EXPRESS definition of Vectorial Tolerancing in product modelling

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Abstract

Tolerance information is essential for manufacturing processes, because all processes will have a certain variation. It is beneficial to treat the tolerance data in a unified manner in product modelling systems. For this purpose, we took an approach to describe tolerance information of Vectorial Tolerancing (VT) in a formal way using EXPRESS developed by STEP. In VT, surface location and orientation is described with vectors in a Workpiece Coordinate System. VT provides a clear distinction between the size, form, location, and orientation deviations with magnitude and direction and is therefore useful for functional analysis and the control of manufacturing processes.

Keywords

Vectorial Tolerancing, EXPRESS, STEP, Product Modelling

1   INTRODUCTION

Manufacturing processes will always have a variation. The function of a product, the chosen manufacturing processes and thereby also the manufacturing costs are dependent on the tolerances. So, it is important to develop a tolerancing model which can express the functional relations as well as manufacturing considerations in a unified manner in three dimensional product modelling systems.

The objective of this paper is to define a formal description of Vectorial Tolerancing (VT). This will be a basis of the future information infrastructure system to realize a fully integrated intelligent manufacturing system. The definition is done in EXPRESS, which is developed in order to define product model data in a formal manner (ISO 10303-11, Schenck, 1994). This

makes possible a clear comparison to ISO tolerances and other tolerancing methods. The EXPRESS definition can also be used for implementation of VT in product modelling systems.

The existing ISO tolerances are to some extent ambiguous and need human interpretations as they are based on one-dimensional measuring. ISO tolerances on orientation, location and size are sums of different tolerancing features where the magnitude of each feature is unknown. ISO defines for example a size of a cylinder as a distance between two points. The two-point distance will be influenced by the local form deviation in each of the two points as well as the orientation deviation of the cylinder. A measured distance between two planes, on the other hand, will be a sum of the form, orientation, and location deviation on each surface. Tolerance ambiguity occurs because the ISO-tolerance does not define any measuring direction for the distance tolerance. Orientation tolerances are in ISO defined as a one dimensional distance between two enveloping surfaces, see Figure 1. The orientation measurement is because of this unable to give information about the direction of the orientation deviation. Corrections of orientation deviations in the manufacturing process are therefore impossible. Furthermore, because form deviations are included in the ISO orientation tolerance, there is no information about how much of the orientation deviation is caused by deviation of form.
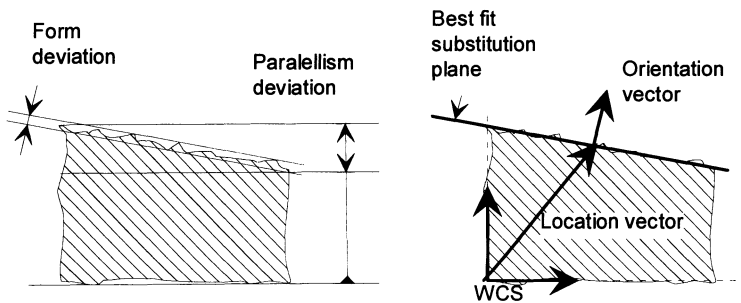

Figure 1. Orientation deviation, Comparison of ISO and Vectorial Tolerancing.

Many new methods are proposed to implement tolerances in product modelling systems. Requicha (1983) uses tolerance zones that cover all types of deviations in form, size, orientation and location. This means that the ISO tolerances of flatness, etc. have become superfluous. Other authors (Farmer and Gladman 1986, Weill 1988) have argued that this definition takes no account of functional, manufacturing, assembly and measuring requirements. Jayaraman and Srinivasan (1989) describes a method where tolerances are given as the theoretical limit boundaries when the combined effects of all associated tolerances are taken into account. This approach assures interchangeability of parts in assembly. J.U. Turner et. al. (1990) and J.U. Turner (1993) suggested a tolerancing theory where tolerance specifications are interpreted as constraints on a normal vector space of model variations, i.e., a vectorial representation of all ISO geometrical and dimensional tolerances constraining the actual surface. Technologically and Topological related Surfaces (TTRS) was introduced by Clement (Dufosse 1993, Gaunet 1993, Clement 1993, Clement 1995 and Desrochers 1995). In TTRS the association of two surfaces or group of surfaces is described with the 6 degrees of freedom (DOF). There are therefore 6 independent tolerancing parameters. Clement defines a Minimum Geometric Datum element (MGDE) which is the minimum set of point, line or plane necessary and sufficient to

define the displacements. Both VT and TTRS are based on the six degrees of freedom, however, VT uses location and orientation vectors and TTRS using the six degrees of freedom directly. TTRS implies using a tangential surface as the Substitute surface while VT is using best fit substitute surface. Separation of form deviation is therefore not possible in the TTRS model. The TTRS model are arranging surfaces and surface groups in pairs, while VT are using Workpiece Coordinate Systems.

In the following sections, we will introduce constructs of shape data in VT one by one in EXPRESS. Only the essential of the EXPRESS code is given here, using plane and cylinder as examples. The other types of surfaces: general, prismatic, spherical and rotation symmetrical surfaces, will not be shown here. This grouping of surfaces is according to the open DOF for each type of surface and is almost identical to the TTRS groups. (Dufosse 1993, Gaunet 1993, Clement 1993, Clement 1995 and Desrochers 1995)

2   VECTORIAL GEOMETRY MODEL

Vectorial Tolerancing (VT) was introduced by Wirtz (Wirtz 1988, Wirtz et al. 1990, Wirtz 1991, Wirtz et al. 1992). A similar model is proposed as a new ISO standard; new work item to ISO TC 10, ISO TC 3, dimensioning and tolerancing. This is also described by Henzolt (1993). Martinsen (1993) showed VT can be used for all types of surfaces. VT is a mathematically unambiguous model for describing nominal vectorial geometry and tolerances. It is suited for computer representation in the link between design, manufacturing, measuring and process control. VT utilises 3D tolerances as an integrated part of the Vectorial product model with automatic generation of NC-codes and measuring programs (Wirtz, et al., 1993). VT provides a clear distinction between size, form, location and orientation for each surface. Such a distinction is important for both functional analysis a manufacturing process control (Martinsen, 1995).

2.1 Degrees of freedom

The principle of 6 degrees of freedom (DOF) is a basic concept for VT. An infinite plane can be translated in two directions and rotated in one without changing the location and orientation of the plane. This is called the open DOF for a plane. An infinite plane has 3 open DOF, and therefore 3 fixed DOF. Only the fixed DOF of a surface needs tolerances. In the case of a plane, the position of a plane is toleranced by one tolerance on location, and two on orientation. An infinite cylinder can be translated in the axis direction, and rotated around the axis without changing the location and orientation of the cylinder. Hence, a cylinder has 2 open DOF, and needs tolerances on two location components and two orientation components, perpendicular to the cylinder axis.

2.2 Vectorial surface description

A surface is described by its location, orientation, form and size. In VT, location is described with a location vector, and orientation with a unit orientation vector. A nominal surface has a nominal location vector and orientation vector which describes the nominal position of the

surface. On a real workpiece, the real location, orientation and size are defined by a geometri-cally ideal substitution surface with the same form as the nominal surface. The substitute sur-face is calculated by the Gaussian best fit algorithm from the assessed coordinate measuring points on the real surface. Figure 2 shows the VT model of a plane. Deviation vectors are the subtraction of the nominal from the real vector. The location vector fixes the translation DOF of a surface. For surface types such as torus and sphere, the location is given as the centre point of the surface. For surfaces that do not have any well-defined centre point, the point has to be chosen. For cylinders, a point on the cylinder axis is chosen, and for a plane a point in the plane. This should, however, be done with a view to the function the surface will have in the assem-bled product. The orientation vector is a unit vector which fixes 2 rotational DOF of a surface. The orientation vector of a cylinder is the direction of the axis and for a plane the normal vector.
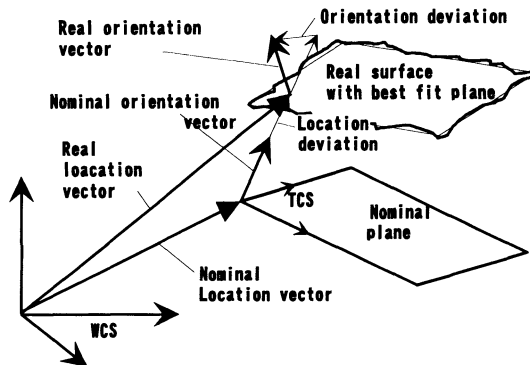

Figure 2. VT model of a plane.

```
ENTITY location_vector;
name : STRING;
x,y,z: lenght_measure_with_unit;
END_ENTITY ;

ENTITY lenght_measure_with_unit;
unit : STRING; -- e.g. mm.
value : REAL;
END_ENTITY;
```

```
ENTITY orientation_vector;
name : STRING;
x,y,z: REAL;
WHERE x**2 + y**2 + z**2 = 1 ; -- Length = 1
END_ENTITY;
```

In addition to location and orientation, a surface has a form and size. The form of the surface is described with an equation (or a set of parametric equations) with sizes as parameters. The sizes tells the size of the surface. It can be the radius of a cylinder or the apex angle of a cone. A torus will have two sizes, one small and one large radius. The corresponding size of a surface is by definition negative for inner surfaces and positive for outer surfaces. Other surfaces can have several sizes. The form deviations are in VT filtered out by the best fit algorithm. The form feature can then be treated separately.

The following is the EXPRESS definition of surfaces in VT. The definition of tolerancing attributes is described in section 3. Every surface is defined in a coordinate system, which is discussed in section 2.4.

```
ENTITY vt_face_surface ABSTRACT SUPERTYPE OF (ONEOF (general, prismatic, rotational, cylinder,
    plane, sphere));
name : STRING;
basis : coordinate_system;
END_ENTITY;
```

```
ENTITY plane SUBTYPE OF (vt_face_surface);          ENTITY cylinder SUBTYPE OF (vt_face_surface);
nom_location_vector: location_vector;               nom_location_vector: location_vector;
nom_orienation_vector: orientation_vector;          nom_orienation_vector: orientation_vector;
z_location_tolerance: loca-                          size : lenght_measure_with_unit;
    tion_vector_component_tolerance;                x_location_tolerance,y_location_tolerance: loca-
x_orientation_tolerance,                                tion_vector_component_tolerance;
    y_orientation_tolerance:: orienta-              x_orientation_tolerance, y_orientation_tolerance:
    tion_vector_component_tolerance;                   orientation_vector_component_tolerance;
form_tolerance: envelope_form_tolerance;            r_tolerance: size_tolerance;
END_ENTITY;                                         form_tolerance: envelope_form_tolerance;
                                                    END_ENTITY ;
```

2.3 Derived elements

The geometrical elements defining a coordinate system can be a face surface or elements derived from combinations of face surfaces. A derived element can be intersection point or line, line connecting two points, etc.

```
ENTITY derived_element
ABSTRACT SUPERTYPE OF (ONEOF(intersection_point, symmetry_point, intersection_line, perpendicu-
    lar_line, parallell_line, connection_line, symmetry_line, best_fit_line, perpendicular_plane, paral-
    lell_plane, connection_plane, symmetry_plane, best_fit_circle));
basis : coordinate_system;
name : STRING;
END_ENTITY;
```

```
ENTITY intersection_point                           ENTITY intersection_line
SUBTYPE OF (derived_element);                        SUBTYPE OF (derived_element);
source_elements: SET[1:?] OF geometric_element;     source_elements: SET[1:?] OF geometric_element;
location : location_vector;                          location: location_vector;
END_ENTITY;                                          orientation: orientation_vector;
                                                    END_ENTITY;
```

2.4 Coordinate systems

There can be several coordinate systems on a workpiece forming a tree structure of coordinate systems. The *Workpiece Coordinate System* (WCS) is the common basis. Position relations between surfaces with a special functional relationship, can be described in a Sub Coordinate System (SCS). Both these types of coordinate systems are clearly defined by the surfaces of the workpiece. The *primary direction* of a coordinate system is defined by a unit vector, fixing two rotational DOF. Second, the *secondary direction* is defined by a unit vector which are perpendicular to the primary direction. The secondary direction can be defined by the projection of an orientation vector not parallel to the primary direction. The third direction of the coordinate system is given by the cross product of the primary and secondary direction vectors. Finally is the origin of the coordinate system defined by a point, thereby fixing the three translation DOF.

```
ENTITY datum_feature_relationship;                  TYPE geometric_element = SELECT
name: STRING;                                            (vt_face_surface, derived_element);
relating_ element : geometric_element;              END_TYPE;
```

```
related_ element : datum;
END_ENTIY;

ENTITY datum ABSTRACT SUPERTYPE OF
(ONEOF(origin_datum, primary_direction_datum,
    secondary_direction_datum));
INVERSE relationship: datum_feature_relationship
    FOR related_element;
END_ENTIY;

ENTITY primary_direction_datum SUBTYPE OF
    (orientation_vector,datum);
END_ENTITY;

ENTITY secondary_direction_datum SUBTYPE OF
    (orientation_vector,datum);
END_ENTITY;

ENTITY origin_datum SUBTYPE OF
    (location_vector,datum);
END_ENTITY;
```

```
ENTITY coordinate_system
    ABSTRACT SUPERTYPE OF (ONEOF(
    root_coordinate_system, work-
    piece_coordinate_system,
    sub_coordinate_system, sur-
    face_coordiante_system));
name : STRING;
END_ENTITY;

ENTITY workpiece_coordinate_system
SUBTYPE OF (coordinate_system);
reference_coordinate_system :
    root_coordinate_system;
location: origin_datum;
primary_direction : primary_direction_datum;
to_be_secondary_direction : OPTIONAL secon-
    dary_direction_datum;
DERIVE
p : LIST[3:3] OF orientation_vector :=
    build_axes(location, primary_direction,
    to_be_secondary_direction);
WHERE dot_product(primary_direction,
    to_be_secondary_direction) > 0.0;
END_ENTITY;
```

The Root Coordinate System (RCS) is a superior coordinate system defining the position of the whole workpiece in a machine tool, measuring machine or in a the assembly with other workpieces. The WCS can be defined in this RCS.

2.5   Workpiece

A workpiece consists of a set of geometric elements of planes, cylinders, lines, points and so on. These geometric elements are the surfaces as well as derived elements.

```
ENTITY workpiece;
name : STRING;
basis : workpiece_coordinate_system;
coordinate_system_tree: SET [0:?] OF sub_coordinate_system;
face: SET [1:?] OF vt_face_surface;
END_ENTITY;
```

3   VECTORIAL TOLERANCES

3.1   Tolerances on location and orientation

The Vectorial tolerances are the tolerances on the location and orientation vector for the toleranced surface. The tolerance is maximum and minimum allowed components of the deviation vector. If the surface has any open DOF, the corresponding deviation vector components are zero. These components have therefore no tolerance.

If the orientation vector of the surface is [0, 0, 1], orientation tolerances will be the tolerances on the E_x and E_y components of the orientation deviation vector. The orientation tolerances are the tolerances on the components perpendicular to the orientation vector. The location

tolerances will be the tolerances on the x_0, y_0 and z_0 components of the location deviation vector. Figure 3 shows the tolerances of a plane. The translation DOF in x_0 and y_0 direction and the rotation around z-axis are open DOF, there are therefore no tolerances on these components. In the case of a cylinder, E_z orientation and z_0 location is open and has no tolerance.
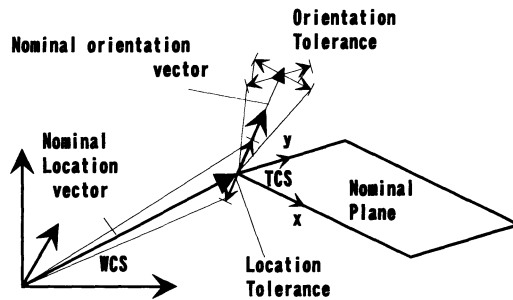

Figure 3. Vectorial tolerances on a plane

```
ENTITY location_vector_component_tolerance;
name : STRING;
tcs: tolerance_coordinate_system;
max, min : lenght_measure_with_unit;
lenght_measure_with_unit;
END_ENTITY;
```

```
ENTITY orientation_vector_component_tolerance;
name : STRING;
tcs: tolerance_coordinate_system;
max, min: REAL;
END_ENTITY;
```

3.2   Tolerance Coordinate System, TCS

The TCS is the coordinate system where a tolerance of a surface is described. The TCS is always defined according to nominal geometry and is defined by the *directions that is to be toleranced*, i.e., defined by the function of the surface. The reference coordinate system to the TCS is the coordinate system where the tolerances are referring to. A TCS describes the tolerance space and the transformation of a deviation vector from the reference coordinate system to the tolerancing space for evaluation. For example: defining tolerances to a plane referenced but not aligned to the WCS, a TCS with the z-axis aligned with the plane normal can be introduced. When measuring the real surface, the vectors for this plane must be transformed from the WCS to the TCS for calculation of the deviation vectors and a evaluation of tolerance conformance.

```
ENTITY tolerance_coordinate_system;
name : STRING;
reference_coordinate_system : coordinate_system;
origin : location_vector;
x_axis, y_axis, z_axis: orientation_vector;
END_ENTITY;
```

3.3   Size tolerances

The tolerances to the location and orientation are the tolerances to the position of the surface in WCS. Sizes are constant parameters which describe the size of the surface. A size is independent from the position of the surface, and needs therefore no basis in a coordinate System. The size tolerances will be maximum and minimum allowed deviation of the nominal sizes.

```
ENTITY size_tolerance;                    ENTITY envelope_form_tolerance;
name : STRING;                            name : STRING;
r_max, r_min: lenght_measure_with_unit;   max_point_dev : lenght_measure_with_unit;
END_ENTITY;                               WHERE max_point_dev.value > 0;
                                          END_ENTITY;
```

3.4   Tolerances on form deviations

In Vectorial tolerancing, form deviations are filtered out from location and orientation through the Gaussian best fit algorithm. The form deviations are therefore treated separately. The simplest way to limit the form deviations is to define an envelope tolerance region. This means the distance from any point on real surface to the best fit substitute surface must be within the tolerance limit.

```
ENTITY envelope_form_tolerance;
max_point_dev : REAL;
END_ENTITY;
```

Another option which is feasible for planes and cylinders, is to use tangential surfaces to express the form deviations. When tangential surfaces are used, the form deviations are described with the location and orientation or size deviation of one or two tangential surfaces relatively to the best fit surface. An advantage with the tangential surface approach is that this approach ensures 100% compatibility with ISO tolerance standards. Wirtz (1993) writes, however, that the difference between tangential and parallel region to best fit is in practice much smaller than the measuring uncertainty caused by low number of measuring points and the difference in measuring direction.

4   EXAMPLE

Here follows an example of the vectorial geometry and tolerances on a simple workpiece using the ISO standard for clear text encoding of exchange structure: ISO 10303-21 (STEP part 21). The workpiece, shown in Figure 4 and Figure 5, consists of seven surfaces, 6 planes and one cylinder. The function of the workpiece requires tight tolerances on position, perpendicularity to plane BP6, and cylindricity of the cylinder C1. Other important tolerances are the parallellity of planes P5 and BP6 and position of plane P5, as well as perpendicularity and flatness of the planes BP1, BP4 and BP6. Figure 5 shows corresponding tolerances on the workpiece according to the ISO 1101 standard. The planes BP6, BP1 and BP4 is here the datum planes A, B, and C which forms the datum system ABC similar to the WCS in the VT case. One important difference between VT and ISO are, however, VT planes are based on a Gaussian best fit substitution plane on the real workpiece. ISO planes on the other hand, are based on minimum movement contact planes. When coordinate measuring machines are used the VT surfaces is based on a all measured points, while a ISO interpreted contact surface is based on only few peak points. The latter requires a large number of measuring points on the surface. Other differences between ISO and VT are that ISO position tolerance includes form and orientation deviation, ISO orientation tolerance includes form deviation. The magnitude of each deviation type is not known. Furthermore, the direction of the orientation deviation is unknown.
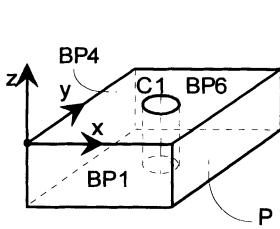
Figure 4. Example
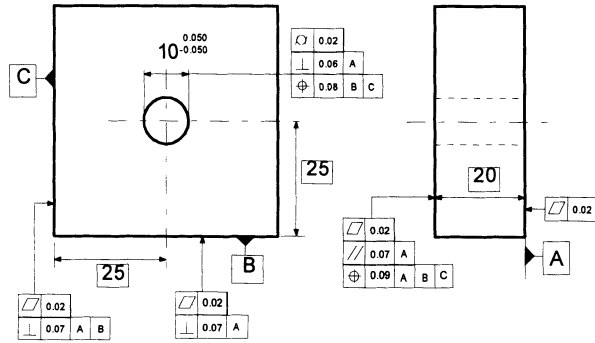   workpiece.   **Figure 5.** ISO tolerances.

   Two TCS are introduced, TCS_root and TCS_wcs. TCS_root has the RCS as reference, the 6 components defining the WCS are toleranced here, and are thereby the tolerances of the WCS in the RCS. All other tolerances are defined in the TCS_wcs. Plane BP6 defines the primary direction (z-axis) of the WCS with the orientation vector of BP6. In other words; the unit vector **k** of the WCS is identical with the orientation vector of BP6, on nominal as well as manufactured workpieces. The orientation of BP6 has therefore by definition no deviation in WCS. BP6 will, however, have deviation in the RCS, and the tolerances on BP6 must refer to the RCS. Since the orientation vector of plane A is identical with the primary direction of the WCS, these tolerances will be the tolerances on the primary direction of WCS in RCS. The secondary direction is defined by the intersection line between BP6 and BP1. This means Plane BP1 defines the secondary direction of the WCS with its E_x-orientation component, and the E_x-orientation component of BP1 is therefore toleranced in TCS_root referring to the RCS. The origin of the WCS is the intersection of plane BP6, BP1 and BP4. This means the location tolerance of BP6, BP1 and BP4 are toleranced in the TCS_root as well. This sums up 6 tolerance components of the planes defining the WCS, consequently 6 DOF. These components are defining the WCS, and the tolerances on them will be the tolerances of the WCS in the TCS_rcs. The remaining components; E_y-orientation for BP1 and both orientations for BP4, as well as all other surfaces will be toleranced in the TCS_wcs.

```
ISO-10303-21; DATA;
#1= LENGTH_MEASURE_WITH_UNIT('mm',0); /* 0 mm */
#2= LENGTH_MEASURE_WITH_UNIT('mm',50); /* 50 mm */
#3= LENGTH_MEASURE_WITH_UNIT('mm',25); /* 25 mm */
#4= LENGTH_MEASURE_WITH_UNIT('mm',-20); /* -20 mm */
#10 = LOCATION_VECTOR('root_origin',#1,#1,#1); /* origin of rcs */
#11 = ORIENTATION_VECTOR('root_x',1,0,0); /* x-axis of rcs */
#12 = ORIENTATION_VECTOR('root_y',0,1,0); /* y-axis of rcs */
#13 = ORIENTATION_VECTOR('root_z',0,0,1); /* z-axis of rcs */
#14 = ROOT_COORDINATE_SYSTEM('root',#10,#11,#12,#13); /* rcs */
#15 = TOLERANCE_COORDINATE_SYSTEM('tcs_root',#14,#10,#11,#12,#13);
#30 = ORIGIN_DATUM('WCS_origin',#1,#1,#1); /* origin datum for WCS */
#31 = PRIMARY_DIRECTION_DATUM('WCS_z',0,0,1); /* primary direction for WCS */
#32 = SECONDARY_DIRECTION_DATUM('WCS_x',1,0,0); /* secondary direction for WCS */
#33 = WORKPIECE_COORDINATE_SYSTEM('WCS', #14,#30,#31,#32); /* The WCS */
```

#34 = LOCATION_VECTOR('origin',#1,#1,#1); /* Origin of tcs_wcs */
#35 = ORIENTATION_VECTOR('x',1,0,0); /* x-axis of tcs_wcs */
#36 = ORIENTATION_VECTOR('y',0,1,0); /* y-axis of tcs_wcs */
#37 = ORIENTATION_VECTOR('z',0,0,1); /* z-axis of tcs_wcs */
#38= TOLERANCE_COORDINATE_SYSTEM('tcs_wcs',#33,#34,#35,#36,#37); /*tcs with wcs as reference */
#40 = LOCATION_VECTOR('lbp1',#1,#1,#1); /* location vector of plane bp1 */
#43 = LOCATION_VECTOR('lbp4',#1,#1,#1); /* location vector of plane bp4 */
#44 = LOCATION_VECTOR('lp5',#1,#1,#4); /* location vector of plane p5 */
#45 = LOCATION_VECTOR('lbp6',#1,#1,#1); /* location vector of plane bp6 */
#46 = LOCATION_VECTOR('lc1',#3,#3,#1); /* location vector of cylinder c1 */
#50 = ORIENTATION_VECTOR('obp1',0,-1,0); /* orientation vector of plane bp1 */
#53 = ORIENTATION_VECTOR('obp4',-1,0,0); /* orientation vector of plane bp4*/
#54 = ORIENTATION_VECTOR('op5',0,0,-1); /* orientation vector of plane p5 */
#55 = ORIENTATION_VECTOR('obp6',0,0,1); /* orientation vector of plane bp6 */
#56 = ORIENTATION_VECTOR('oc1',0,0,1); /* orientation vector of cylinder c1 */
#60 = LENGTH_MEASURE_WITH_UNIT('mm',0.010); /* max */
#61 = LENGTH_MEASURE_WITH_UNIT('mm',-0.010); /* min */
#70 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_bp1',#15,#60,#61); /* location tolerance for
    bp1. Note that the TCS is the tcs with RCS as reference, this is because bp1 is used to define WCS origin. The
    6 components used to define the WCS. These components therefore have no tolerances in the WCS, but in the
    RCS. This can also be viewed as the tolerances of the WCS in its superior coordinate system, RCS. */
#73 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_bp4',#15,#60,#61);
#74 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_p5',#38,#60,#61);
#75 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_bp6',#15,#60,#61);
#76 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_x_c1',#38,#60,#61);
#77 = LOCATION_VECTOR_COMPONENT_TOLERANCE('loctol_y_c1',#38,#60,#61);
#80 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_x_bp1',#38,0.001,-0.001);
#81 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_y_bp1',#15,0.001,-0.001);
#86 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_x_bp4',#38,0.001,-0.001);
#87 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_y_bp4',#38,0.001,-0.001);
#88 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_x_p5',#38,0.001,-0.001);
#89 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_y_p5',#38,0.001,-0.001);
#90 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_x_bp6',#15,0.001,-0.001);
#91 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_y_bp6',#15,0.001,-0.001);
#92 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_x_c1',#38,0.002,-0.002);
#93 = ORIENTATION_VECTOR_COMPONENT_TOLERANCE('oritol_y_c1',#38,0.002,-0.002);
#94 = LENGTH_MEASURE_WITH_UNIT('mm',0.010); /* max form deviation */
#95 = ENVELOPE_TOLERANCE('form tolerance for all surfaces',#94);
#96 = LENGTH_MEASURE_WITH_UNIT('mm',0.050); /* max size deviation */
#97 = LENGTH_MEASURE_WITH_UNIT('mm',-0.050); /* min size deviation */
#98 = LENGTH_MEASURE_WITH_UNIT('mm',10.000); /* radius of cylinder c1 */
#99 = SIZE_TOLERANCE('size tolerance of c1', #96,#97); /* Size tolerance of cylinder c1 */
#100= PLANE('BP1',#33,#40,#50,#70,#80,#81,#95); /* Plane bp1 */
#103= PLANE('BP4',#33,#43,#53,#73,#86,#87, #95); /* Plane bp4 */
#104= PLANE('P5', #33,#44,#54,#74,#88,#89,#95); /* Plane p5 */
#105= PLANE('BP6',#33,#45,#55,#75,#90,#91,#95); /* Plane bp6 */
#106= CYLINDER('C1',#33,#46,#56,#98,#76,#77,#92,#93,#99,#95); /* Cylinder c1 */
#110 = LOCATION_VECTOR('loc_point1',#1,#1,#1); /* location of intersection point */
#111 = LOCATION_VECTOR('loc_line1',#1,#1,#1); /* location of intersection line */
#112 = ORIENTATION_VECTOR('ori_line1',1,0,0); /* orientation of intersection line */
#113 = INTERSECTION_POINT('point1',(#100,#103,#105),#110);
#114 = INTERSECTION_LINE('line1',(#100,#105),#111,#112);
#115 = DATUM_FEATURE_RELATIONSHIP('origin_rel',#113,#30); /* Origin is defined by the intersection point
    between BP1, BP4 and BP6 */
#116 = DATUM_FEATURE_RELATIONSHIP('pr_dir_rel',#105,#31); /* Plane BP6 defines the primary direction of
    the WCS */
#117 = DATUM_FEATURE_RELATIONSHIP('sec_dir_rel',#114,#32); /*The secondary direction is defined by the
    intersection line between BP6 and BP1 */
#200 = WORKPIECE('Square plate with hole', #33, (),(#100, #101, #102, #103, #104, #105, #106));
ENDSEC; END-ISO-10303-21;

5   CONCLUSIONS

This paper shows the formal description of VT with examples using the EXPRESS language developed by STEP. Obtained result can be used in general to help understand how to use VT. The description includes the procedures of the definition of coordinate systems, coordinate system tree with root coordinate system, workpiece coordinate system and sub-coordinate system, as well as the relations between tolerances, tolerance coordinate systems and the tolerances on surfaces defining a coordinate system.

In the future work, the obtained EXPRESS definition will be a basis for a formal Comparison of VT and other tolerancing methods, such as tolerances after the ISO standards and TTRS. ISO/DIS 10303-47 of Integrated generic resources: Shape variation tolerances is to provide a general description of dimensioning and tolerancing. This paper will be an example to show how the general description can be applied. The obtained EXPRESS definition will be used as a reference description of product data model based on Vectorial geometry and tolerancing.

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