ} = P_Z \cdot C_{ANZ} \cdot U_{ANZ0}/U_{EX} \qquad (7)$$

Calculate radius at positions 0, 1 and 2, and ZERO-L or ZERO-R, PY (L or R), PZ (L or R), PYZ (L or R) with Formula (8).

$$R = I_{DC} + C_{DC} \cdot U_{DC}{}^{EXP} \qquad (8)$$

NOTE For ratio metric sensors EXP = 1 is applied.

Calculate Z-angle φ_Z in positions 1 and 2 with Formula (9).

$$\varphi_Z = P_Z \cdot C_{ANZ} \cdot U_{ANZ}/U_{EX} + \varphi_{ORIENT} - \varphi_{OSZ} \qquad (9)$$

Using reference angle, Formula (9) will take the form of:

$$\varphi_Z = P_Z \cdot C_{ANZ} \cdot U_{ANZ}/U_{EX} + \varphi_{REF}$$

Calculate Y-angle and Z-angle in positions ZERO (L or R), PY (L or R), PZ (L or R), PYZ (L or R) with Formulae (10) and (11).

$$\varphi_Y = P_Y \cdot C_{ANY} \cdot U_{ANY}/U_{EX} - \varphi_{OSY} \qquad (10)$$

$$\varphi_Z = P_Z \cdot C_{ANZ} \cdot U_{ANZ}/U_{EX} - \varphi_{OSZ} \qquad (11)$$

To verify the distance zero-position, check if the distance sensor pass criteria is met with known distances in applicable fixture positions and actual radius. Pass if the absolute difference is less than 3 % of calibration range. Calculate pass with Formula (12).

$$\text{Pass if } |D_{ZERO} - R_{ZERO}| < 0{,}03 \cdot d_E \qquad (12)$$

Pass if $|D_{P1} - R_1| < 0{,}03 \cdot d_E$

Pass if $|D_{P2} - R_2| < 0{,}03 \cdot d_E$

Pass if $|D_{PY} - R_{PY}| < 0{,}03 \cdot d_E$

Pass if $|D_{PZ} - R_{PZ}| < 0{,}03 \cdot d_E$

Pass if $|D_{PYZ} - R_{PYZ}| < 0{,}03 \cdot d_E$

To verify the angle zero-positions, check if the angle sensor pass criteria is met with known fixture angle and actual angle. Pass if the absolute difference is less than 1,35° (corresponds to 3 % of operational angle range of ±45°). Calculate pass with Formula (13).

Pass if $|\Theta_{Z\,ZERO} - \varphi_{Z0}| < 1{,}35°$ (13)

Pass if $|\Theta_{Z1} - \varphi_{Z1}| < 1{,}35°$

Pass if $|\Theta_{Z2} - \varphi_{Z2}| < 1{,}35°$

Pass if $|\Theta_{Y\,ZERO} - \varphi_{Y0}| < 1{,}35°$

Pass if $|\Theta_{Y\,PY} - \varphi_{Y\,PY}|$ and $|\Theta_{Z\,PY} - \varphi_{Z\,PY}| < 1{,}35°$

Pass if $|\Theta_{Y\,PZ} - \varphi_{Y\,PZ}|$ and $|\Theta_{Z\,PZ} - \varphi_{Z\,PZ}| < 1{,}35°$

Pass if $|\Theta_{Y\,PYZ} - \varphi_{Y\,PYZ}|$ and $|\Theta_{Z\,PYZ} - \varphi_{Z\,PYZ}| < 1{,}35°$

6.5 Zero-position verification with DAS parameters implemented

For application of a multidimensional measurement system in a dummy and a crash test, the values for sensor offsets, polarity and orientation angle need to be implemented in a data acquisition system (DAS). To assure that the sensor parameters are correctly implemented in the DAS system, it is highly recommended that, after implementation, the zero-position verification is repeated with a live DAS in online mode and verified that the expected sensor results, D_{P0}, D_{P1}, Θ_{Z0}, Θ_{Z1}, etc. are reproduced closely by the DAS and that, in case the outputs are outside the acceptable limits, corrective actions are taken. The expected engineering unit values for 2D systems can be found in B.3, Table B.3 and for 3D systems in Table B.4. A generic workflow is given in Annex E. Generally, data acquisition systems used for automotive testing apply 16 bit data channel identification codes, which are specified in ISO/TS 13499. Relevant examples of these MME codes for multidimensional sensors can be found in Annex F.

Note that it is essential that the DAS settings are such, that the sensors are **not** zeroed at time zero, $t = t_0$, to assure that the sensor offsets (angles and distance) with respect to the local orthogonal coordinate system are maintained throughout the duration of the test.

When the sensors are assembled in the dummy, they will provide information of the initial (pre-test) position of the ribs. This information can be used to get a rough indication whether DAS parameters are correctly implemented. Annex G lists expected initial outputs for dummies and sensor locations, which can help to identify errors with DAS parameters or indicate larger than normal permanent rib deformation.

7 Coordinate system transformation

7.1 Conditions

The formulae to calculate the position of the (rib-, abdomen-, feature-) in *x*, *y* and *z* orthogonal coordinates from the 2D or 3D sensor radius and angle(s) are given in 7.2. The coordinate system transformation method, spherical to orthogonal, is explained in-depth in Annex C.

Note that the 2D and 3D formulae share the same terms, with additional terms in the 3D formulae due the 3rd dimension and the presence of the mechanical offset (δ) in some of the 3D sensors. One will find by filling out 0 in 3D formulae for Y-angle and δ that those 3D terms become zero and the remaining terms become simplified 2D system formulae.

IMPORTANT NOTICE 1 For the formulae to be valid and applicable in all 4 quadrants of the local orthogonal coordinate systems, it is essential that the distance intercept I_{DC}, as well as the offset angles φ_{OSY} and φ_{OSZ} and orientation angle φ_{ORIENT} (or reference angle φ_{REF}) and polarity of the angle sensors are implemented in the data acquisition system according to the sensor assembly orientation in the dummy. *The example zero-position verification sheet gives reference angles and angle sensor polarities for all sensor locations and orientations in the dummies, see example in Annex D.

IMPORTANT NOTICE 2 For the formulae to be valid, it is essential that the DAS settings are such, that the sensors are **NOT** zeroed at time zero ($t = t_0$), and that the sensor offsets (angle and distance) are maintained throughout the duration of the (crash or certification) test.

IMPORTANT NOTICE 3 Filtering of the sensor signals per applicable protocol (e.g. vehicle test, dummy test, etc.) shall be applied before executing the calculations.

7.2 Sensor data processing spherical to orthogonal coordinate system

Calculate the coordinates of the rib interface joint centre with respect to its local orthogonal coordinate system with Formulae (14), (15), and (16). Remember to apply the correct values for δ for 3D sensors.

δ = +15,65 [mm] Upper thorax 3D sensor

δ = -15,65 [mm] Lower thorax 3D sensor

δ = 0 [mm] Abdomen 3D sensor

$$x_i = \delta \cdot \sin(\varphi_{Yi}) + R_i \cdot \cos(\varphi_{Zi}) \cdot \cos(\varphi_{Yi}) \tag{14}$$

$$y_i = R_i \cdot \sin(\varphi_{Zi}) \tag{15}$$

$$z_i = \delta \cdot \cos(\varphi_{Yi}) - R_i \cdot \cos(\varphi_{Zi}) \cdot \sin(\varphi_{Yi}) \tag{16}$$

For 2D systems, by filling out 0 for y-angle and δ, z_i becomes 0 and Formula (14) will take the simplified form of:

$$x_i = R_i \cdot \cos(\varphi_{Zi})$$

Calculate the x, y and z deflection of the rib interface joint centre with Formulae (17), (18) and (19):

$$Dx_i = x_i - x_0 \tag{17}$$

$$Dy_i = y_i - y_0 \tag{18}$$

$$Dz_i = z_i - z_0 \quad (19)$$

(For 2D systems $Dz_i = 0$)

Calculate the resultant deflection of the rib interface joint centre with Formula (20):

$$D_i = \sqrt{\left(Dx_i^2 + Dy_i^2 + Dz_i^2\right)} \quad (20)$$

Annex A
(informative)

Measurement orthogonal coordinate systems

A.1 Global (dummy) coordinate system

The global coordinate system in this document is orthogonal and corresponds to 'ORIENTATIONS OF STANDARDIZED DUMMY COORDINATE SYSTEMS FOR STANDING AND SEATED POSTURES' according to SAE-J1733[1], see Figure A.1 (right image). The positive X-axis is directed forward from posterior to anterior, the Y-axis is aligned with the lateral axis positive directed from left to right and the Z-axis is directed superior to inferior. It is a right-handed coordinate system (Figure A.1 left image). The positive angle definition follows the right-handed screw rule (Figure A.1 middle image). The coordinate system will translate and /or rotate with the dummy part to which it is attached, there for a local orthogonal coordinate system is defined for each body segment.

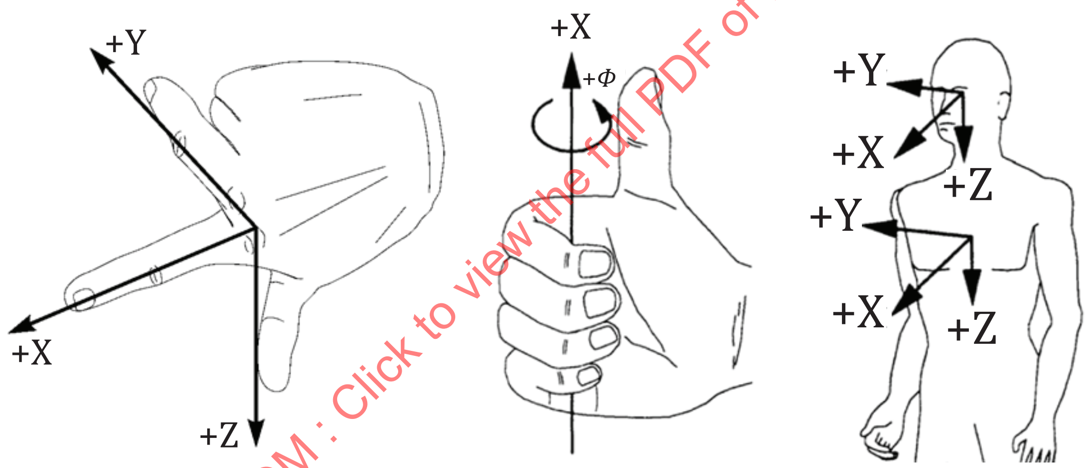


Figure A.1 — SAE-J1733 Right-handed global orthogonal coordinate system

A.2 Local coordinate systems

A.2.1 WorldSID 50th percentile male dummy

The local coordinate systems are specified with respect to the bottom and rear faces of the spine, see Figure A.2.

NOTE The WorldSID 50th percentile male and 5th percentile female dummies have 12 rib sets, 6 on the left-hand side and 6 on the right-hand side of the spine. The rib sets have slightly different orientations on the spine. The 2nd and 3rd thoracic and all abdomen ribs are aligned with the thoracic tilt sensor plane, see Figure A.2 (middle image). The 1st thoracic ribs and shoulder ribs are rotated along the Y-axis with respect to global orthogonal coordinate system by +5°, +10° respectively. The local X-axis and Z-axis of the measurement system follow the individual rib inclination angles inside the dummy, see Figure A.2 (middle image). Figure A.2 left image shows a top view of the rib cage instrumented for right hand side impact and the local X-Y coordinate system, the local X-Z positions of the sensor origins (Figure A.2 right image, dummy right-hand view), with respect to the spine rear and bottom faces, see also Table A.1.

Dimensions in millimetres

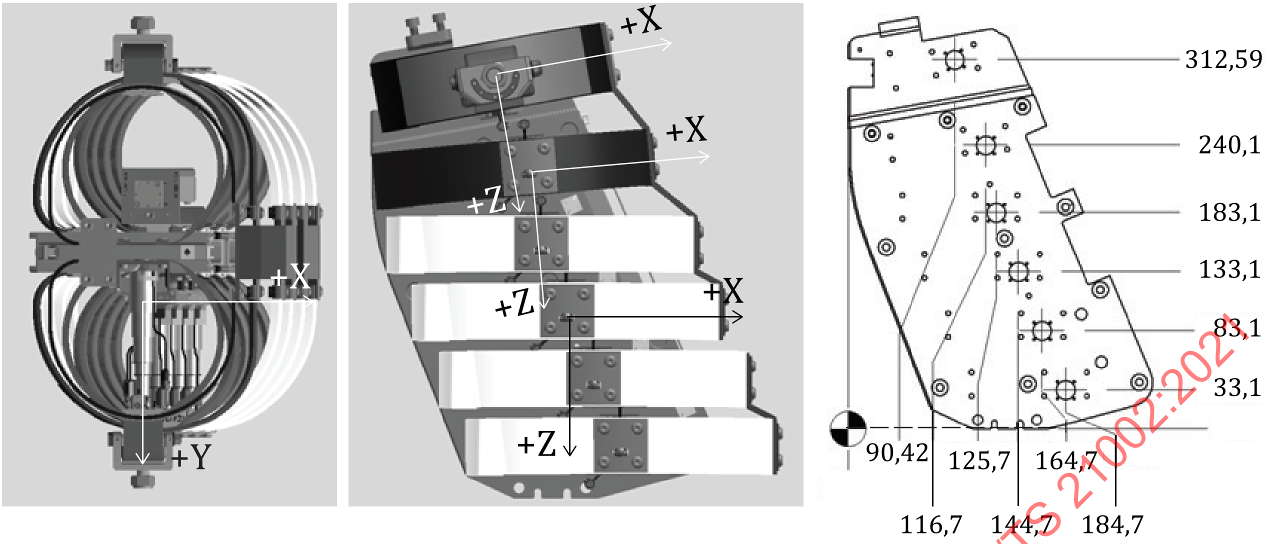


Figure A.2 — WorldSID 50M top view (left image), right side view (middle image) and local orthogonal coordinate system positions

A.2.2 Local orthogonal coordinate systems WorldSID 5th percentile female

The local coordinate systems are specified with respect to the bottom face and rear of the spine, see Figure A.3.

Dimensions in millimetres

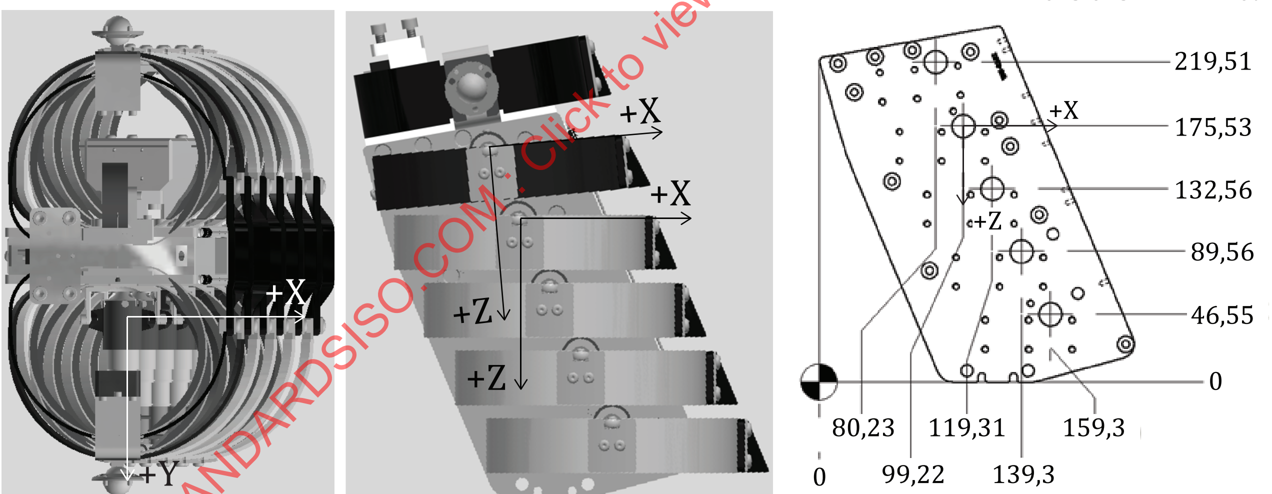


Figure A.3 — WorldSID 5F top view (left image) right-side view (middle image) and local orthogonal coordinate system positions

A.2.3 Local orthogonal coordinate systems Q10, 10-year-old child dummy

The local coordinate systems are specified with respect to the bottom and rear faces of the spine, see Figures A.4 and A.5.

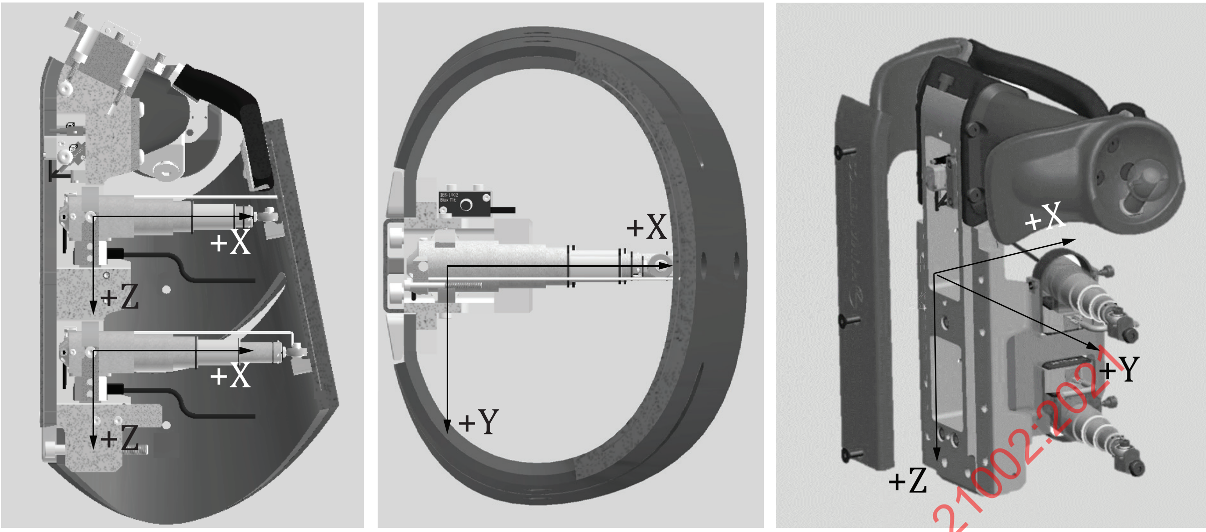


Figure A.4 — Q10 Cross section right view (left image), top view (middle image) and set up for right-side impact

Dimensions in millimetres

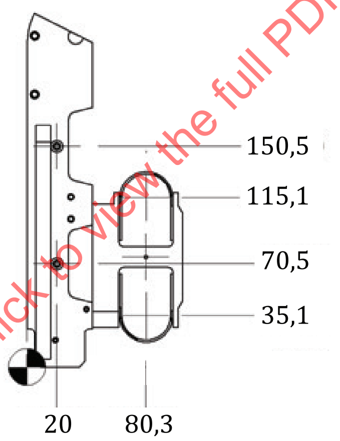


Figure A.5 — Q10 local X-Z positions of the sensor origins with respect to the spine rear and bottom faces, for both frontal and lateral oriented sensors (right view)

Table A.1 — 2D Sensor origin coordinates with respect to dummy spine origin, see Figures A.2, A.3 and A.5

Dummy	Dummy position	*x*-coordinate	*y* coordinate from midsagittal plane	*z*-coordinate
WorldSID 50M	Shoulder	90,42	±41,1	-312,59
	Thorax Rib 1	116,70		-240,1
	Thorax Rib 2	125,70		-183,1
	Thorax Rib 3	144,70		-133,1
	Abdomen Rib 1	164,70		-83,1
	Abdomen Rib 2	184,70		-33,1

Table A.1 *(continued)*

Dummy	Dummy position	*x*-coordinate	*y* coordinate from midsagittal plane	*z*-coordinate
WorldSID 5F	Thorax Rib 1	80,23	±41,1	-219,51
	Thorax Rib 2	99,22		-175,53
	Thorax Rib 3	119,31		-132,56
	Abdomen Rib 1	139,30		-89,56
	Abdomen Rib 2	159,30		-46,55
Q10 Frontal	Upper	20	0	-150,50
	Lower	20		-70,50
Q10 lateral	Upper	80,30	0	-115,10
	Lower	80,30		-35,10

A.2.4 Local orthogonal coordinate systems THOR 50th percentile male dummy

The local coordinate systems are specified with respect to the bottom and rear faces of the upper thoracic spine, the lower thoracic spine and the lumbar spine, see Figure A.6 and Figure A.7.

NOTE 1 In the 50th percentile male and 5th percentile female THOR dummies there are 6 and 4 three-dimensional position measurement systems, see Annex D, Table D.1. The THOR 50th percentile male dummies have three-dimensional position measurement systems in thorax (four systems); and two more systems in lower abdomen.

NOTE 2 The global orthogonal coordinate system of the THOR dummies corresponds to SAE-J1733:2007, Figure 2 (left image) and Figure 2 (right image). The position sensors are located in upper thorax, lower thorax and abdomen and are mounted on respectively the upper thoracic spine, lower thoracic spine and pelvis/lumbar block. The body segments to which these systems are attached are separated by flexible and adjustable components, therefore these body segments do not have a fixed orientation with respect to each other. Consequently, each of the three body segments has its own local orthogonal coordinate system, upper thoracic spine (UTS), lower thoracic spine (LTS) and lumbar spine (LS), see Figure A.7 (right image).

NOTE 3 On thoracic 3D sensors, the radial axis along which the distance is measured is not intersecting with the Y-axis; there is a mechanical link creating an axis offset between the radial axis and the Y-axis, see Figure 2 and Figure 3 (see parameter δ).

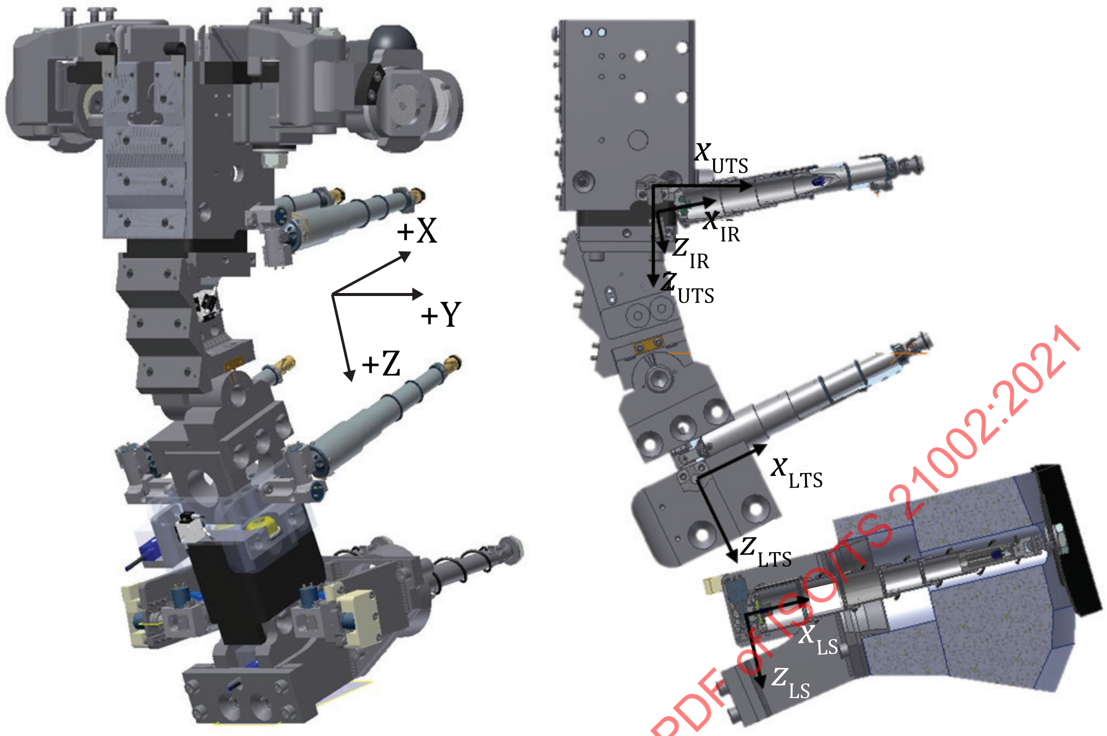
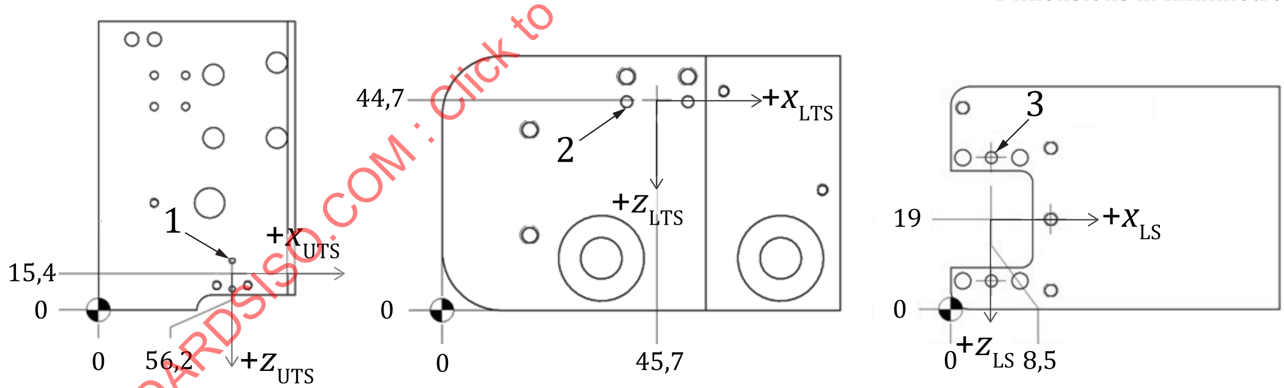


Figure A.6 — THOR 50M global coordinate system view on right-rear (left image), local orthogonal coordinate systems view on right side (right image)

Dimensions in millimetres



Key

1 UTS top dowel

2 LTS rear dowel

3 LS top dowel

Figure A.7 — THOR 50M local orthogonal coordinate system positions (right hand view), from left to right respectively upper thoracic, lower thoracic and lumbar spine

A.2.5 Local orthogonal coordinate systems THOR 5th percentile female upper thorax

The local coordinate systems are defined with respect to the bottom and rear faces of the upper thoracic spine see Figures A.8 and A.9.

NOTE The 5th percentile Female THOR has a very similar set up of 3D position sensors to the midsize Male THOR in upper thorax, however the local orthogonal coordinate systems are rotated -2,6 degrees about a lateral axis on the upper spine.

A.2.6 Local orthogonal coordinate systems THOR 5th percentile female lower thorax

The local coordinate systems are defined with respect to the bottom and rear faces of the lower thoracic spine see Figures A.8 and A.9 (right image).

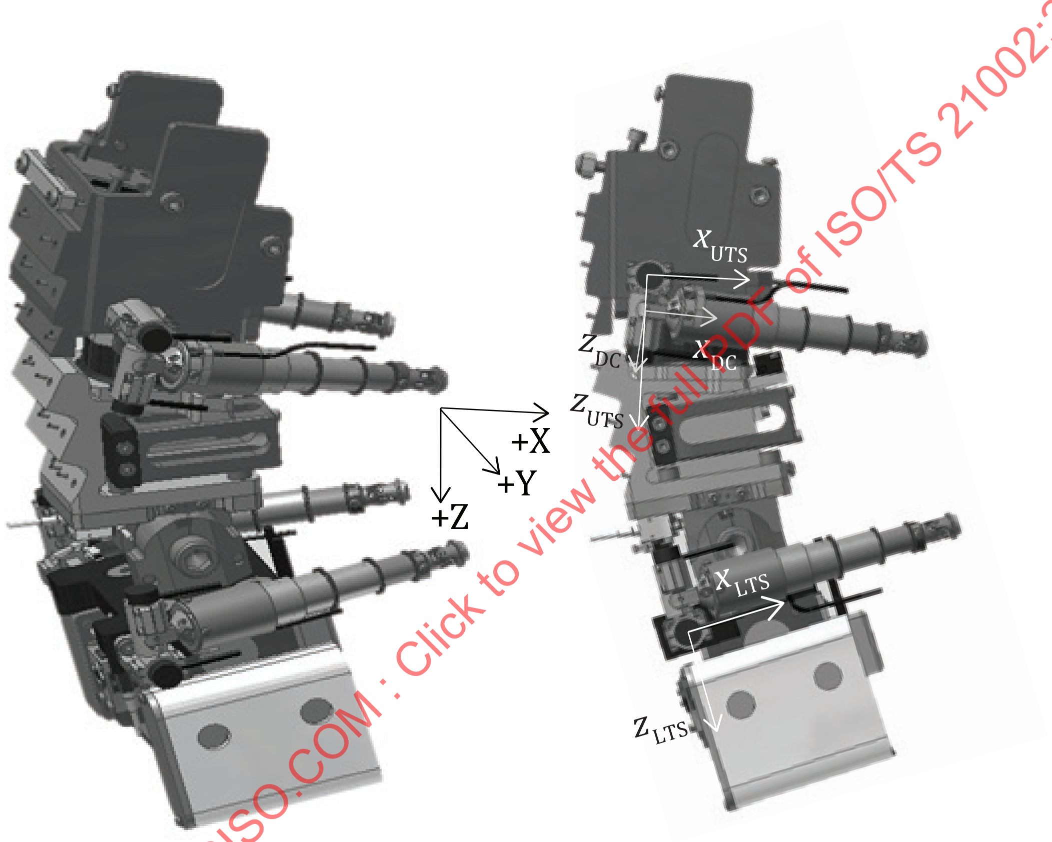
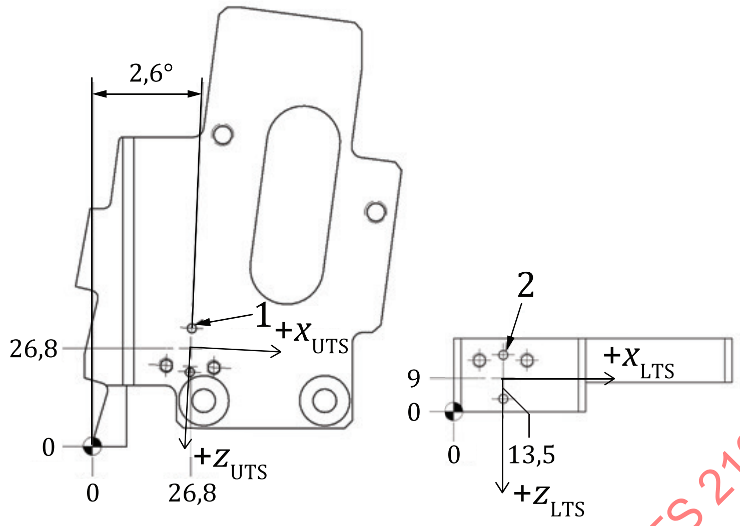


Figure A.8 — THOR 5F global coordinate system view on right-rear (left image), local orthogonal coordinate systems UTS and LTS view on right side (right image)

Dimensions in millimetres



Key

1 UTS top dowel

2 LTS top dowel

Figure A.9 — THOR 5F local orthogonal coordinate system positions (right hand view), upper thorax left image, lower thorax right image

Table A.2 — 3D Sensor origin coordinates with respect to dummy spine origin, see Figures A.6, A.7, A.8, and A.9

Dummy	Dummy position	*x*-coordinate	±*y*-coordinate from midsagittal plane	*z*-coordinate
THOR 50M	UTS	56,2	±74,0	-15,4
	LTS	45,7	±84,3	-44,7
	LS	8,5	±64,8	-19,0
THOR 5F	UTS[a]	26,8	±71,7	-26,8
	LTS	13,5	±77,7	-9,0

[a] THOR-5F UTS is rotated -2,6 degrees about the origin lateral axis.

Annex B
(informative)

Zero-position fixture and data collection examples

B.1 Zero-position fixtures

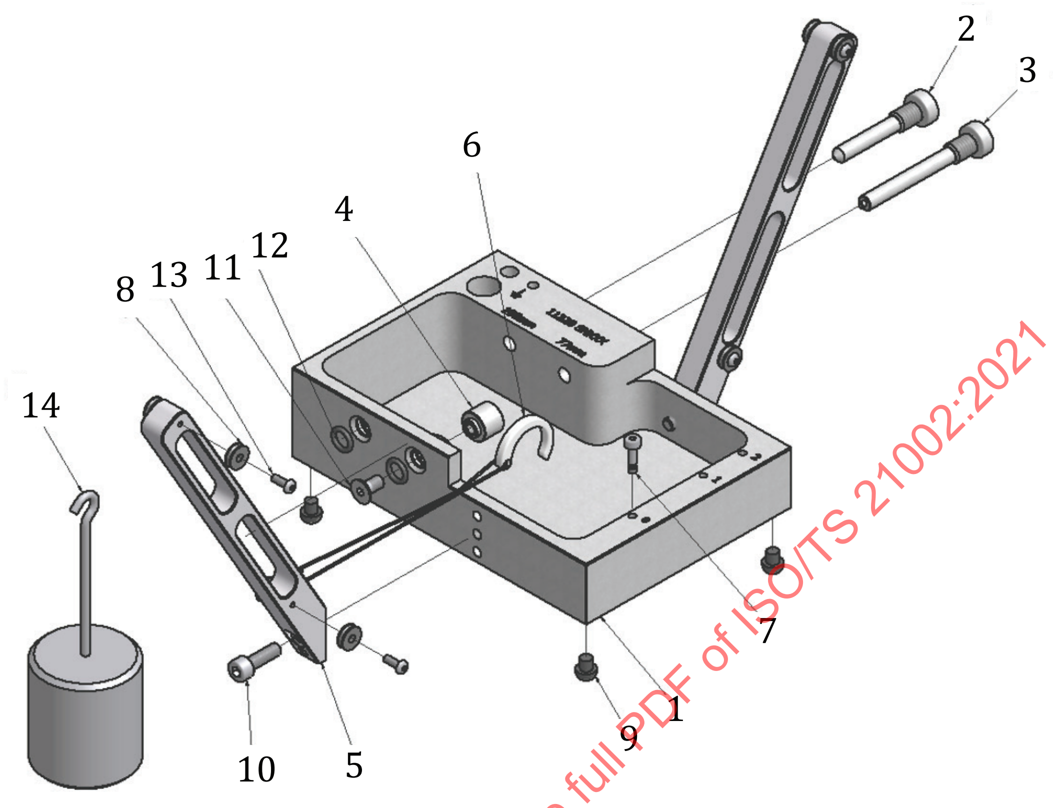
B.1.1 2D Zero-position Fixture

The example 2D zero-position fixture (part TH-4000-2D) is shown in Figure B1. This fixture can be used to set up 2D IR-TRACCS for WorldSID 50th %-ile male, WorldSID 5th %-ile female and Q10. The design data of the fixture are given in Table B.1. Two distance ranges (DZERO = 105 mm and 77 mm) are available on the fixture. The rib interface mount marked ‘0’ is obviously the zero-position. The fixture has two more positions for polarity and position verification purposes (positions marked ‘1’ and ‘2’). When the rib interface is mounted in position 1, a -36mm translation in Y-direction has occurred; in position 2 a -56 mm Y-axis translation has occurred. In position 1 and 2 the radius is larger than in the zero-position. Also the Z-angle changes in negative direction, the value depending on standard or short range and position 1 or 2 on the fixture, see Table B.1. The 2D zero-fixture assembly includes a ballast of 0,44 kg to 0,47kg, clip and twine, and outriggers. These are used to pull lateral bending play out of the distance sensor into two extreme conditions, in order to obtain reproducible zero-angle data.

Table B.1 — 2D zero-position fixture data specific to example fixture TH-4000-2D

Position	x mm	y mm	Z-angle Θ_z °	Distance D mm	Applications
0	77	0	0	77	WorldSID 5F: IF-371
1		-36	-25,1	85	
2		-56	-36,0	95,2	
0	105	0	0	105	Q10: IF-372[a] WorldSID 50M: IF-367 and IF-368
1		-36	-18,9	111	
2		-56[b]	-28,1[b]	119[b]	

[a] Outside range of IF-372 position sensor.



Key

1	2D zero-position fixture
2	centre pin
3	centre pin for IF-372
4	spacer for IF-372
5	outrigger
6	clip and twine
7	shoulder screw M3x8
8	pulley wheel
9	rubber bumper
10	screw SHCS M5 x16
11	screw FHCS M5 x10
12	o-ring
13	screw #4-40 x 5/16" BHCS
14	ballast 0.440 kg to 0.470kg

Figure B.1 — 2D Zero-position fixture example (part TH-4000-2D)

B.1.2 3D Zero-position fixture

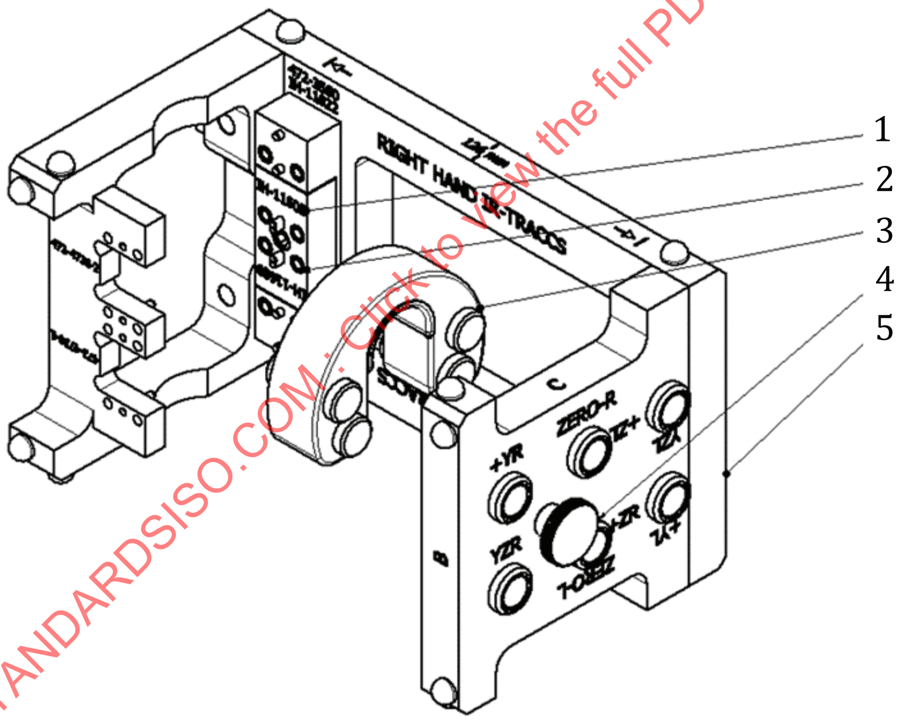
The example 3D zero-position fixture (part TH-472-6001) is shown in Figure B.2. This fixture (key item 5) is a tool to set up 10 different 3D position sensors aligned with their local orthogonal coordinate system. The fixture simulates the left-hand and right-hand side of the spine of the THOR dummies (see Figure B.3) with 10 different mounting locations for all variations of 3D position sensors. There are two separate interface blocks for the THOR-5F lower left and lower right models, key items 1 and 2. There is a thumb screw, key item 4, to secure the rib interface to the fixture.

Note that the fixture can be flipped 180° about its long axis to simulate a left-hand or right-hand spine, see Figure B.3. The 3D fixture package includes a ballast of 0,44 kg to 0,47 kg (key item 3) to drive the distance sensor into four conditions of lateral bending to obtain the extreme bending angles in the zero-position. The fixture has 16 rubber feet and four faces marked A, B, C, D to allow setting it in four quadrants and have the ballast exert lateral bending force in four directions spaced 90 degrees.

The fixture has accurately defined rib interface holes for the 3D sensor in its zero position with a fixed distance of 126mm in X-direction. The zero-positions are marked ZERO-L and ZERO-R for a left-hand and right-hand sensor respectively. Note that the zero-position holes have a double function, see next alinea.

The other four holes are for verification of the positive translation: holes marked +YL, +ZL, +YZL for left-hand sensors and marked +YR, +ZR, +YZR for right-hand sensors. The functions +ZL and ZERO-R are using the same hole; also +ZR and ZERO-L functions share one hole. When the right-hand sensor rib interface is mounted in +YR hole a 32 mm translation in positive Y-direction occurs. Translation in +32mm y-direction corresponds to +14,25° Z-angle rotation. The radius of the distance sensor changes from 126mm to 130mm in +YR hole.

In the +ZR hole the rib interface translates 32 mm in positive Z-direction, which corresponds to -14.25° Y-angle rotation. When the right-hand sensor interface is mounted in YZR hole, a simultaneous translation occurs in +Y and +Z direction. For left-hand sensors corresponding 32mm translations occur in +YL and +ZL and YZL holes, see Table B.2.



Key

1 mounting THOR-5F lower right

2 mounting THOR-5F lower left

3 lateral ballast 0.44 kg to 0.47kg

4 thumb screw M5 × 16

5 3D zero-position fixture

Figure B.2 — 3D Zero-position fixture example (part TH-472-6001)

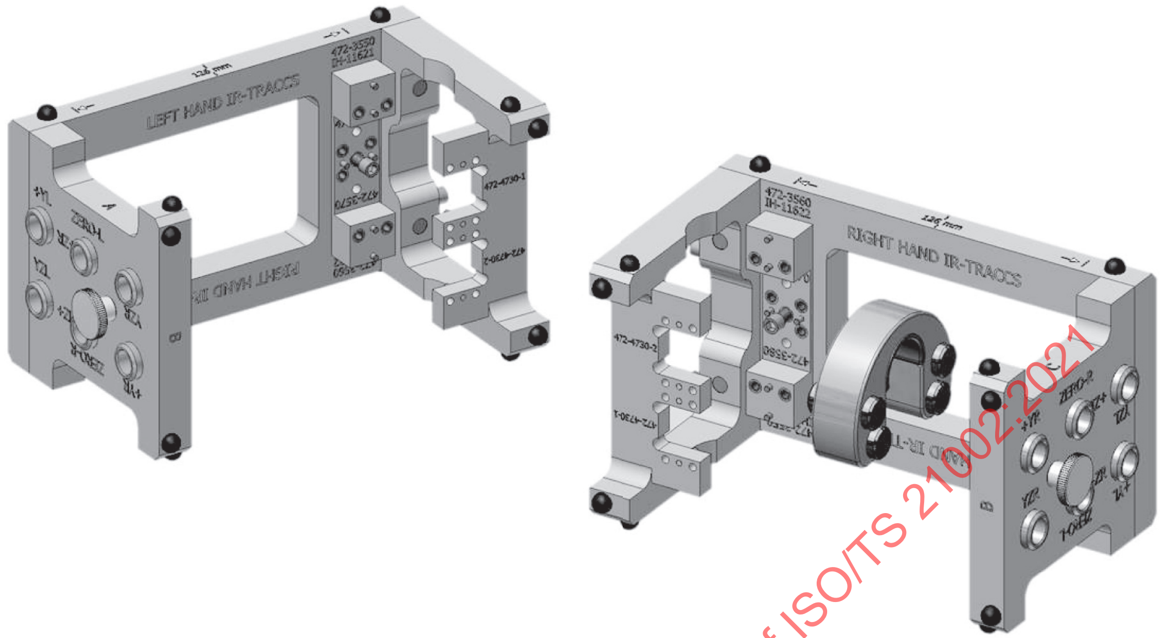


Figure B.3 — 3D Zero-position fixture; flipped for left hand manipulations (left image) and for right hand manipulations (right image)

Table B.2 — 3D zero-position fixture data (with respect to local orthogonal coordinate system) specific to fixture part number TH-472-6100

Position	*x* mm	*y* mm	*z* mm	Z-angle Θ_z °	Y-Angle Θ_y °	**Distance** *D* mm
ZERO (L or R)	126	0	0	0	0	126
PY (L or R)	126	+32	0	+14,25	0	130
PZ (L or R)	126	0	+32	0	-14,25	130
PYZ (L or R)	126	+32	+32	[c]	-14,25	[a]

[a] Depending sensor model number. Different outputs in position YZL, YZR is caused by the link (15,65mm), depending sensor position upper, lower or abdomen. The example template provides the correct value upon entering the model number.

B.2 Zero-position data collection

— Organise the necessary tools and equipment on a clean and stable laboratory work bench with sufficient space and an efficient and ergonomic set up with all necessary items at reach.

— Connect the sensors to measurement systems according adequate and accepted laboratory practise to measure the sensor outputs.

B.2.1 2D Zero-position data collection

Set up the 2D sensor assembly on the 2D fixture according to instructions specific for the fixture. Manipulate the sensor, ballast, rib interface, etc. on the fixture in various positions according to the test sequence as specified in Table 4 and Figure B.4, Figure B.5 and Figure B.6. Take measurements according to Table 5 and verify that the sensor responses are corresponding with the design values and are within the accepted limits. Refer to manufacturer's fixture manual for detailed instructions.

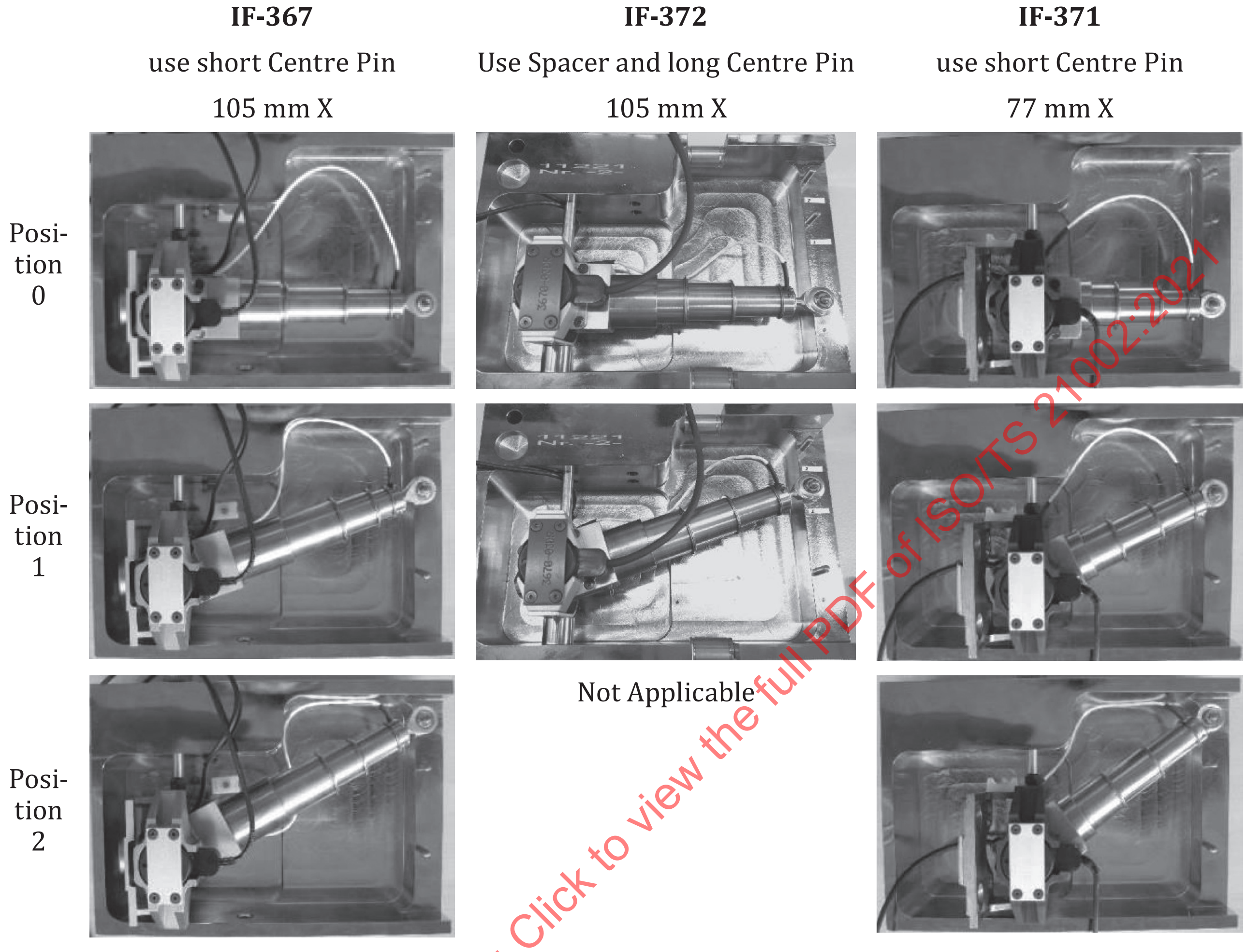
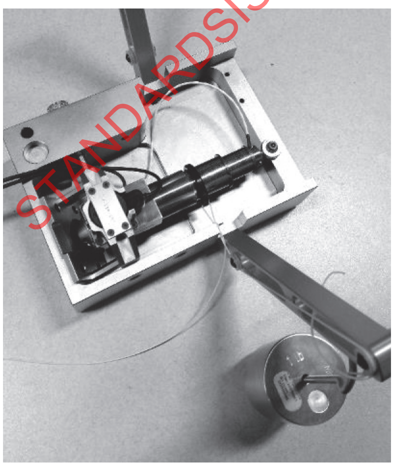
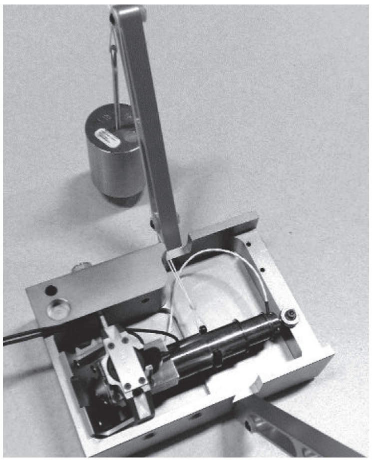


Figure B.4 — Matrix of three positions of 2D zero-position verification and examples IF-367, IF-372 and IF-372 (Respectively WorldSID-50, Q10, and WorldSID-5F)

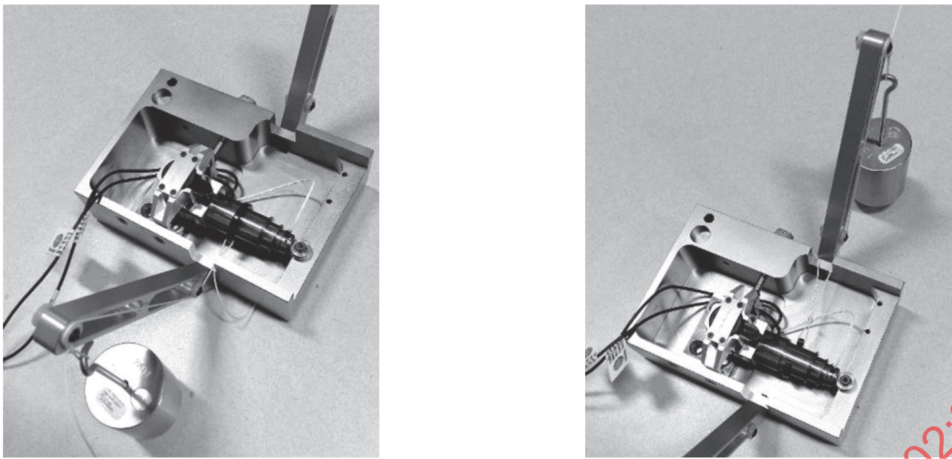


a) Ballast on near side long range



b) Ballast on far side long range

Figure B.5 — Ballast long range

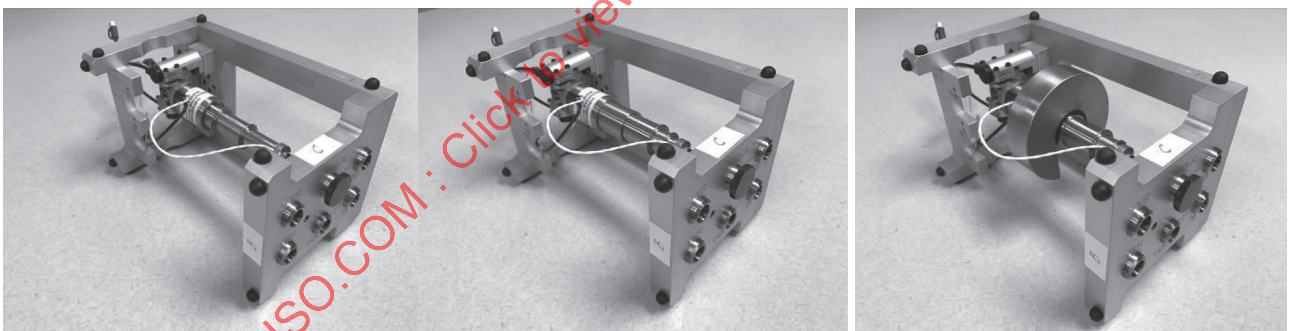


a) Ballast on near side short range b) Ballast on far side short range

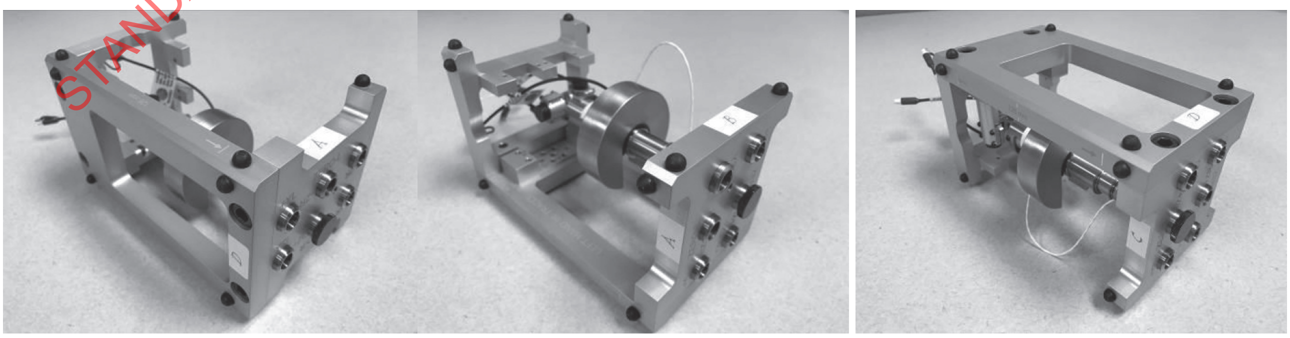
Figure B.6 — Ballast short range

B.2.2 3D Zero-position data collection

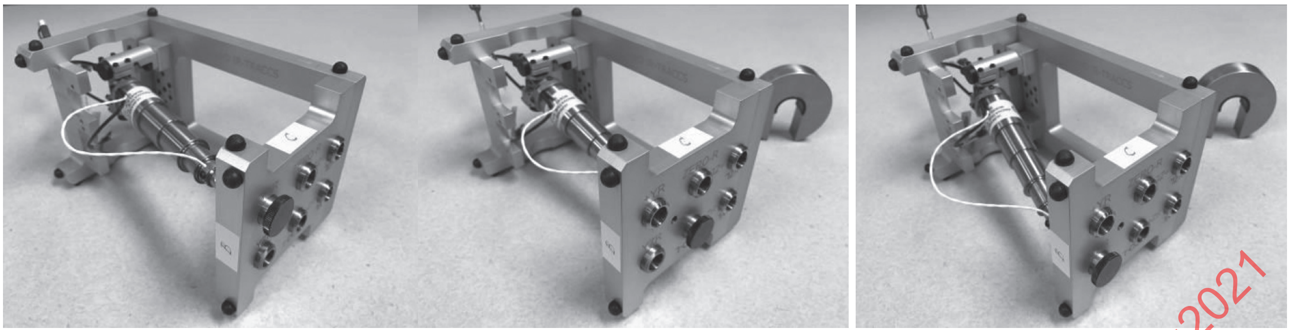
Set up 3D sensor assembly on the 3D fixture according to instructions specific for the fixture. Manipulate the sensor, ballast, rib interface, etc. on the fixture in various positions according to the test sequence as specified in Table 5 and Figure B.7. Take measurements according to Table 6 and verify that the sensor responses are corresponding with the design values and are within the acceptance limits. Refer to manufacturer's fixture manual for detailed instructions.



a) Pos'n ZERO-R, no ballast, tubes in b) Pos'n ZERO-R, no ballast, tubes out c) Position ZERO-R, ballast



d) Position ZERO-R, ballast, face A up **e) Position ZERO-R, ballast, face B up** **f) Position ZERO-R, ballast, face D up**



g) Position +YR, no ballast, face C up **h) Position +ZR, no ballast, face C up** **i) Position YZR, no ballast, face C up**

Figure B.7 — Nine conditions of zero-position verification (example upper right 3D IR-TRACC)

B.3 Expected outputs of multidimensional sensors on zero-position fixtures

Table B.3 — Expected 2D system outputs on zero-ing fixture per fixture position, dummy application, sensor position & orientation and polarity

Dummy	Dummy position and orientation	Struck side	Rib interface position 0		Rib interface position 1		Rib interface position 2		P_Z
			D_{ZERO} mm	Θ_{ZERO} °	D_{P1} mm	Θ_{Z1} °	D_{P2} mm	Θ_{Z2} °	
WorldSID-50M	Thorax abdomen	Left	105	-90	111	-108,9	119	-118,1	1
WorldSID-50M	Thorax abdomen	Right	105	90	111	71,1	119	61,9	1
WorldSID-50M	Shoulder	Left	105	-90	111	-71,1	119	-61,9	-1
WorldSID-50M	Shoulder	Right	105	90	111	108,9	119	118,1	-1
WorldSID-5F	Thorax/ abdomen shaft down	Left	77	-90	85	-115,1	95,2	-126,0	1
WorldSID-5F	Thorax/ abdomen Shaft up	Left	77	-90	85	-64,9	95,2	-54,0	-1
WorldSID-5F	Thorax/ abdomen shaft down	Right	77	90	85	64,9	95,2	54,0	1
WorldSID-5F	Thorax/ abdomen shaft up	Right	77	90	85	115,1	95,2	126,0	-1
Q10	Upper lower frontal	Front	105	0	111	18,92	NA	NA	-1
Q10	Upper lateral	Left	105	-90	111	-71,1	NA	NA	-1
Q10	Lower lateral	Left	105	-90	111	-108,9	NA	NA	1
Q10	Upper lateral	Right	105	90	111	108,9	NA	NA	-1
Q10	Lower lateral	Right	105	90	111	71,1	NA	NA	1

Table B.4 — Expected 3D system outputs on zero-ing fixture per fixture position, dummy application, sensor position and polarity

Dummy	Dummy position			Rib interface position Zero (L and R)			Rib interface position PY (L and R)			Rib interface position PZ (L and R)			Rib interface position PYZ (L and R)			Polarity	
				D_{ZERO} [mm]	Θ_{YZERO} [°]	Θ_{ZZERO} [°]	D_{PY} [mm]	$\Theta_{Y\,PY}$ [°]	$\Theta_{Z\,PY}$ [°]	D_{PZ} [mm]	$\Theta_{Y\,PZ}$ [°]	$\Theta_{Z\,PZ}$ [°]	D_{PYZ} [mm]	$\Theta_{Y\,PYZ}$ [°]	$\Theta_{Z\,PYZ}$ [°]	P_Y	P_Z
THOR-50M	Thorax	upper	left	126	0	0	130	0	14,25	133,9	-14,25	0	137,6	-14,25	13,45	1	-1
THOR-50M	Thorax	upper	right	126	0	0	130	0	14,25	133,9	-14,25	0	137,6	-14,25	13,45	-1	-1
THOR-50M	Thorax	lower	right	126	0	0	130	0	14,25	126,1	-14,25	0	130,1	-14,25	14,23	-1	1
THOR-50M	Thorax	lower	left	126	0	0	130	0	14,25	126,1	-14,25	0	130,1	-14,25	14,23	1	1
THOR-50M	Abdomen		left	126	0	0	130	0	14,25	130,0	-14,25	0	133,9	-14,25	13,83	1	1
THOR-50M	Abdomen		right	126	0	0	130	0	14,25	130,0	-14,25	0	133,9	-14,25	13,83	-1	1
THOR-5F	Thorax	lower	right	126	0	0	130	0	14,25	126,1	-14,25	0	130,1	-14,25	14,23	-1	1
THOR-5F	Thorax	lower	left	126	0	0	130	0	14,25	126,1	-14,25	0	130,1	-14,25	14,23	1	1
THOR-5F	Thorax	upper	left	126	0	0	130	0	14,25	133,9	-14,25	0	137,6	-14,25	13,45	1	-1
THOR-5F	Thorax	upper	right	126	0	0	130	0	14,25	133,9	-14,25	0	137,6	-14,25	13,45	-1	-1

B.4 Zero-position verification example template

Example zero-position verification software (template) is available in Microsoft Excel format specifically for the use with 2D and 3D IR-TRACCs, see Figures B.8 and B.9. The use of the software is voluntary, not mandatory. The template contains two sheets, one for 2D and one for 3D sensors. It helps the user of the fixtures to run the zero-position verification and collect and organize the data in a structured manner. The template provides instructions for sensor and fixture manipulations, and also gives data for DAS parameter implementation with expected and actual verification data. The template implements the expected results per verification step based on the sensor part number and intended dummy location and compares the actual values with the expected values, with pass-fail indication based on accepted criteria. Note that cells to enter data are coloured light orange but may appear a different colour depending individual computer settings or software versions. The software has pop-up comments with clarifications or instructions at various cells (marked with a red triangle in the upper right cell corner).

In the top section information can be entered on the test, such as test date and operator name, climate conditions, test number and sensor type. In the second sections calibration data and serial numbers of the sensors can be entered. In the third section the zero-position data can be entered, and results are shown. The fourth section is for entering data to verify polarity, and to check that the zero-position verification is passing the acceptance criteria. This section provides information for implementation of sensor parameters in DAS systems. Finally, there is a section with expected coordinates of the measurement system in 2D or 3D space on the fixture. This section can help when validating data processing software.

Lab logo	Company Name Company Address Company Address	Tel: Fax: Web site:

2D Sensor Zero-Position Verification Template for use with Fixture TH-4000-2D
Conforms to ISO-TR21002

Date	19/Nov/18	Temperature [°C]	23	Verification Nr	1234567	Dummy	Position		
Technician	type name here	Humidity [%]	45	Part nr	IF-372(2)	Q10	Lateral	Upper	Left

Calibration Factors

IR-TRACC Serial Number			xxxxxxxx		Z Angle Sensor Serial Number			zzzzzzzz
Sensitivity S_{IR}		Calibration factor C_{IR}			Sensitivity S_{ANZ}		Calibration factor C_{ANZ}	
0,033332	$[V_{LIN}/mm]$	$[mm/V_{LIN}]$	30,001		0,0033332	[V/V/deg]	[deg/V/V]]	300,01
33,332	$[mV_{LIN}/mm]$	EXPonent [-]	-0,4501		3,3332	[mV/V/deg]	[deg/mV/V]	0,30001
							Polarity P_Z	-1
EXCITATION VOLTAGE U_{EX} [V]			5	Angle sensor EXCITATION VOLTAGE U_{EX} [V] (during 0 position measurements)				5

Zero Postion Data Collection

Rib Interface Position	Ballast	Tubes	IR-TRACC Radius R Output U_{IR} [V] or [LSB]				Z Angle Sensor Output U_{ANZ} [V] or [LSB]			
0	NO	IN	0,087							
0	NO	OUT	0,085							
0	NEAR	OUT					0,0501			
0	FAR	OUT					0,03			
			I_{DCV}	Distance Intercept		I_{DC}	Z Angle Sensor Offset φ_{OSZ}			
			0,4828	$[V_{LIN}]$	[mm]	14,49	0,0401	[V]	[Deg]	-2,403
			482,8	$[mV_{LIN}]$	104,5	105,5	40,1	[mV]	-3,01	-1,8
					D_{ZERO} [mm]	105	Φ_{ORIENT} [deg]	-90	Φ_{REF} [deg]	-87,6
Offset definitions			$D_{ZERO} = I_{DC} + C_{IR} * (U_{IR0}$ ^ EXP); $I_{DC} = D_{ZERO} - C_{IR} * (U_{IR0}$ ^ EXP) [mm]; $I_{DVC} = I_{DC} / C_{IR}$				$\varphi_{OSZ} = P_Z * C_{ANZ} * U_{ANZ0}/U_{EX}$			
Formulas R and φ_Z			$R = I_{DC} + C_{IR} * U_{IR}$ ^ EXP [mm]				$\varphi_Z = -\varphi_{OSZ} + P_Z * C_{ANZ} * U_{ANZ}/U_{EX} + \varphi_{ORIENT}$ [degrees]			
Formulas R and φ_Z			Radius = 14,49 + 30,001 * (Uir ^ -0,4501) [mm]				Z Angle = 2,4 - 300,01 * Uanz /5 + -90 [degrees]			

Zero Postion and Polarity Verification and coordinate system rotation applied for assembly orientation

Rib Interface Position	Ballast	Tubes	IR-TRACC Radius R (Distance) Output U_{IR} [V]	Expected [mm]	Actual [mm]	Pass/Fail	Z Angle Sensor Output U_{ANZ} [V]	ϕZ Expected [deg]	ϕZ Actual [deg]	Pass/Fail
			0,086	105	105	NA	0,0401	-90	-90	Pass
1	NO	Random	0,075	111	110,8	Pass	-0,27	-71,1	-71,4	Pass
2	NO	Random	0,063	NA	NA	NA	-0,45	NA	NA	NA

Coordinates for Post Processing Calculation Verification

Rib Interf. Pos.	X_i coordinate [mm] Expected			Y_i coordinate [mm] Expected		
0	0			-105		
1	36			-105		
2	NA			NA		
	$x_i = R_i * \cos(\phi_{Zi})$ [mm]			$y_i = R_i * \sin(\phi_{Zi})$ [mm]		

Figure B.8 — Example 2D zero-position verification template with data from a 2D IR-TRACC verification

Lab logo	Company Name Company Address Company Address	Tel: Fax: Web site:	

3D Sensor Zero-Position Verification Template for use with Fixture TH-472-6100
Conforms to ISO-TR21002

Date	19/Nov/18	Temperature [℃]	22	Verification Nr	12345678	Dummy	Position		
Technician	type name here	Humidity [%]	45	Part nr	4XX-3550	THOR-50M	Thorax	Upper	Left

Calibration Factors

IR-TRACC Serial Number			xxxxxxxx	Y Angle Sensor Serial Number			yyyyyyyy	Z Angle Sensor Serial Number			zzzzzzzz
Link Length δ [mm]			15,65	Sensitivity S_{ANY}		Calibration factor C_{ANY}		Sensitivity S_{ANZ}		Calibration factor C_{ANZ}	
Sensitivity S_{IR}		Calibration factor C_{IR}		0,0033333	[V/V/deg]	[deg/V/V]	300	0,0033333	[V/V/deg]	[deg/V/V]	300
0,033333	[V_{LIN}/mm]	[mm/V_{LIN}]	30	3,3333	[mV/V/deg]	[deg/mV/V]	0,3	3,3333	[mV/V/deg]	[deg/mV/V]	0,3
33,333	[mV_{LIN}/mm]	EXPonent [-]	-0,45			Polarity P_Y	1			Polarity P_Z	-1
EXCITATION VOLTAGE U_{EX} [V]			5	Angle sensor EXCITATION VOLTAGE U_{EX} [V] (during 0 position measurements)							5

Zero Postion Data Collection

Fixture Manipulation	Rib Interface Position	Ballast	Tubes	IR-TRACC Radius R Output U_{IR} [V]				Y Angle Sensor Output U_{ANY} [V]				Z Angle Sensor Output U_{ANZ} [V]			
FACE A UP	ZERO-L	NO	IN	0,112											
FACE A UP	ZERO-L	NO	OUT	0,115											
FACE A UP	ZERO-L	YES	On 4th smallest tube					0,003							
FACE C UP	ZERO-L	YES	On 4th smallest tube					0,007							
FACE B UP	ZERO-L	YES	On 4th smallest tube									0,02			
FACE D UP	ZERO-L	YES	On 4th smallest tube									0,03			
				I_{DCV}	Distance Intercept		I_{DC}	Y Angle Sensor Offset φ_{OSY}				Z Angle Sensor Offset φ_{OSZ}			
				1,5377	[V_{LIN}]	[mm]	46,13	0,005	[V]	[Deg]	0,3	0,025	[V]	[Deg]	-1,5
				1537,7	[mV_{LIN}]	126,5	125,5	5	[mV]	0,18	0,42	25	[mV]	-1,2	-1,8
Offset definitions				$D_{ZERO} = I_{DC} + C_{IR} * (U_{IR0}$ ^ EXP); $I_{DC} = D_{ZERO} - C_{IR} * (U_{IR0}$ ^ EXP) [mm]; $I_{DVC} = I_{DC} / C_{IR}$				$\varphi_{OSY} = P_Y * C_{ANY} * U_{ANY0} / U_{EX}$				$\varphi_{OSZ} = P_Z * C_{ANZ} * U_{ANZ0} / U_{EX}$			
Formulas R, φ_Y and φ_Z				$R = I_{DC} + C_{IR} * U_{IR}$ ^ EXP [mm]				$\varphi_Y = -\varphi_{OSY} + P_Y * C_{ANY} * U_{ANY} / U_{EX}$ [degrees]				$\varphi_Z = -\varphi_{OSZ} + P_Z * C_{ANZ} * U_{ANZ} / U_{EX}$ [degrees]			
Formulas R, φ_Y and φ_Z				Radius = 46,13 + 30 * (Uir ^ -0,45) [mm]				Y Angle = -0,3 + 300 * Uany /5 [degrees]				Z Angle = 1,5 - 300 * Uanz /5 [degrees]			

Zero Postion and Polarity Verification

				IR-TRACC Radius R (Distance)				Y Angle Sensor				Z Angle Sensor			
Fixture Manipulation	Rib Interface Position	Ballast	Tubes	Output U_{IR} [V]	Expected [mm]	Actual [mm]	Pass/Fail	Output U_{ANY} [V]	ϕY Expected [deg]	ϕY Actual [deg]	Pass/Fail	Output U_{ANZ} [V]	ϕZ Expected [deg]	ϕZ Actual [deg]	Pass/Fail
				0,1135	126	126	NA	0,005	0	0,3	Pass	0,025	0	-1,5	Pass
FACE A UP	+YL	NO	Random	0,1	130	130,7	Pass	0,006	0	0,06	Pass	-0,21	14,25	14,1	Pass
FACE A UP	+ZL	NO	Random	0,09	133,9	134,8	Pass	0,24	-14,25	14,1	Fail	0,003	0	1,32	Pass
FACE A UP	YZL	NO	Random	0,083	137,6	138,1	Pass	0,245	-14,25	14,4	Fail	-0,2	13,45	13,5	Pass

Coordinates for Post Processing Calculation Verification

Rib Interface Position	X_i coordinate [mm]			Z_i coordinate [mm]			Y_i coordinate [mm]		
	Expected			Expected			Expected		
ZERO-L	126			15,7			0		
+YL	126			15,7			32		
+ZL	126			47,7			0		
YZL	126			47,7			32		
	$x_i = \delta * \sin(\phi_{Yi}) + R_i * \cos(\phi_{Zi}) * \cos(\phi_{Yi})$ [mm]			$z_i = \delta * \sin(\phi_{Yi}) + R_i * \cos(\phi_{Zi}) * \sin(\phi_{Yi})$ [mm]			$y_i = R_i * \sin(\phi_{Zi})$ [mm]		

Figure B.9 — Example 3D zero-position verification template with data from a 3D IR-TRACC verification

Annex C
(informative)

Mathematical background data processing

C.1 Background

The systems covered in this document are an assembly of one distance sensor and one or two angle sensors, the axes of which are organised in a spherical coordinate system, see Figure C.1. The required output of the sensor system is position of the feature interface (e.g. rib, abdomen) in one of the local orthogonal coordinate systems (distance in *x*, *y* and *z* coordinates).

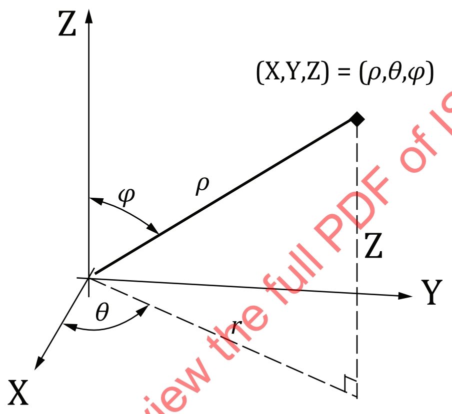


Figure C.1 — Generic graphic spherical and orthogonal coordinate systems

Note that there is a mechanical link on the upper and lower 3D distance sensors creating an offset δ between axis of radius measurement x_{DC} and local UTS or LTS coordinate systems, see Figure C.2. The offset introduces a dependency of the distance sensor output from rotation about the Y-axis. Therefore additional steps of coordinate system transformation are required.

Step 1: Deflection of O_{DC} (DISTANCE SENSOR Origin) local orthogonal coordinate system

Upper thoracic distance sensors, see Figure C.2.

The mechanical link on the upper 3D distance sensors create an offset δ between axis of radius measurement x_{DC} and local UTS coordinate system and in the upper distance sensor it is pointing downward in positive Z-direction. This results in a positive term in the formulae, $+\delta$.

Calculate deflection of O_{DC} (distance sensor origin) in upper thoracic spine coordinate system, see Figure C.1 with Formulae C.1, C.2 and C.3.

$$x_{DC} = +\delta \cdot \sin(\varphi_Y) \tag{C.1}$$

$$y_{DC} = 0 \tag{C.2}$$

$$z_{DC} = +\delta \cdot \cos(\varphi_Y) \tag{C.3}$$

Lower thoracic distance sensors, see Figure C.3.

Note that the mechanical link between axis of radius measurement X_{DC} and local LTS coordinate system is pointing upward in negative Z direction. The link is rotated about 180°, which results in a negative term in the formulae C.1, C.2, and C.3: -δ.

Calculate deflection of O_{DC} in lower thoracic spine coordinate system, see Figure C.2, using Formulae C.1, C.2 and C3 will take the form of:.

$$x_{DC} = \delta \cdot \sin(180° + \varphi_Y), x_{DC} = -\delta \cdot \sin(\varphi_Y) \quad \text{(C.1)}$$

$$y_{DC} = 0 \quad \text{(C.2)}$$

$$z_{DC} = \delta \cdot \cos(180° + \varphi_Y), z_{DC} = -\delta \cdot \cos(\varphi_Y) \quad \text{(C.3)}$$

Abdomen distance sensors, see Figure C.4.

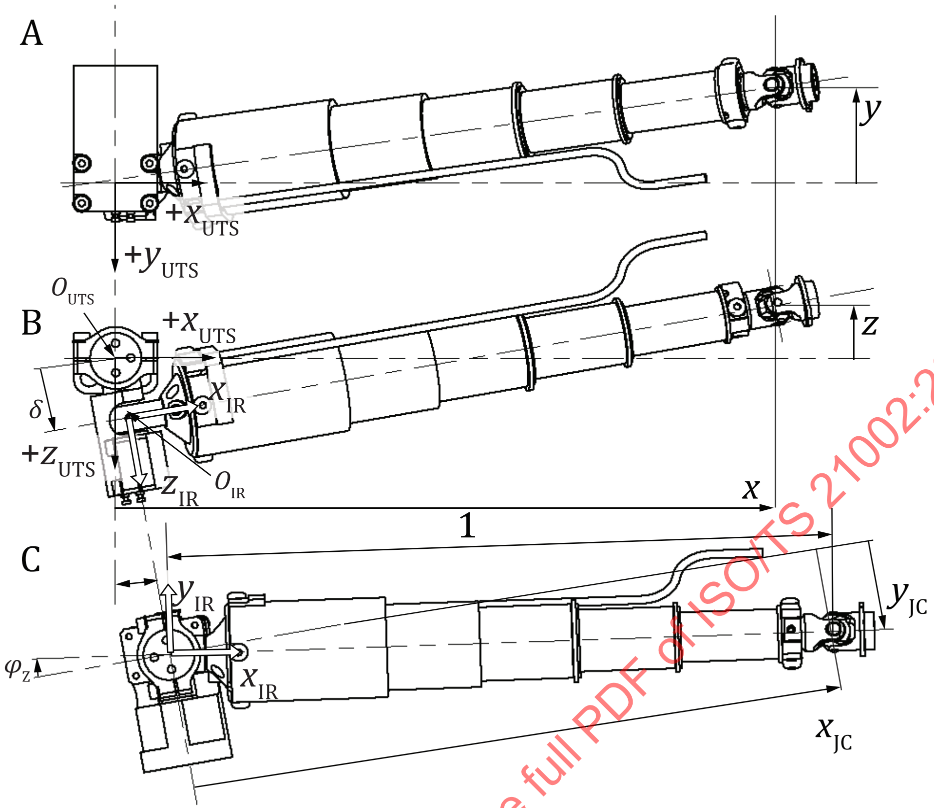
The abdomen 3D distance sensors have no offset and all axes of the transducers are intersecting, see Figure C.4. The offset on abdomen distance sensors δ = 0 mm. This results in a zero term in the Formulae C1, C.2, and C.3.

The value and sign of the offset δ is the only difference to process 3D distance sensor assembly varieties. All other processing formulae are identical between distance sensor varieties. The recommended practice is to give the δ parameter a value and sign dependent on the type of distance sensor, which is being processed, see below.

Upper distance sensor δ = +15,65 mm

Lower distance sensor δ = -15,65 mm

Abdomen distance sensor δ = 0 mm



Key

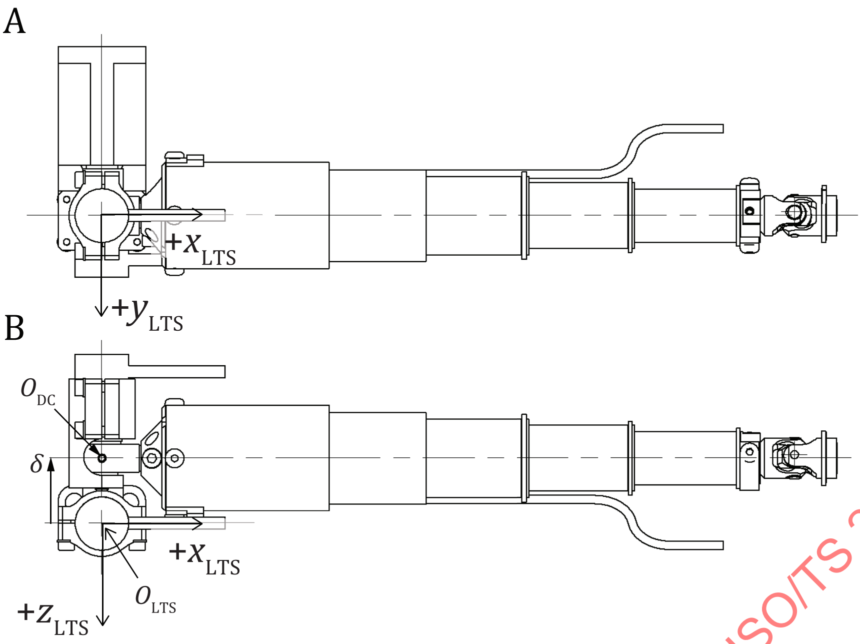
A top view

B right view

C bottom view

1 radius, R_i

Figure C.2 — Example upper right thoracic IR-TRACC

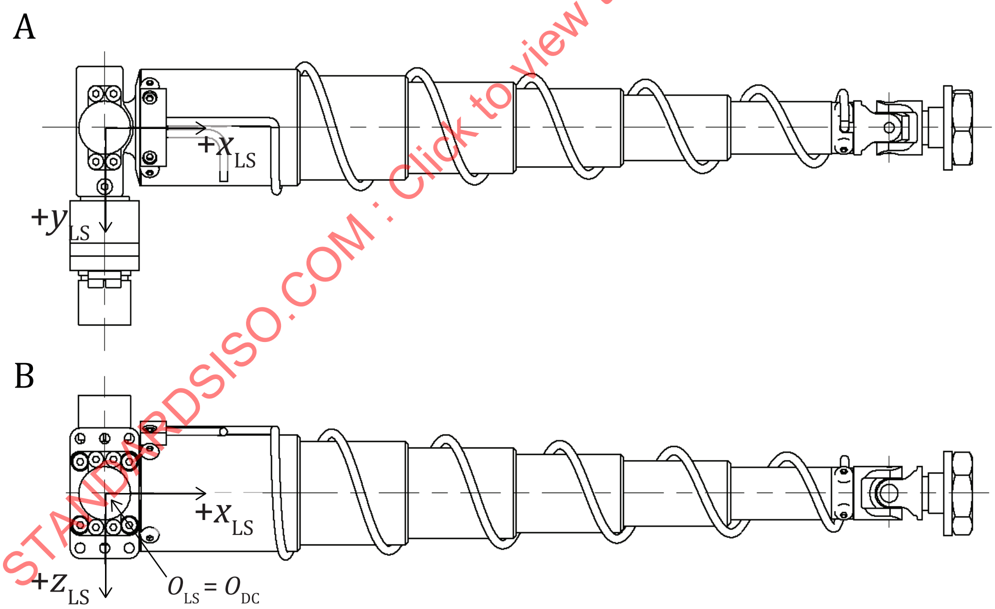


Key

A top view

B right view

Figure C.3 — Example lower right thoracic IR-TRACC



Key

A top view

B right view

Figure C.4 — Example right abdomen IR-TRACC

Step 2 Calculate deflection of joint centre in $X_{DC}Y_{DC}Z_{DC}$ coordinate system

$$x_{\mathrm{JC}} = R \cdot \cos(\varphi_{\mathrm{Z}}) \quad \text{(C.4)}$$

$$y_{JC} = R \cdot \sin(\varphi_Z) \tag{C.5}$$

$$z_{JC} = 0 \tag{C.6}$$

where x_{JC}, y_{JC} and z_{JC} are deflections of joint centre in $x_{DC}y_{DC}z_{DC}$ coordinate system.

Project the Formulae C.4, C.5, and C.6 result to the UTS coordinate system (rotate $x_{DC}y_{DC}z_{DC}$ by φ_Y to $x_{JC}y_{JC}z_{JC}$ along Y_{UTS} axis).

Step 3 Apply the coordinate system transformation to result of step 2 Formulae C.4, C.5, and C.6,

$$x_1 = R \cdot \cos(\varphi_Z) \cdot \cos(\varphi_Y) \tag{C.7}$$

$$y_1 = R \cdot \sin(\varphi_Z) \tag{C.8}$$

$$z_1 = -R \cdot \cos(\varphi_Z) \cdot \sin(\varphi_Y) \tag{C.9}$$

where x_1, y_1 and z_1 are the deflection of joint centre at O_{DC} projected in UTS coordinate system.

Step 4 Calculate deflection of joint centre in UTS coordinate system (superpose the result of step 1 and step 3 together), see Formula C.10, Formula C.11 and Formula C.12. This step finally results in Formula 14, Formula 15 and Formula 16 in 7.2, respectively.

$$x = x_{DC} + x_1 \tag{C.10}$$

$$y = y_{DC} + y_1 \tag{C.11}$$

$$z = z_{DC} + z_1 \tag{C.12}$$

Annex D
(informative)

Applicable sensors

The applicable sensors for this document are listed in (but not limited to) Table D.1.

Table D.1 — Applicable sensors

Model nr	Dummy application	Dummy location	Radius fully collapsed – extended mm	Y angle range °	Z angle range °
IF-367	WorldSID 50M	Thorax and abdomen ribs	~43 - ~132	Not measured	±~45
IF-368	WorldSID 50M	Shoulder ribs	~43 - ~132	Not measured	±~45
IF-371	WorldSID 5F	Shoulder, thorax and abdomen ribs	~36 - ~110	Not measured	±~45
IF-372	Q10	Frontal upper and lower Lateral upper Lateral lower	~43 - ~132	Not measured	±~25
4XX-3550	THOR 50M	Thorax upper left	~70 - ~164	~+35 to ~-29	±~45
4XX-3560	THOR 50M	Thorax upper right	~70 - ~164	~+35 to ~-29	±~45
4XX-3570	THOR 50M	Thorax lower right	~70 - ~164	~+29 to ~-35	±~45
4XX-3580	THOR 50M	Thorax lower left	~70 - ~164	~+29 to ~-35	±~45
4XX-4730-1	THOR 50M	Abdomen left	~69 - ~192	0-360	±~15
4XX-4730-2	THOR 50M	Abdomen right	~69 - ~192	0-360	±~15
IH-11621	THOR 5F	Thorax upper left	~65 - ~140	~+35 to ~-29	±~45
IH-11622	THOR 5F	Thorax upper right	~65 - ~140	~+35 to ~-29	±~45
IH-11608	THOR 5F	Thorax lower right	~65 - ~140	~+29 to ~-35	±~45
IH-11609	THOR 5F	Thorax lower left	~65 - ~140	~+29 to ~-35	±~45