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Kinematical product specifications in engineering design

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ABSTRACT

The basics of kinematic modelling in CAD applications are to define motion constraints for components relative to other components for the purpose of motion studies. The main concepts are links and joints with information about degree of freedom, actuation and motion range which combined build the topology and geometry to characterise a mechanism. For translating design intent into motion requirements more accurate modelling of the mechanism is needed, including tolerances on error motion in addition to tolerances on functional surfaces. This paper identifies existing limitations and new possibilities for model based kinematical product specification and verification.

1. Introduction

The basics of kinematic modelling in CAD applications are to define motion constraints for components relative to other components for the purpose of motion studies. For design synthesis and analysis of kinematic mechanisms, model simplification is common. Typical simplifications are for instance to assume that a part is completely rigid and with its nominal shape, even if we know that it bends under load. Or neglect that there are motion tolerances or plays in kinematic pairs. E.g. a rotational kinematic pair typically also allows axial play.

Motion tolerances are commonly specified implicitly in technical product specifications. For products in general, motion requirements are instead converted and only specified as tolerances on its components' functional surfaces. Machine tools differentiate from products in general, with definitions for error motion characterisation, tolerances and test procedures, as standardised in ISO 230-1 *Test code for machine tools* [1]. Even though the standard is developed for machine tools, it is made applicable for mechanisms in general.

Shape variation and motion variation on a manufactured product are interrelated and dependent on the design specification. Ability to specify motion tolerances in addition to shape tolerances enables a more complete translation of design intent into the design specification. Similar to the specification of shape tolerances which requires a nominal shape representation as its context, the specification of motion tolerances requires a nominal mechanism representation as its context.

It is common that CAD applications support shape representation and tolerances based on Geometrical Product Specifications (GPS) [2], while for kinematics the functionality is limited to mechanism representation without motion tolerances. There are CAM applications for machine tool simulation, as presented by Fesperman et al. [3] utilising machine tool specialised data schema for simulation of kinematic performance in machining. The high performance requirements for machine tools have driven research and development of fundamental principles and methods for error motion characterisation. These principles and methods are valuable for design synthesis and analysis for any type of mechanism.

2. Kinematic modelling principles

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 in year 1876 [4] on the concept of kinematic pairs, joints and links is today practiced in CAD applications. Reuleaux showed how his notation can be used for analysis and synthesis of mechanisms and how similarities between mechanisms can be identified.

CAD mechanism modelling conforming to ISO/NP 10303-105 [5], also known as STEP kinematics, addresses kinematic joints and links as a topological aspect of a mechanism. In a graph, the joint is represented as an edge, and the link as a vertex. A kinematic pair is

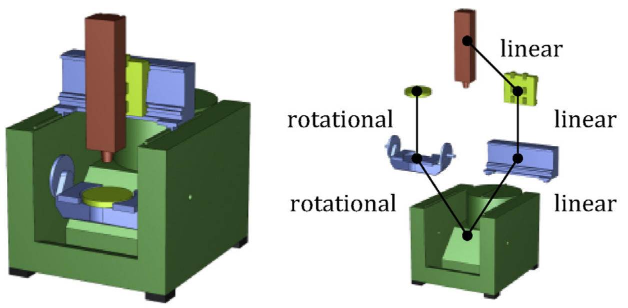

Fig. 1. Kinematic topology structure for representing functional motion constraints of a 5-axis milling machine tool.

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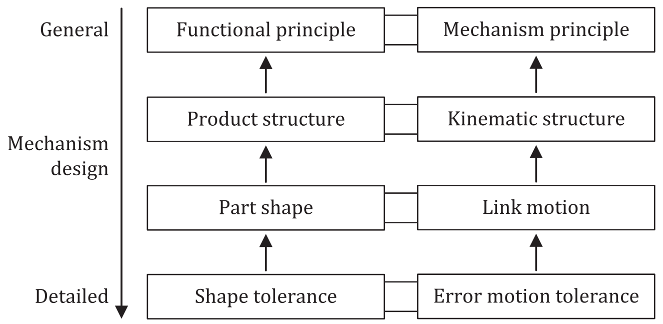


Fig. 2. Representation context in mechanism design detailing.

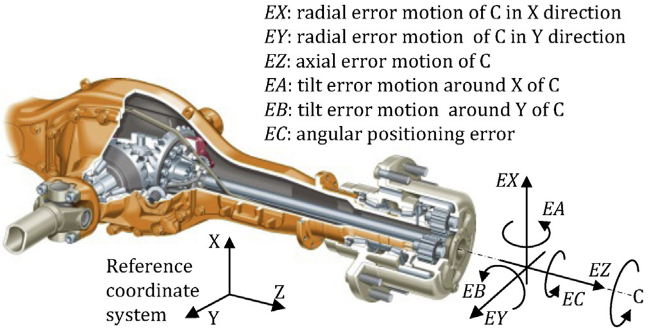
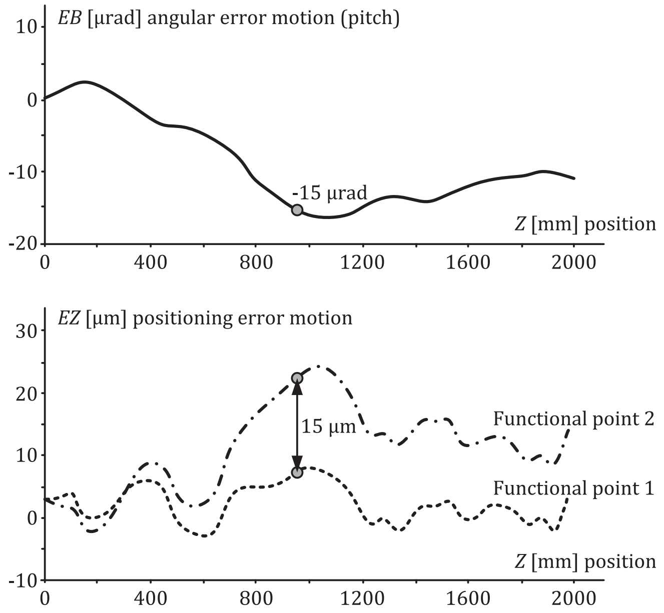


Fig. 3. Error motions of axis of rotation according to ISO 230-1 *Test code for machine tools* [1] applied for kinematic characterisation of a vehicle rear axle.



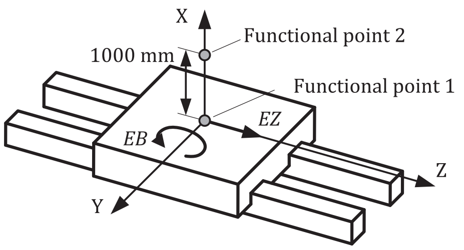


Fig. 4. The concept of functional point illustrated on angular error motion effect on positioning error motion, adopted and modified from ISO 230-1 [1]. When moving the axis, the angular error *EB* measured at the functional point 1 is equal to the angular error in functional point 2, but the positioning error *EZ* differ between the functional points.

the geometric aspect of a joint and provides information about degree of freedom, actuation and motion range. The kinematic data schema is a specialisation of the geometry and general topology schema used for shape representation in STEP [6].

From the viewpoint of kinematic structure modelling in general, ISO 230 does aggregate physical kinematic joints to abstract joints describing the functional motion constraints. Fig. 1 illustrates this modelling principle. There are two physical kinematic joints between tilting table and machine tool base while the kinematic model represent this as a single joint.

In this paper a CAD modelling approach is proposed. Motion requirements for mechanisms in general are represented explicitly in a kinematic mechanism context based on STEP kinematics [5] and referencing ISO 230-1 [1] concepts originating from machine tool metrology. Fig. 2 illustrates this modelling approach in relation to modelling product structures and part shape tolerances, which in a similar way utilise GPS concepts originating from shape metrology. Based on mechanism functional principles the product structure and kinematic structure are defined. In detailing the mechanism design, part shapes and link motions provides the context for shape tolerances and error motion tolerances respectively.

2.1. Design data integration

Generally, the representation of information can be viewed as relating data to its valid interpretation context. This is common information modelling basics. Further applied, new possibilities of reasoning on a coherent data set are created. For machine tool modelling, this principle has been applied to relate data to its semantic context [7]. To fully utilise this principle for product design is of major importance. It is also important that models and model schemas are decoupled from where, how and when the models are created, manipulated and finalised. Generated models should be applicable in new design strategies and methodologies. The models should not constrain strategies nor methodology for manipulating or using the models; i.e. where, how and when the models are applied. The basis for this is the STEP data model, extended and applied for kinematical product specifications with new schema elements added.

2.2. Modelling error motion tolerances

Specification of error motion tolerances should mirror error motion measurement and methods for verification.

For error motion characterisation two main principles are direct and indirect measurement [8]. Direct measurements detect errors of single abstract joints and enables compensation of error at its source. Indirect measurement detects errors of a set of abstract joints and enables compensation of superposed errors.

Component errors and location errors are two used concepts for the characterisation of rotation and linear motions [8].

For a rotational motion the component errors are; two radial errors, one axial error, two tilt errors, and one angular positioning error, as illustrated in Fig. 3 applied for a vehicle rear axle. For a linear motion the component errors are; one positioning error, two straightness error, and three angular errors. Location error is defined as the deviation of the error motion average axis from its nominal position and orientation.

For evaluation of the linear error motion, the concept functional point [1] is of importance, as these errors include the effects of angular error motions as illustrated in Fig. 4.

In machine tool metrology, the naming convention for the error types is based on a three letter combination. For a rotation axis *C* these are e.g. *EXC* for radial error motion and *EZC* for axial error motion. The last letter indicates the direction of motion using a nomenclature as defined in ISO 841 for a set of NC machines. For CAD modelling, the direction of motion is defined by the kinematic pair in the geometric context of the mechanism and the last letter can preferably be omitted from the name. This gives a uniform representation of error types, independent of the axis name.

3. Data schema for kinematic modelling

The recent development in kinematic modelling [6] being applied to STEP has provided new capabilities for CAD based

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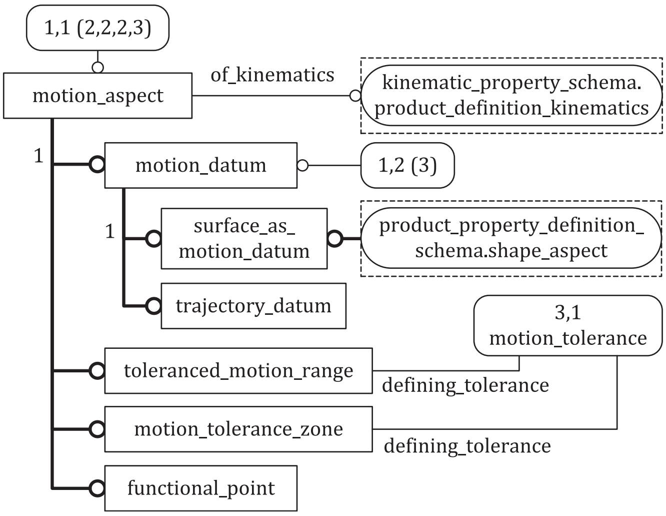

Fig. 5. Motion aspect EXPRESS-G diagram (1 of 3).

kinematical product specifications. In this research a schema for kinematic variation tolerances is developed to communicate a solution fulfilling the required kinematic modelling principles. The schema structure is similar to the STEP schema structure for shape variation tolerances. For design verification and validation [9] new capabilities are enabled with the developed data schema.

For the development of the core data schema of STEP, semantic and syntactic rules have been defined based on principles and requirements for the standard. One of the fundamental rules is to relate information elements based on their existence dependence. These rules together with the principles and requirements are documented by Danner et al. [10] and applied in this research.

The presented schema is not complete by itself for kinematical product specifications; it is intended to be used as a part of STEP. Integrated use with STEP kinematics [5] is essential.

3.1. Motion aspect schema

Fig. 5 illustrates the concept of motion aspect used to identify a motion element of a mechanism, for instance the motion related to a kinematic pair, or a motion used as datum for another toleranced motion. The range and zone is used to define a motion region for a tolerance, for instance a direction for a radial error motion. The functional point is used to identify a point on the moving link (of a kinematic pair), not necessarily on the physical boundary of its shape. The corresponding concept in shape modelling is shape aspect, which is used to identify a shape element.

3.2. Motion dimension schema

Fig. 6 illustrates the concept of motion location and extent. The motion location is used to specify the location of a motion in relation to another motion, for instance the eccentricity between two rotational motions. The motion extent is used to specify the

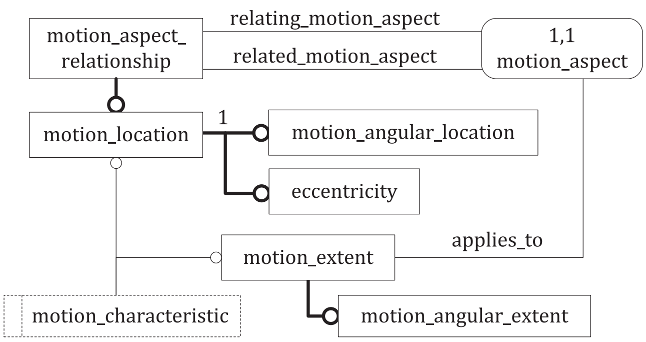

Fig. 6. Motion dimension EXPRESS-G diagram (2 of 3).

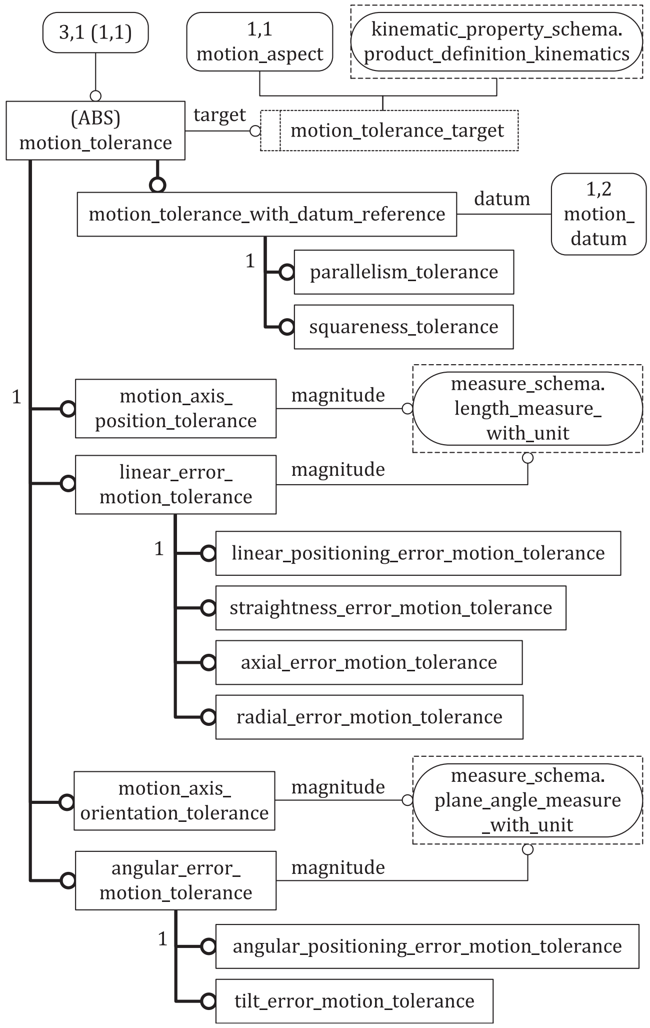

Fig. 7. Motion tolerance EXPRESS-G diagram (3 of 3).

motion independent of its location, for instance a rotation angle. The STEP kinematic model [5] can implicitly define these dimensions. A data schema for motion location and extent is needed for an explicit definition. The representation of these motion characteristics will use the common representation structure of STEP. The corresponding concepts in shape modelling are dimensional location and dimensional size.

3.3. Motion tolerance schema

Fig. 7 illustrates the concept of motion tolerance used to specify the magnitude of the allowed error motion for a motion aspect, or for the all-over mechanism motion. The motion tolerance with datum reference may be used together with other motion tolerance subtypes, for instance a squareness tolerance combined with a motion axis orientation tolerance to define the allowed angular deviation from 90° between a reference (possibly a motion) and a target motion aspect. The corresponding concept in shape modelling is geometric tolerance.

4. Application of kinematical product specifications

Error motion tolerances expressing permissible deviations, for instance due to effect of thermal issues [11], enables validation of a mechanism function.

Identification of basic information units independent of product type [12] is the approach enabling the presented solution for CAD based kinematical product specification. In engineering design application, the product type specific data augment the product generic data model. This supports efficient development and use of

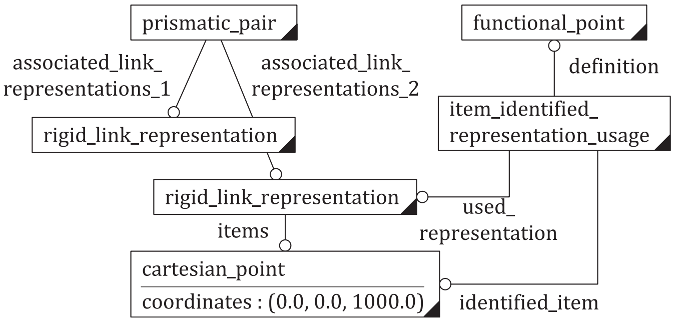

Fig. 8. Data instance diagram for representation of a functional point.

CAD and CAM implementations through reuse of application functionality.

Representation of manufacturing resources such as machine tools, robots and fixtures, are within the scope of the STEP standard, with the approach to treat these as any other type of product. Information requirements and applications of virtual machine tools [13] are supported through the integration of product specific concepts and product generic data schemas. This combination provides a stable data model also capable of representing manufacturing resources developed in the future.

Fig. 8 illustrates the developed data schema in proposed use as a part of STEP for the representation of a functional point. The Cartesian point, as one of the items of the rigid link representation, is identified and associated to the defined functional point.

4.1. Semantic representation

Semantic representation of shape tolerances, as supported by STEP (in addition to tolerance presentation), enables computer aided shape tolerance and variation analysis. Semantic representation of error motion tolerances, applying presented data schema, enables computer aided error motion tolerance and variation analysis. Based on semantic representation the tolerance synthesis can be made more efficient, considering mechanism's interrelated part shapes and link motions, and support model based verification and validation.

4.2. Design rationale representation

Representation of design intent in terms of design constraints in CAD is important for communication, manufacturing and reuse of design solutions, and is not limited to shape modelling [14]. Translating design intent into shape requirements is a part of the specification process defined in the GPS standards [2]. Application of the presented CAD based kinematical product specifications supports representation of the design rationale for specified shape requirements in a design solution. For instance, a component used as guideway for another component's relative motion, with shape requirements on surfaces in contact, makes the information on error motion tolerances provide a more complete translation of the design intent.

5. Conclusion

The presented solution for CAD based kinematical product specification addresses needs in diverse engineering fields in industry and academia. Tolerances on error motion for products in general are commonly converted to shape tolerances of the components. With the proposed modelling approach, these functional requirements can instead be represented explicitly in a geometric context in addition to tolerances on functional surfaces. In this way the translation of design intent is improved enabling a more complete representation and accurate communication of a design solution as well as supporting more efficient product variant management.

Geometric and topological similarities in the representation of shapes and mechanisms are utilised in STEP kinematics [6]. For the tolerance representation of shapes and error motions, similarities are utilised in the presented data schema. Error motion concepts developed in machine tool metrology is used for the presented solution for CAD based kinematical product specifications, and can be compared with the use of GPS concepts in CAD shape modelling.

The main principle of relating data to its valid context, applied to kinematic modelling, gives new possibilities for increased design productivity.

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