

Title:

Eucentric and Compucentric Transformation of Kinematic Virtual Prototype

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Introduction:

Using a digital model of a virtual prototype of a part or the whole device is a standard tool for analyzing selected functional characteristics of the proposed kinematic system [1,9,16]. Typical examples include mechatronic elements [7,8,10,12] that precisely control the system's position using all specified degrees of freedom [11]. In the design phase, these procedures are crucial for defining collisions within the device's functional motion range [6,13]. At the same time, the functional range can be precisely defined [13]. In addition to the design of the relevant devices [14], the presented procedures are applicable to the design of accessories, such as fixtures and adaptations, to increase the efficiency of application deployment [5,15,18,19]. The virtual prototype in a digital CAD model serves as an important information tool during the development and technical preparation phases of production [17]. In addition to serving as the basis for the direct production of parts in the form of drawings or drawingless model documentation, they are the starting point for simulations and analyses tailored to the proposed equipment's purpose. A typical example of simulation and analysis is the examination of the system's kinematics in its entirety by combining the possible cases of the mutual position of the individual bodies. The position is usually defined with respect to a selected reference coordinate system, where the selected point is transformed to the specified position within the system's degrees of freedom. The inverse case is to achieve the position of the selected elements of the system when the position of the selected point on the moving platform must be maintained. The basic principle for solving eucentric and compucentric simulation procedures is the use of advanced CAD tools. The basis is the application of general rules to create individual models and assemblies. The primary aspects are the orientation of the coordinate systems of the sub-models and the specific definition of constraints - the conditions of mutual position of the models in the assembly. Parameterization is primarily done using internal tools. A spreadsheet interface is introduced to increase efficiency and enable sub-procedures for non-CAD users, allowing appropriate controls using general analytical procedures. Practical use is possible at all of these levels, including combinations thereof. The methods presented in the text are implemented in the NX CAD tool, which is particularly open to implementing a broader range of procedures to achieve the same or similar results. This creates conditions for optimization of procedures and possible modification according to the specifics of particular tasks. At the same time, emphasis is placed on generality and versatility, enabling the implementation of procedures across a broader range of CAD tools from different categories and maturity levels. The benefit of applying the above concept is the ability to demonstrate the control of a virtual prototype's kinematics through external parameters. The key feature is that the parameterization is independent of the model geometry. The kinematics are directly linked to the reference geometry, providing a wide range of variability in educational processes that align with practical procedures. In parallel with general procedures for implementing kinematic processes in a CAD environment, the presented procedures can be used to teach specific technological processes based on kinematics and, where applicable, the external control of relevant parameters, such

as tool or beam paths. This is significant for teaching the principles of operation of tracking devices at the level of optical, opto-digital, or electron microscopes. The implementation of these procedures is intended for the theoretical and practical training of technical personnel at secondary schools and universities, as well as in workplaces engaged in industrial design and system application [2-4]. The teaching of procedures based on eucentric and compcentric transformations is particularly relevant in the design of mechatronic systems. Linking the concept to coordinate systems provides a systematic framework for demonstrating and implementing variable solutions, including options for analysis and comparison. The benefits can be verified using both qualitative and quantitative factors. Qualitative factors include the expansion of skills in systematically linking reference geometry to external values while adhering to general and specific modeling procedures. Quantifiable factors include, in particular, the speed of task processing while maintaining the corresponding qualitative factors, as well as the frequency of errors or deviations from defined rules in the resulting data.

Main Idea:

Both compucentric and eucentric kinematics are implemented in assembly mode. The realistic component models visualize the presented procedures, which are always related to coordinate systems, making the configuration universal and applicable to any engineering solution. The general and specific rules for creating individual models are secondary to implementing the procedures presented; parametric and non-parametric models can be used. Under certain circumstances, data without model geometry can also be used, where the only object is the coordinate system. Thus, imported third-party geometry can also be placed in the appropriate files. A criterion for the success of the procedures is the uniformity of orientation of the coordinate systems of the subcomponents and the parent levels of the assemblies. The component position control is implemented in a three-dimensional coordinate system, with the basic orientation TOP-View: the horizontal X-axis, vertical Y-axis, and Z-axis, which is perpendicular to the XY-plane and points towards the observer. The above configuration may vary depending on the specifics and nature of the real-world application. The transformations are realized by displacements along each axis and by rotations about each axis. The transformation matrices are constructed following the coordinate system. The initial layout of the assembly and the orientation of the coordinate system, implemented for the components and the superordinate levels, are shown in Figure 1.

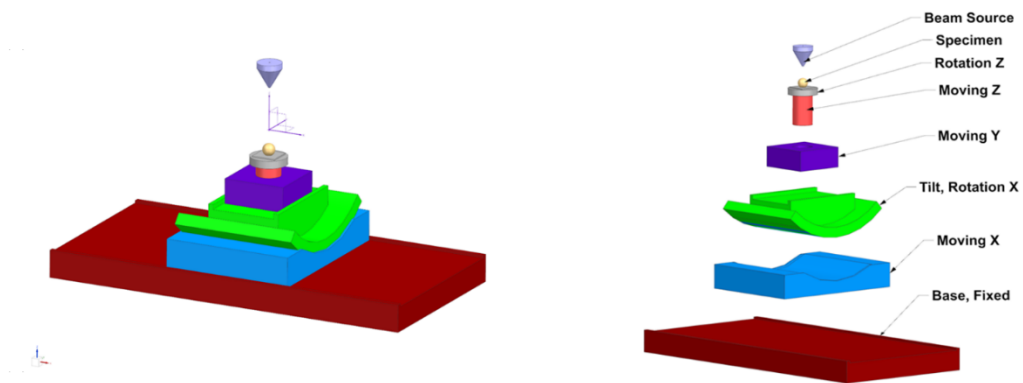


Fig. 1: Initial layout and exploded view of the generic assembly with a description.

Figure 2 presents a decomposed view of the assembly, including a description of its components, as outlined below. An example of the report navigator, with components and definition state indicated, is also shown in Figure 2. The coordinate system elements define all constraints, position, and orientation conditions. The elements represent the X, Y, and Z axes, the XY, XZ, and YZ planes, the origin point of the coordinate system, and the coordinate system object used to determine orientation. These objects are part of the CSYS datum, representing a user-defined coordinate system.

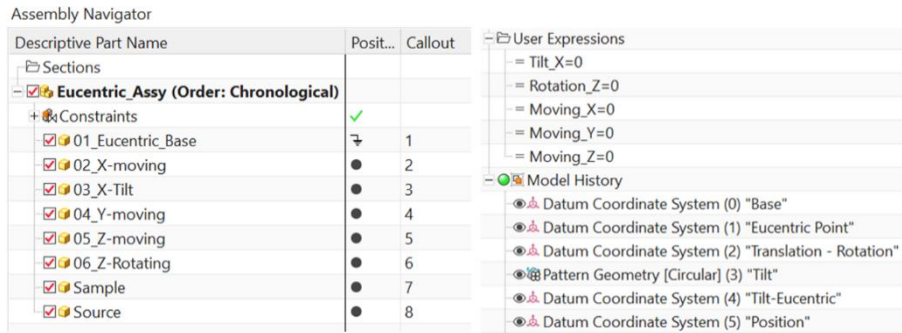


Fig. 2: Assembly Navigator with related components and expressions of transformation.

The basic coordinate system is the CSYS datum, located and oriented relative to the part's absolute coordinate system. It corresponds simultaneously to the eucentric point of the modeled system. No other object is defined associatively to the Base Datum CSYS object and serves as a general reference. The associative reference to which the associated coordinate systems controlling the positions of the components are associatively defined is the Datum CSYS eucentric point. It is a position and orientation reference for motion control. The range of motions in the direction of all principal axes and rotations about the vertical axis of the table is controlled by Datum CSYS Translation-Rotation. The tilt of the table plane about the X-axis of the eucentric coordinate system is controlled by an associative copy of Datum CSYS Translation-Rotation, rotating about the X-axis by a defined tilt angle.

The amount of table extension is controlled along the axis, which also controls the table's rotation. It ensures visibility of any object on the table from all directions of the hemisphere. All links are provided exclusively through coordinate systems, thus ensuring independence from the model geometry. The system can be considered a universal template for technical solutions of a given category. A system of user-defined variables controls the range of motions. Variable values can be entered directly or via an external source. A representation of the alignment of the coordinate systems defined for motion control is shown in Figure 4. The coordinate systems of all components are aligned identically and independently of the model geometry. The alignment of the coordinate systems with respect to the eucentric point serves as the initial reference for coordinate values in space. The subsequent transformation, covering the complete reaching of any selected point from the range given by the design solution, consists of the transformation of the displacement for individual coordinates according to the transformation matrix (1):

$$[x, y, z] = [0, 0, 0] \quad (1)$$

The transformation matrix for translation about the XYZ axis and rotation around the X and Z axes (2).

$$\begin{aligned}
 T_{\varphi x} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \varphi x & -\sin \varphi x & 0 \\ 0 & \sin \varphi x & \cos \varphi x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} T_{\varphi z} = \begin{bmatrix} \cos \varphi z & -\sin \varphi z & 0 & 0 \\ \sin \varphi z & \cos \varphi z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} T_{x, y, z} \\
 &= \begin{bmatrix} 1 & 0 & 0 & X \\ 0 & 1 & 0 & Y \\ 0 & 0 & 1 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}
 \end{aligned} \quad (2)$$

Examples of transformation matrices created in MS Excel are shown in Fig. 3. The transformation matrix determines the coordinates of the reference coordinate system of the component during computer-centered rotation.

Stage coordinates (kinematic order)		Transformation Matrix X -Tx	Tilt Matrix (Around X)-Tt	Transformation Matrix Y-Ty	Transformation Matrix Z -Tz	Rotation Matrix R (about Z) -Tr
X	4,035	1 0 0 4,035	1 0 0 0	1 0 0 0	1 0 0 0	0,707 -0,71 0 0
T	0	0 1 0 0	0 1 0 0	0 1 0 -40,8	0 1 0 0	0,707 0,707 0 0
Y	-40,771	0 0 1 0	0 0 1 0	0 0 1 0	0 0 1 4,6	0 0 1 0
Z	4,6	0 0 0 1	0 0 0 1	0 0 0 1	0 0 0 1	0 0 0 1
R	45					

Transformation results Tx*Tt*Ty*Tz*Tr		Compuotation Matrix Tc
0,707	-0,71	0 4,035
0,707	0,707	0 -40,8
0	0	1 4,6
0	0	0 1

Fig. 3: Examples of transformation matrices created in MS Excel.

The above table system can be used to generate variables for transforming coordinate systems, which determine the position and orientation of components. The connection is possible using internal CAD application functions, via macros, or the above matrix relationships can be implemented directly in the mathematical function editor for variable control.

According to the transformation matrix, the rotation transformation for individual coordinates is controlled around each axis. The transformation is implemented only around the X-axis and the Z-axis. In this way, any point orientation can be achieved in combination with translations.

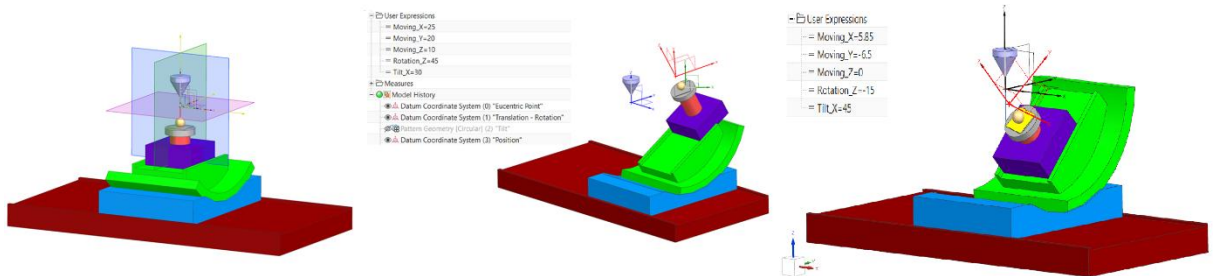


Fig. 4: Datum Geometry, Eucentric and Compucentric motion.

Conclusions:

This paper compares two possible approaches to controlling eucentric and compucentric kinematic simulations using CAD tools. Both approaches are implemented in assembly mode, where the primary controlled component objects are coordinate systems transformed by defining variable constraints that determine their position, or position relative to the coordinate system of one of the parent assembly levels. Using only reference geometry, associatively linking both within components and concerning parent assemblies, produces a general system applicable to a wide range of similar applications with different models. Using a transformation matrix via an external table is advantageous for motion control without the need to know how to operate the corresponding CAD tool. At the same time, the method's portability across different assemblies, workstations, and possibly different CAD systems is advantageous. The prerequisite is the existence of an assembly model template with consistent parameterization of the constraints controlling the components' relative positions, the components themselves, or the components' positions in relation to the coordinate system. A disadvantage is the risk of transferring rounding errors when a requirement for repeated high-order accuracy is present. The advantage of using an internal variable system is the integrity of the parameters and the ability to control the components' positions through constraints. The transferability of the concept is possible

only within a particular system or within systems with a certain degree of compatibility. Specific, in-depth knowledge of the procedures in a given CAD application is required. Portability is made possible by the concept of dependency on coordinate systems and an optimised template. The significant contribution of this concept to the education and skill development of technical staff is evident from the qualitative research, which assesses technical proficiency and the fulfillment of assignment objectives in relevant contexts, taking into account acceptable task completion times and low error rates. The research is conducted in the education sector as part of the teaching of a set of design and technology-oriented courses in a vocational university program. At the same time, the research is conducted in industrial practice, as part of staff training and the subsequent solving of real-world tasks. The results are determined for individual participants. For verification, tasks or parts of tasks corresponding to individual research samples are selected. The qualitative benefit in the academic sector, comparing the control and experimental groups, is 46 percentage points of the achievable score for the control group and 58 percentage points for the experimental group. A key feature of the experimental group is the application of the presented concept to teaching practices. In the industrial sector, the benefit is even more significant, primarily because the baseline knowledge level is more homogeneous across the experimental and control groups. In the industrial sector groups, the resulting qualitative parameters for the solved tasks are 84% for the control group and 95% for the experimental group. In both cases, the benefit can be considered in terms of increasing the effectiveness of implementing the aforementioned approaches in educational processes and, subsequently, in solving industrial tasks.

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