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KINEMATIC STRUCTURE REPRESENTATION OF PRODUCTS AND MANUFACTURING RESOURCES

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ABSTRACT

The basics of kinematic modelling in majority of CAE applications are about to define motion constraints for components relative to other components. The main concepts are links and joints which combined build the topology and geometry of the mechanism. With the additional information about joint type, actuation and motion range, the model provides useful information for motion study. The kinematic structure schema of the standard ISO 10303-105 provides proven capability to represent this information. In the second edition of this standard, currently under development, the granularity and functionality of the model will be increased and further integrated with other parts of the standard ISO 10303. Case studies are presented on utilization of the added capabilities in different applications within product and manufacturing resource representation to illustrate the importance of these features. This paper reports on the author's contribution to this standard.

KEYWORDS

Kinematic, Modelling, Computer aided engineering (CAE)

1. INTRODUCTION

Kinematic data models provided in current ISO 10303 standards is not addressing all needs in the engineering area. Another disadvantage of the current data model is that it is not fully integrated into the overall framework provided by the general representation approach used throughout ISO 10303.

The research results provided in this paper shows how kinematics is going to be further integrated into the general representation structure of ISO 10303, allowing to address further needs in engineering.

There are two known implementation projects of current kinematics representation scheme p105ed1 (ISO 10303-105 edition 1) as used in the application protocol ISO 10303-214. The first was the European project IDA-STEP (Integrating Distributed Applications on the Basis of STEP Data Models) (Rech et al, 2004) and later the Swedish project DFBB (Digital Factory Building Block) (Li et al, 2011). During these projects limitations of the standard were identified. Together with possible solution strategies they have been presented to ISO TC184 SC4 (2009) by Klein and Hedlind which lead to the initiation of a new edition of the kinematic data models in ISO 10303.

This paper presents the research that has contributed to the first draft (ISO TC184 SC4 WG12, 2011) of p105ed2 (ISO 10303-105 edition 2 working draft). The main principle of how kinematics is represented is preserved from p105ed1, but the data model for p105ed2 has been reworked to facilitate new functionalities and reuse of data structures from the integrated generic resources of ISO 10303. With this increased integration, the granularity of the kinematics representation elements is made available for association with other non-kinematic properties.

The kinematic model in p105ed1 is overconstrained, preventing from re-using the same constructs in variations of the same model. E.g. for a topological model only one mechanism could be provided. These limitations have been overcome in p105ed2 by deep integration with ISO 10303 representation structures.

Also it is ensured that each part of the model can be re-used, e.g. for variations.

2. REPRESENTATION OF KINEMATICS

During analysis and synthesis of kinematic mechanisms, model simplification is common. Typical simplifications are e.g. to assume that a part is completely rigid, even if we know that it bends under stress. Or neglect that there are tolerances or plays in kinematic pairs. E.g. a rotational pair typically also allows axial play.

Ability to represent complicated mechanisms with a simplified model requires understanding of the principles of kinematics. This section focus on how the principles of kinematics are represented in ISO 10303.

2.1. REPRESENTATION PRINCIPLES

Kinematic joints and links are the topologic aspect of a mechanism. In a graph the joint is represented as an edge, and the link as a vertex. It is important to notice that a joint is always relating exactly two links. So in the case that 3 links are related to each other then 2 or even 3 joints have to be used; even if this is not immediately obvious.

Figure-1 illustrates the kinematic topology with open and closed kinematic loops for an ABB IRB6660 robot (3D model and link names are provided by ABB). This 3D model consists of 108 components and for the purpose of analyzing the reachable work volume of the robot 9 links and 9 joints have been identified.

A kinematic pair is the geometric aspect of a joint and provides motion constraints between two links. Each link comes with its own coordinate system, also called geometric context together with geometric elements such as locations, orientations, curves and surfaces that are needed to formulate the kinematic interaction with other links. The kinematic interaction is described by a pair that is relating geometric elements of the two involved links with each other together with other information.

Motion constraints can be done for translation and rotation, which in 3 dimensions become 6 DOF (degrees of freedom). These constraints can also be expressed as rolling or sliding with reference to a curve or surface. For the robot in Figure-1 are all kinematic pairs constrained to revolute motion i.e. only 1 DOF. Additional information to a kinematic pair is motion range, actuation and pair value. The pair value is data defining a specific state, e.g. an angle for e revolute pair.

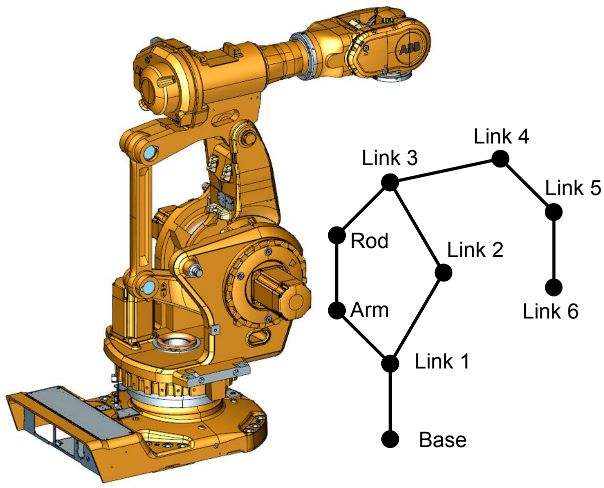

Figure 1 – Kinematic topology with open and closed kinematic loops

The behavior of a mechanism can be analysed in two ways, either forward or backward.

In forward analysis the pair values are given, and the objective is to find the position and orientation of one or several links. With a sequence of pair values, possible continuously described by a function, motion paths for the links can be calculated. Pair values can only be set for actuated pairs and the motion path is constrained by the actuated direction.

In backward analysis the position and orientation for one or several links is given. The objective is to find the corresponding pair values. A link motion path can be turned into functions describing pair values. Actuated pairs are used to achieve the links position and orientation constrained by the actuated direction.

In kinematic synthesis the objective is to design a mechanism that achieves a specified motion. This process starts with defining the kinematic topology and continues with the geometric aspect as pair types, motion range and actuated directions. This process is typically iterative with interrelated decisions to be made. During this elaborative work, pairs with suitable DOF and actuated direction can be chosen in variants without having a direct corresponding physical realizable mechanism.

Notations for representing kinematics are essential in engineering to find mechanism design solutions, similar to the notation for mathematics. Design of clock mechanisms was one of the early engineering domains to drive research on a notation for kinematics. The basic notation set by Reuleaux (1876) on the concept of kinematic pairs, joints and links is today practiced in CAE applications. Reuleaux showed how his notation can be used for analysis and synthesis of mechanism and how similarities between mechanisms can be identified.

For this paper it is of interest to point out Reuleaux proposal (1876) on how to treat mechanism with non-rigid links. For this Reuleaux introduced the concept of tension-organ (e.g. wire or chain) and pressure-organ (e.g. fluid or gas). This enabled kinematic modeling of links capable only to pull or push. This is a capability that is still not common in CAE applications nor supported in p105ed1. In p105ed2 this issue is addressed with the added functionality to represent the actuated direction of a kinematic pair.

A graphical notation for kinematic mechanisms, consisting of pairs and links and their motion is provided in ISO 3952 "Kinematic diagrams".

2.2. HISTORY OF ISO 10303 KINEMATICS

The only ISO 10303 application protocol using p105ed1 is ISO 10303-214. An application protocol based on ISO 10303 framework and modelling methodology using p105e1 is DIN PAS 1013 developed by the MechaSTEP industry research group in Germany.

The first proposal for a kinematic representation schema in ISO 10303 was developed by the European research projects NIRO Neutral Interfaces for Robotics (Bey et al, 1994) and later InterRob Interoperability of Standards for Robotics in CIME (Mikosch, 1997). This proposal was accepted by ISO as basis for further integration with the ISO 10303 framework. During this integration process several changes were made to align it with modelling principles used throughout ISO 10303. These changes were, by the NIRO project, considered to make implementation less efficient (Bey et al, 1994).

The NIRO proposal was more compact in number of entities compared to p105ed1 while still covering similar scope. The NIRO schema did not require the same degree of reasoning over a data set to get all information. This is also exemplified when comparing the different schemas to describe a kinematic pair (Bey et al, 1994). Figure-2 shows a comparison of instantiated data set for a prismatic pair using the different schemas. In the NIRO proposal the pair entity has mandatory attributes for the pair values and optional attributes for the motion range. In p105ed1 three entity instances are required instead. First the kinematic pair entity itself, and then one entity for the motion range, and another entity for the pair value, both referencing the pair entity. In p105ed2 this requires two entities. A pair entity can directly describe motion range optionally, while pair values is kept as a separate entity.

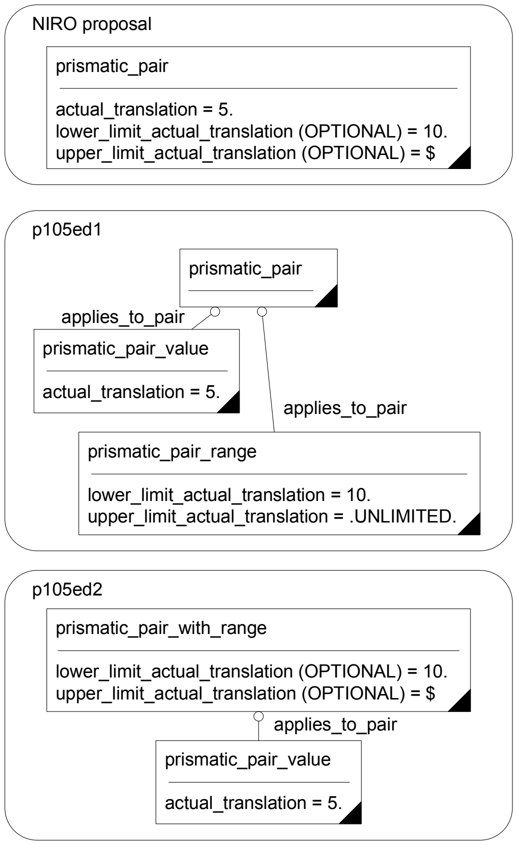

Figure 2 – Instantiation of prismatic pair and data for motion range and pair value using different schemas

One underlying reason for these differences is how an optional attribute is viewed. The argument during p105ed1 development was that an optional attribute should be avoided as the cardinality then can be considered as unclear. For p105ed2 this has been resolved with normative text declaring that absence of motion range data imply that the motion range is unlimited. It is also possible to describe a pair without range using a supertype entity that does not specify motion range but have the same constraints in DOF.

Even though p105ed1 is done according to the modelling principles applied in ISO 10303, there is low use of the integrated generic resources and this limits the association between elements of the kinematic representation and other properties. In p105ed2 a higher integration with the integrated generic resources has been accomplished, enabling e.g. properties as friction to be associated to a kinematic pair. The integration is done through reused representation structures retrieved via declaring more entities as subtypes of integrated generic resource entities. This required also rearrangements of the p105ed1 overall structure. With these changes it is also believed that it will be easier for understanding and implementation. The level of changes makes p105ed2 not compatible with p105ed1, but the kinematic representation principles are unchanged; all concepts from p105ed1 are preserved or transformed into equivalent concepts.

Below are the overall structure of p105ed1 and p105ed2.

The p105ed1 consist of following 3 schemas.

- Kinematic structure schema
- Kinematic motion representation schema
- Kinematic analysis control and result schema

The p105ed2 consist of following 6 schemas.

- Kinematic property schema
- Kinematic topology schema
- Kinematic structure schema
- Kinematic state schema
- Kinematic motion representation schema
- Kinematic analysis control and result schema

The p105ed1 Kinematic structure schema has been split into 4 more refined and specialised schemas. In focus for this paper are the 3 schemas for kinematic topology, structure and state.

3. ISO 10303 KINEMATICS EDITION 2

Following are excerpts from p105ed2, with instantiation examples that illustrate the benefits of the higher integration and increased functionality.

General representation structure of ISO 10303 is defined in ISO 10303-43. It provided concepts for the entities; representation, representation_context and representation_item and how to relate them. In ISO 10303-42 the general representation capabilities are specialized for geometry and general topology. P105ed2 provides further specialization of these concepts for kinematics.

For these examples a single acting cylinder is used, illustrated in Figure-3, as this is a common machine component and with properties were the improvements in p105ed2 become obvious. This machine component consists of 2 links, a cylinder and a piston. The piston have 2 DOF, it can translate and rotate. There is one actuated direction which drives the piston to the right, see Figure-3. To move the piston to the left will require an external applied force. The piston rotates freely.

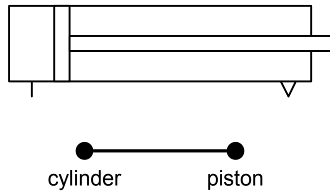

Figure 3 – Single acting cylinder (ISO 1219 symbol) and corresponding kinematic topology

3.1 KINEMATIC TOPOLOGY SCHEMA

Figure-4 illustrates an excerpt of the p105ed2 kinematic topology schema. Kinematic_joint and kinematic_link are made subtypes of the generic topological entities edge respectively vertex declared in the topology schema of ISO 10303-42 were these concepts are well recognized for shape representations. From a viewpoint of an application protocol using p105ed2 the granularity of kinematic representation is now increased for association with other properties. In p105ed1 the joint and link entities are isolated from the main representation structure of ISO 10303 which prohibits relationship with other properties.

The introduced entity kinematic_topology _structure is made a subtype of the representation entity from ISO 10303-43 and collects kinematic joints as representation items. In a similar way, but with more specialized entities is it also possible to explicit represent substructures, network structures and directed structures as tree structures.

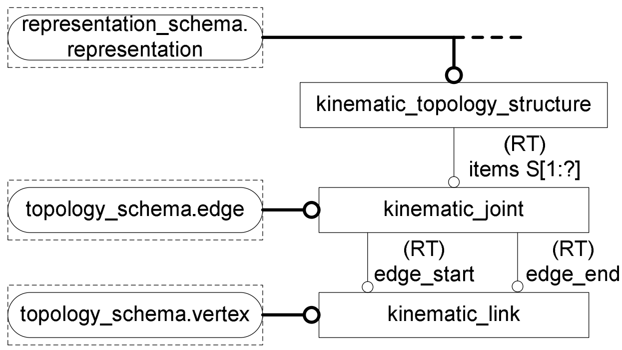

Figure 4 – Kinematic topology schema

3.2 KINEMATIC STRUCTURE SCHEMA

Figure-5 illustrates an excerpt of the p105ed2 kinematic structure schema. As a kinematic pair is the geometric aspect of a joint, this entity is made a subtype of geometric_representation_item from ISO 10303-42, which brings a geometric context. This can be combined with globally defined units for the whole mechanism.

In kinematics low and high order pairs are common concepts. A low order pair does not require a reference to a shape for defining its DOF. A high ordered pair requires references to surfaces or curves to define its motion constraints.

The concept of low and high order kinematic pairs was used in the NIRO schema proposal, but removed from the schema in the integration process for p105ed1 with the argument that it does not carry any clear semantics and thereby this distinction was considered superfluous. For p105ed2 this distinction has been taken back. The semantics has been increased by a new breakdown of the different pair types with added functionality to better support kinematic synthesis. Most of the low order pairs can primarily be described by listing their DOF in terms of rotation and translation. However there are some pair types that require additional geometric information and therefore an additional classification have been introduced, the low_order_pair_with_motion_coupling.

This arrangement made it possible to have a supertype of "simple" low order pairs enabling control of the different DOF individually, which supports kinematic synthesis. Instance of this supertype should only be used when there is no specific low order pair subtype with the desired DOF configuration.

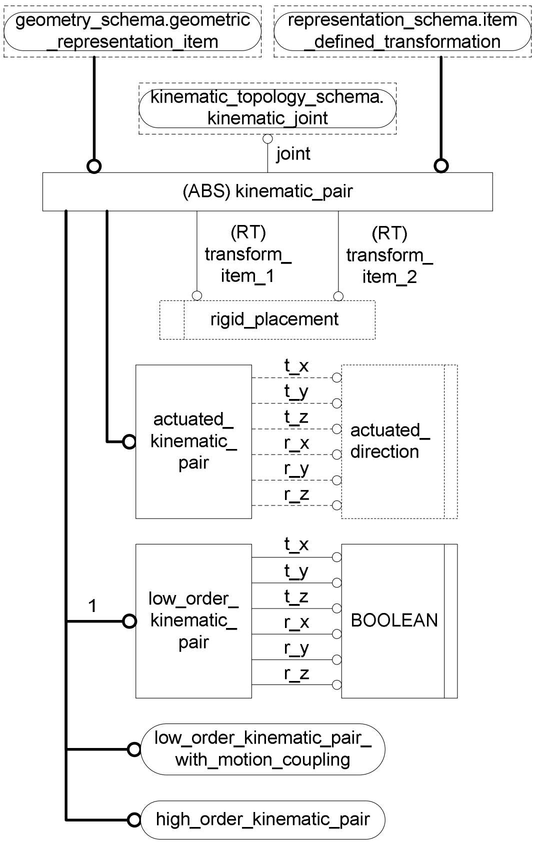

Figure 5 – Kinematic structure schema

The following specialized pair types are available in p105ed2.

Low order pairs:

- fully constrained pair (no DOF);
- revolute pair (one rotation DOF);
- prismatic pair (one translation DOF);
- cylindrical pair (one rotation and one translation DOF);
- universal pair (two rotation DOF);
- homokinetic pair (two rotation DOF);
- spherical pair with pin (two rotation DOF);
- spherical pair (three rotation DOF);
- planar pair (one rotation and two translation DOF);
- unconstrained pair (three rotation and three translation DOF);

Low order pairs with motion coupling:

- screw pair;
- rack and pinion pair;
- gear pair;

High order pairs:

- point on surface pair;
- sliding surface pair;
- rolling surface pair;
- point on planar curve pair;
- sliding curve pair;
- rolling curve pair.

The introduced specialized pairs are homokinetic pair and spherical pair with pin. The homokinetic_pair was first introduced in ISO 10303-214, and is now included in p105ed2. Spherical_pair_with_pin was included because it is also supported by ISO 3952.

Figure-6 illustrates how subtypes of the low_order_kinematic_pair redeclare each DOF attribute and derive valid DOF configuration from local domain rules. This way the DOF configuration is explicitly provided for all the subtypes of low_order_kinematic_pair.

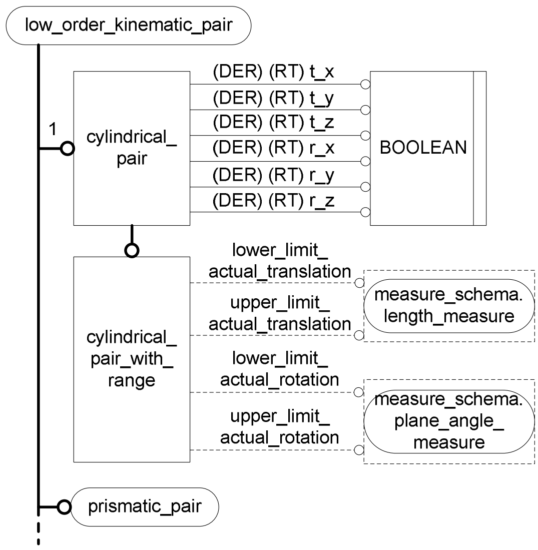

Figure 6 – Low order kinematic pair

As defined in p105ed1 a kinematic pair can only be actuated in all its DOF or not at all. A consequence of this is that one or several artificial links is needed if the pair is not actuated in all DOF. Figure-7 illustrates this for the cylinder component. The actuated prismatic pair can move the piston in both directions and the non-actuated revolute pair enables the piston to rotate freely. As this is an unnatural way of describing motion constraints this part has been changed in p105ed2 with a solution also enabling representation of single acting actuation.

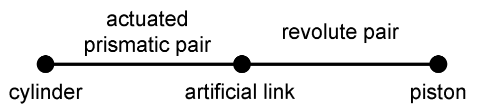

Figure 7 – Use of artificial link to emulate the kinematic pair of a cylinder component

The coordinate system of the kinematic pair, named contact frame, is used as reference for the direction. For low order pairs the contact frame and the pair frame for second link coincide. The enumeration items of actuated direction are:

- bidirectional;
- positive_only;
- negative_only;
- not_actuated.

In this way the cylinder component can be represented without use of an artificial link as illustrated in Figure-8.

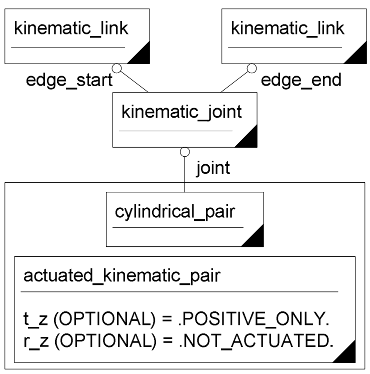

Figure 8 – Cylindrical pair actuated in one direction

Figure-9 illustrates how the property static friction can be assigned to a specific kinematic pair in a specific structure using p105ed2 in an application protocol. The complete set of entities to represent the property e.g. the measure value of the static friction is left out due to limited space, but it follows the established way for property modeling in ISO 10303.

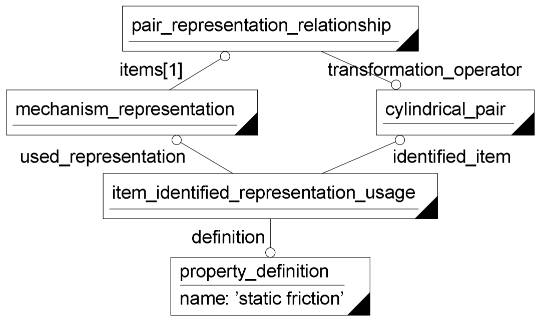

Figure 9 – Kinematic pair with assigned static friction property

3.3 KINEMATIC STATE SCHEMA

Figure-10 and Figure-11 illustrates excerpts of the p105ed2 kinematic state schema. A mechanism state representation is made a subtype of the representation entity from ISO 10303-43 and collects pair values as representation items.

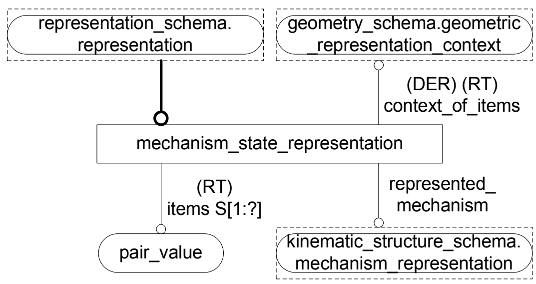

Figure 10 – Kinematic state schema

Subtypes of the pair_value entity for each type of kinematic pair declare values to define a state of the pair. Pair_value is made subtype of the geometric_representation_item entity from ISO 10303-42, which brings a geometric context and defined units to the pair value.

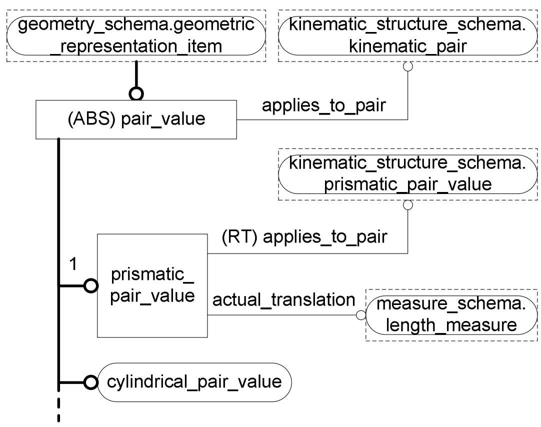

Figure 11 – Kinematic pair value

One example of what this higher integration with ISO 10303-42 and ISO 10303-43 enables is the possibility to associate a nominal state with measured deviation.

4. KINEMATIC PAIR ERRORS

A mechanisms geometric accuracy is of interest for both products and manufacturing resources. Identification of systematic kinematic errors enables compensation to get higher accuracy.

For machine tools kinematic errors are one of the major error sources affecting geometric accuracy. Kinematic errors for both linear and rotation axis are divided in component errors and location errors. (Schwenke et al., 2008)

Component errors address deviation with six measure values that are dependent on axis motion. For a linear axis these measures are; one positioning error, two linear errors, and three angular errors. Location errors for a linear axis address deviation with three measure values, one position in plane error and two angular errors. Location error is defined as the average line of the axis motion.

When p105ed2 is used in an application protocol, kinematic errors can be represented as properties of a kinematic pair. Component errors as measured would be associated to the kinematic pair in a given state defined by a pair value. An interpolation of component errors for different pair values would be associated to the kinematic pair in a given mechanism.

Volumetric accuracy for a machine tool is defined as “The maximum error between any two points in a specified volume of measurement” (McKeown, 1973). Calculating volumetric accuracy from kinematic pair errors using p105ed2 data imply error stack-up analysis based on the kinematic topology schema and kinematic structure schema.

Figure-12 illustrates how deviation from straight-line motion (component error) for a prismatic pair will be represented using p105ed2 in an application protocol. On the left side is the representation structure for interpolated deviation data using bounded curves (defined by ISO 10303-42 as a curve of finite arc length with identifiable end points). On the right side is the representation structure for measured deviation in one state for the prismatic pair. The interpolated property definition is related as dependent on the property definition for measured deviation.

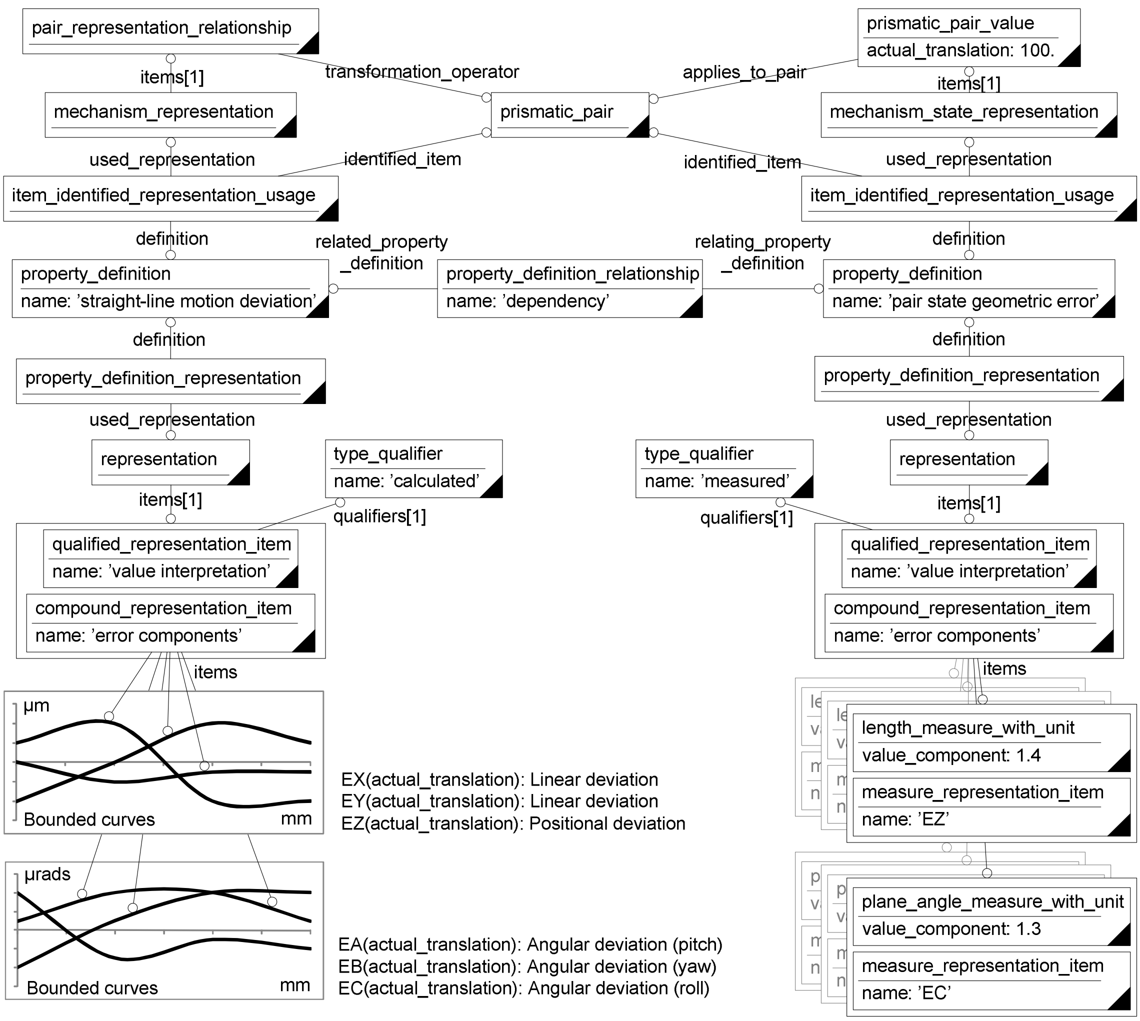

Figure 12 – Prismatic pair with representation of straight-line motion deviation

In machine tool metrology straight-line motion parameters and measure is defined in ISO 230-1 and well known in industry. The parameter naming convention is based on a three letter combination. For a linear axis these are e.g. EXZ for linear deviation and EZZ for the positional deviation. The last letter indicates the direction of motion using a nomenclature defined in ISO 841 for a set of NC machines. As the direction of motion is defined by the kinematic pair, the last letter can preferably be omitted from the name of the measure_representation_item. This gives a uniform representation of error components, independent of the axis name. If the three letter combination is requested it can be represented as alias identification in the context of ISO 841 for the measure_representation_item.

Donmez et al. (1986) provided a general methodology to predict the resulting error of a sequence of kinematic pair errors. This methodology is developed for machine tool error compensation, but can also be applied for other mechanisms and is based on multiplication of homogeneous transformation matrices (HTM). The elements of one HTM are the error elements of one kinematic pair. With this methodology any state, defined by nominal pair values, can be analysed to predict the resulting geometric error.

5. CONCLUSIONS

With p105ed2 new capabilities in kinematic modelling are enabled for the ISO 10303 framework. Artificial constraints in p105ed1 have been removed and the p105ed2 schema gives more compact data sets. The presented examples on enabled capabilities and higher integration with other parts of ISO 10303 illustrate the importance of these features.

Further research on this will be on enabling usage of mathematical functions to represent continuous motion in kinematic pairs.

For applications on the examples of increased integration a more stringent modelling specification will be required than can be done in this paper. With an application protocol or application modules using p105ed2 the representation will be unambiguous. Note that the schemas presented in this paper are taken from a working draft for the standard on which principle consensus has been achieved.

6. ACKNOWLEDGMENTS

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