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FUNCTIONAL INTERFACE-BASED ASSEMBLY MODELING

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ABSTRACT

Current CAD system approaches to assembly representation do not support the full range of needs for an assembly model. They cannot account for the natural manufacturing and assembly variability that occurs in the assembled interfaces. The current solvers work well for idealized assembly design behaviors at nominal conditions, but in order to make accurate predictions about assembly performance and product quality the variability of the assembled interfaces must be comprehended in the assembly model. This paper will outline two key issues to support a robust approach to assembly modeling based on characterizing the true mating surface contact between parts in the assembly. These assembly interface definitions are adaptable enough to achieve an exact constraint design to ensure a stable analysis. These approaches are based in kinematic theory and support the efficient solution of the assembly constraints in the presence of geometric variation. An example of this approach within the context of a tolerance analysis application will be presented.

INTRODUCTION

The purpose of assembly models in CAD systems and product development has evolved over the years. Initially assembly models were used for addressing basic nominal design issues such as identifying interference and clearance within an assembly. These analyses only required that the components be located in the assembly in their correct absolute position and orientation. Measurements could then be made in this context showing the degree of interference and clearance in the nominal design.

Next, assembly models were used in the design and analysis of nominal kinematics behavior. Knowing only the absolute part positions was no longer sufficient. The relative part motions that were allowed by kinematic constraints were the important factors to be modeled. This led to assembly modeling techniques that defined the axes of rotation and the directions of motion of one part relative to another. As parametric models began to increase in popularity these kinematic constraints were also required to update and stay consistent with the parametric updates. Most major CAD systems currently support at least this level of assembly model and are working toward the next.

Continuing market pressures to develop and deliver new products faster, cheaper, and at higher quality are driving the need for assembly models that not only provide information about design issues but also information about manufacturing issues. How will the assembly behave under the influence of manufacturing variation? How robust is the design given the tolerances and manufacturing process plan? The assembly model used to support this type of analysis requires more than capturing nominal kinematic behavior that updates from key parametric variables. In order to support this level of analysis the assembly model must be able to represent the true assembly interface relationships that will occur when real parts are manufactured and assembled together.

This paper will present two key aspects of an approach to assembly modeling that will support the extended needs of today’s design and manufacturing environments.

BACKGROUND

The basic goal of assembly modeling is to define or determine the position and orientation of each component in the assembly relative to the assembly coordinate system. One simple approach to achieve this goal is to explicitly specify each component’s position and orientation. This method, however simple, does not include a definition of the component relationships that maintain these positions and therefore cannot update under the influence of variation.

In its unconstrained state, each component exhibits six degrees of freedom in its location and orientation relative to the assembly coordinate system. As components are assembled within an assembly, their individual degrees of freedom are removed by the assembly constraints that are imposed. Rather than explicitly specifying each component's position and orientation, the position and orientation is determined indirectly by finding the solution that simultaneously satisfies all the imposed assembly constraints.

Each assembly constraint defines directions of free motion and directions of force transfer of one component relative to another. The system of equations needed to solve for the position and orientation of each component is generated by solving for the magnitude of the motions in the free motion directions while maintaining contact in the force transfer directions.

These free motion and force transfer directions can be explicitly defined for each assembly constraint or they can be derived from the assembly interface that imposes the constraint. [Stoddard, 1995] Basing the assembly constraint directly on the assembly interface definition allows the assembly model to directly respond to component-level feature variation. This paper presents a robust method for extracting the free motion and force transfer directions directly from the assembly feature definition at the point of contact.

The next issue to consider when solving for the position and location of each component is the principle of exact constraint [Blanding, 1999]. In practice most assembly designs are over-constrained in the idealized nominal design. For example, a component may contact another component through two planar contacts in a corner as illustrated below.

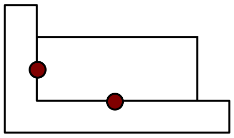

Figure 1: Over-constrained Corner Contact

Each of the planar contacts forms an assembly constraint. The combination of the two planar contacts forms a set of constraint equations that over-constrains the block. This over-constrained set of equations is often solvable in the assembly nominal condition because the two planar contacts provide 'redundant but equal' constraint. Both planar contacts can be maintained simultaneously.

However, when variation is introduced to the system, these two constraints are no longer 'redundant but equal'. For example, if the angle of one of the corners in contact becomes larger than the other corner angle, planar contact can no longer be made on both planar faces. No solution can be found that will satisfy all constraints. In reality, the assembly will maintain planar contact with one of the planar faces and the other planar face will be reduced to an edge contact as shown in Figure 2.

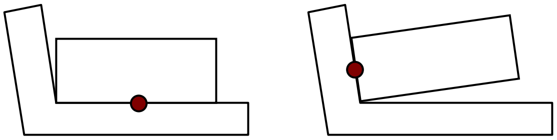

Figure 2: Over-constrained assembly Example

In order to accurately model the propagation of variation throughout an assembly it is important to know which planar contact is more likely to be maintained. It is therefore important that the assembly constraint definition have enough adjustment to be able to achieve an exactly constrained state. In other words, the mathematical representation of the planar contact constraints must be adaptable enough for one of them to be reduced to line contact.

Current CAD systems solve the nominal case well, but they cannot solve the deviated case. Their assembly constraint solvers do not understand how to respond to variation in a generalize way and achieve an exactly constrained state.

Other research has been conducted to find a more generalized approach to the assembly problem. [Larson, 1991] proposed using a set of kinematic joints as the basis for defining assembly constraints. [Clement, 1991] used symmetry or degrees of invariance to define his TTRS, that characterize the allowable degree of constraint of a given feature pair. [Whitney, 2004] defined a set of common assembly interfaces using screw theory.

This paper extends prior work by providing robust solutions to two key issues:

1) Generalized method to extract free motion and force transfer directions for assembly constraints
2) General method for achieving an exactly constrained model of the assembly system

FUNCTIONAL INTERFACE MODELING

The approach presented in this paper builds on a generalized assembly interface definition first introduced by [Stoddard, 1995]. The approach is based in the premise that the identification of the free motion and force transfer directions can be extracted from the parameterization of the mating surfaces of the assembly interfaces. It can be shown that any continuous surface can be exactly characterized by a two parameter equation [Stoddard, 1995]. An example of a parameterized surface is shown below.

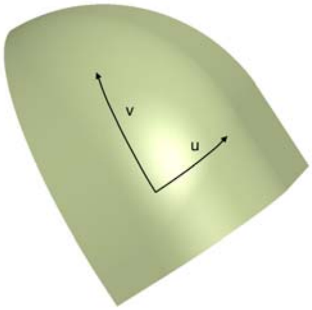

Figure 3: Two Parameter Surface

When this surface is brought in contact with another general surface they will contact at a single point or, in the cases of matched curvature, along a line or area. A point is chosen within the contact area to serve as the origin of the assembly constraint definition. At the point of contact each parameter has a corresponding tangent vector and two instantaneous curvatures in orthogonal directions.

Two surfaces in contact can be characterized in terms of the resulting force transfer and free motion directions. The number of force transfer and free motion directions for a single contact add up to six. The axes at the center of curvature identify the instant centers that characterize two of the free motion directions for this assembly constraint. A corresponding set of instant centers can be found on the other mating surface. This accounts for four of the total six free motion and force transfer directions as illustrated in Figure 4.

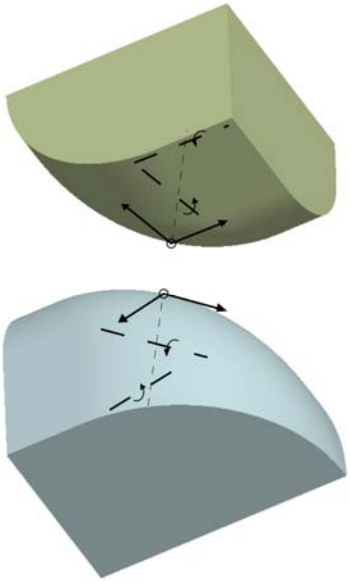

Figure 4: Instant Centers

The final two free motion and force transfer directions come from the fact that at the point of contact both surfaces share a common normal direction. This normal direction is orthogonal to the four instant centers found above. Therefore translation and rotation about this direction provides the final two directions needed to fully describe the free motion and force transfer between the two bodies. These directions are shown in Figure 5.

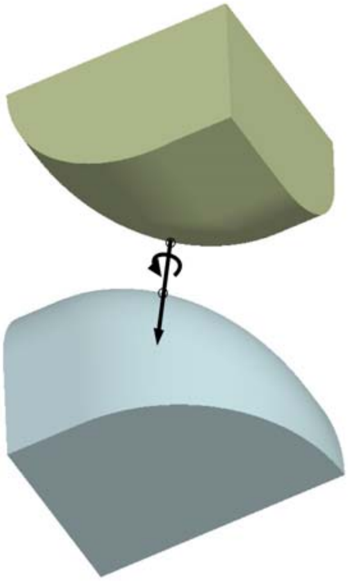

Figure 5: Common Normal Direction

In the case of point contact only the translation along the common normal is able to transfer force. All other directions are associated with free motion between the two components. For the case of line contact, two of the identified free motion directions will become coincident and redundant as shown in Figure 6.

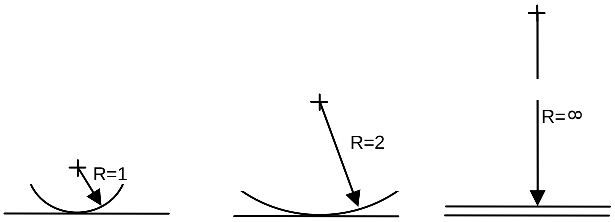

Figure 6: Reduntant Instant Center at Infinity

This is to account for the fact that one of the independent free motion directions has been removed and replaced by another force transfer direction. Line contact transfers force in two directions. Specifically in the case of straight line contact, a moment is added to the original force. Similarly for area contact a second set of free motions directions will become coincident. For example, planar contact can transfer force through a normal force and two orthogonal moments as shown in Figure 7.

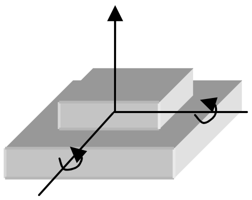

Figure 7: Force Transfer Directions for a Planar Contact

The new force transfer direction must be added to the model to replace the free motion direction that was lost. This is done by adding a new instant center axis parallel to the lost instant center along the line through the point of contact and the combined instant center axis. Since there are an infinite number of parallel axis locations along this line, the approach in this paper is to limit the choice to two options. The point of contact between the functional interfaces is used for the cases where the new combined instant center is at infinity and infinity is used for the cases where the new combined instant center is at a finite location. For cases where there is not a unique point of contact, any point within the contact region can be used. The approach of this paper is to use the center of the contact region.

The advantage of always maintaining the complete set of free motion and force transfer directions is in the ability to adjust individual degrees of freedom of the assembly constraints. Individual instant centers can be changed from free motion to force transfer and back to quickly and robustly modify the local degree of freedom state. This allows for defining an exactly constrained assembly model for variation analysis.

COMMERCIAL APPLICATION

This approach has been successfully implemented in a commercial software application. This application works as an extension of the CAD system to provide tolerance or variation analysis. Since the CAD system assembly constraint definition does not provide an assembly model that is suitable for variation analysis, this application provides a method for redefining the assembly constraint definition that can be solved under the influence of variation. The modeling process that is supported consists of selecting the geometry that will define the mating interface between two assembly components directly from the CAD system. The application then determines an appropriate point for the assembly constraint origin and determines the default assembly constraint behavior and orientation based on the definitions of the two surfaces at this point of contact. A default degree of freedom state is also determined and the user is presented with a simple method for manipulating these degrees of freedom to achieve an exactly constrained assembly model. The application represents the assembly constraints as kinematic joints.

Figure 8 shows a simple example of two parts with two assembly constraints that is nominally over-constrained.

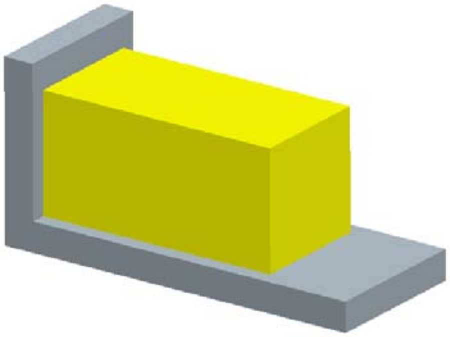

Figure 8: Block in Corner Example

The first step in defining the assembly constraint is to select one pair of mating planar surfaces. From these selections a planar joint type was inferred and three free motion directions are identified, two translational (along the joint X and Z axes) and one rotational (about the joint Y axis) as shown in Figure 8. Three force transfer direction are also found, one translational (along the joint Y axis) and two rotational (about the joint X and Z axis). This is the natural state for this mating pair of surfaces.

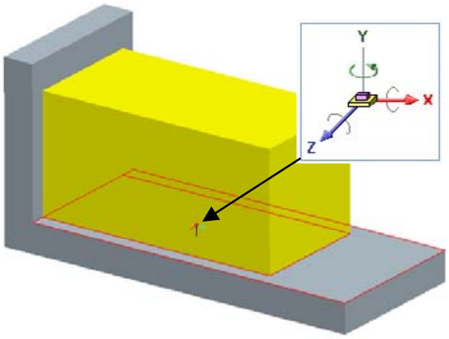

Figure 9: First Assembly Constraint

The second pair of mating planar surfaces is selected to define the other assembly constraint in Figure 10. This again identifies a planar joint type with three free motion and three force transfer directions.

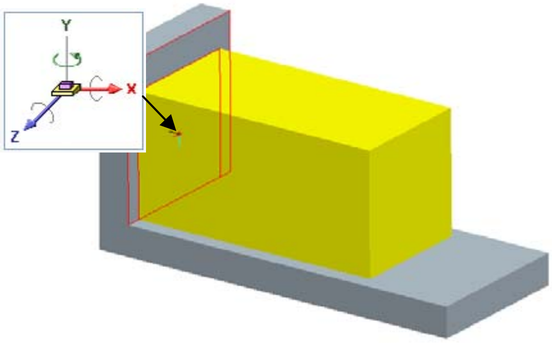

Figure 10: Second Assembly Constraint

Using principles of screw theory similar to those used in [Whitney, 2004] and [Smith, 2001], the application informs the user that this is not an exactly constrained assembly. In fact it is both over-constrained and under-constrained. Looking at the direction of the edge that is shared by both planar surface pairs, it is determined that translation along this direction is not constrained but rotation about this direction is constrained by both assembly constraints. This later condition can be resolved by changing the force transfer about this axis to a free motion. Effectively, this reduces the second constraint from a planar contact to a line contact. (Figure 11)

This process is in line with how real parts will behave when assembled, and allows assembly constraint definitions to properly adjust to rotational deviation between planes

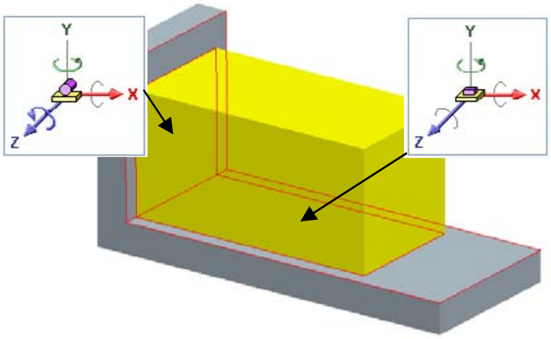

Figure 11: Remove Over-constraint

The final under-constraint can be removed by applying another assembly constraint that will provide constraint in this direction only or by directly removing this degree of freedom from one of the two defined joints.

This application has been successfully used to perform variation analysis on a wide range of complex assemblies, including automotive power train mechanisms, electronic packaging, and medical devices. Each of these assemblies has complex assembly behaviors that are driven by their mating interfaces. These particular industries also require an intimate knowledge of variation at the assembly level in order to reduce cost and limit liability.

One specific example is the seat latch shown in Figure 12. The physical assembly constraint of this latching mechanism is driven by the interaction of several cam profiles. These mating cam profiles must be used directly to create an accurate assembly model for variation analysis. In the CAD model most of the cam to cam interfaces for this latch mechanism are represented by line contacts. All of these line contacts cannot be maintained simultaneously because this is an over-constrained condition. Using the methods outlined in this paper, the line contacts between cam profiles are changed to point contacts where appropriate. This allows the constraint system to be solved in the presence of variation, especially rotational variation of the parts out of the mechanism plane

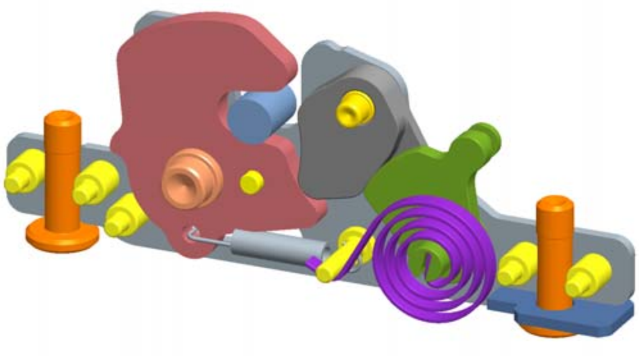

Figure 12: Latching Mechanism Example

The behavior of this mechanism is non-linear and the contact points at each interface changes under the influence of variation. Therefore an iterative solver is used to find the solution to the assembly system. At each step of the solution the location and orientation of the free motion and force transfer directions of each interface were updated to account for the changes in curvature at the points of contact.

This completed model has 22 defined assembly constraints between 9 parts. An exactly constraint assembly definition was achieved and a variation analysis was successfully performed on this model.

CONCLUSION

In order to define an assembly model that captures the true assembly behavior under the influence of manufacturing variation, an assembly constraint definition must be based on the assembly interface features. In order to be robust, it must also be adaptable to achieve an exactly constrained condition. This paper has proposed an approach that uses the parametric definition of the surfaces that compose the mating interfaces to define an assembly constraint definition that will robustly update in the presence of variation and provide a general method for locally adjusting the degrees of freedom.

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