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The Use of a Kinematic Constraint Map to Prepare the Structure for a Dimensional Variation Analysis Model

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Abstract Dimensional variation analysis (DVA) models are widely used in the automotive industry to predict how minor variations in the size, shape and location of the component parts are likely to propagate throughout a body structure, suspension, engine or transmission system and how this will affect the overall assembly, operation and performance. This paper is one of in series of four papers that describe how different techniques can be utilised to aid the creation and application of DVA models. This paper explains the development and use of the kinematic constraint map (KCM) method to prepare, in advance, the most appropriate structure for a DVA model. The KCM method provides a concise and comprehensive graphical method that, in one document, can identify all the physical constraints that govern the location and (where applicable) the motion of each component within a complete mechanical system. Once complete, the KCM for a mechanical system contains sufficient information to fully define the structure of the subsequent DVA model. The other three papers cover the use of virtual fixtures, jigs and gauges to achieve the necessary component location and the required variation measurements; the use of two stage DVA models to simulate interdependence between different model configurations and the use of 3D plots to display large numbers of DVA results as a single 3D shape.

Keywords: *dimensional variation analysis, variation modelling, kinematic constraint mapping*

1. Introduction

Although modern manufacturing methods are becoming increasingly accurate, there is still a small risk that the components produced canvary slightly from the nominal in size and shape. These variations can accumulate and propagate as parts are assembled together into sub assemblies and products, and so maintaining the geometric quality of a product during production and assembly can be problematic. In addition to component part variation, many product variation problems encountered can be traced back to the interface geometry and locating schemes used. The way parts locate relative to each other significantly affects the manner in which variation propagates through the assembly and the effect this variation has on the product key characteristics [1].

DVA (dimensional variation analysis) models have been widely used in the automotive industryfor more than 20 years to optimise the variation behaviour of body structures, suspension, engine, transmission and other vehicle systems [2-14]. DVA models have also been used in the aerospace industry [15,16,17,18] and by other manufacturingindustries [19]. A DVA model can simulate how minor variations in component size, shape and location are likely to propagate in all six degrees of freedom throughout the assembly and operation of a mechanical system. DVA models have proved very successful in predicting whether or not these minor component variations, when taken collectively, are likely compromise the overall assembly, operation, performance or quality of the complete system. The use of aDVA model provides the engineering team with the means to identify potential dimensional variation problems in advance, during the design phase while there is still time to make changes. This gives the engineering team an opportunity to either modify the system design and 'design out' the adverse variation or to devise effective measures to control the variation once in production. As the software used to build DVA models has advanced over the years, in parallel, the DVA users have developed numerous management procedures, application techniques and 'tricks of the trade' to model specific situations [20-27]. The advances in software combined with the development of new procedures and techniques have substantially increased the capability of the DVA model and the complexity of the systems that can be modelled.

A core feature of a DVA model is the mathematical definition of the internal constraints that govern the size and shape of the individual component plus the external constraints that govern the location and motion of each component within the complete system. Drawing on previous work regarding assembly sequences, geometric tolerances and constraint theory, the aim was to develop a graphical method that could, in one document, hold all the following information:

- The dimension and datum schemes specified for each single component (and sub assembly if applicable)
- The connections between mating components and sub assemblies

- The known or intended sequence of assembly operations, including sub assemblies and the use of fixtures or jigs to locate the components.
- The known or intended operational sequence for systems that move between two or more fixed positions, or across a range or through a cycle of operational positions.
- The level of constraint, full, under or over for each component and sub assembly.

The assembly sequence for a product can be determined using Bourjault's method [28] or the "Cut-set" methods proposed by Baldwin [29]. The advantage of these methods is that the chosen assembly sequence is frequently in the form of a liaison, or assembly sequence diagram. These diagrams provide a simple unambiguous method of communicating the assembly sequence to the analyst. The use of assembly relation matrix techniques [30] has allowed significant advances in the automation of assembly sequence planning to the point that automated assembly sequence planning software [31] compatible with commercially available CAD software is now available. In the case of the AutoAssem software [32] the output still retains a strong graphical content.

The variation in size and shape of the component parts can be defined by means of geometric dimensions and tolerances [33]. The same standard also defines a simple method of communicating this information to the analyst by means of the feature control frame. Krulikowski [34] notes that one of the benefits of GD&T is that it provides uniformity in drawing specification and interpretation, thereby reducing controversy, guesswork and assumptions.

The manner in which the component parts of an assembly are constrained relative to each other can be defined by means of screw theory [35,36,37]. Screw theory uses twist and wrench matrices to express the level of constraint between adjacent component parts. By subjecting these matrices to the appropriate mathematical manipulation [38], it is possible to determine if a series of assembly features that comprise an assembly joint or operation, are under or over constrained.

2. Related Graphical Methods

Graphical methods are frequently used to describe the relationships between the component parts or the component part features of an assembly. Several of these methods are based on the liaison diagram and include; assembly networks and datum flow chains [39,40] which denote the presence of a relationship between component parts of an assembly, assembly orientated graphs [41] and annotated liaison diagrams [42,43]. The latter two techniques denote a relationship between specific pairs of mating features on adjacent component parts. Assembly orientated graphs combined datum flow chains with liaison diagrams and introduced the concept of the propagation chain which described how variation propagates through the assembly. Three important rules concerning the construction of assembly orientated graphs were also defined by Mathieu & Marguet [41] namely;

- The graph has one and only one root node (base component) which is not located from another component.
- There is always one chain of relationships on the graph going from the root node to another node.
- The graph cannot contain a chain of relationships that loops upon its self. This would imply that the parts locate themselves.

The methods described above are all capable of denoting a relationship between the component parts of an assembly. Some of the methods are able to refine the nature of the relationship and denote the existence of a relationship between pairs of assembly features located on adjacent component parts. This level of detail may be sufficient when constructing simulation models for analysis using Monte Carlo based DVA software. However, when constructing a simulation model for analysis using vector loop based DVA software it is necessary to communicate the exact nature of the relationship between the component parts. This is beyond the present capabilities of the methods described above. A kinematic constraint map capable of conveying the exact constraint scheme to be used in the construction of a simulation model for analysis by vector loop based software would be of considerable benefit.

3. DVA Software Requirements

The major DVA platforms commercially available make use of two different analysis methods, Monte Carlo simulation and vector loop analysis [44,45]. The two methods have differing requirements with regard to the amount of information required to build the simulation model. Those platforms based on Monte Carlo simulation are often capable of accommodating a certain degree of under and/or over constraint in the simulation model. Over constraint is often accommodated by employing the principle of constraint redundancy, while under constrained components may be held in their nominal positions. In such platforms, the assembly of two adjacent component parts is achieved by means of a single assembly operation. To complete the assembly operation it is only necessary to define the primary, secondary, etc locations in terms of mating pairs of assembly features one of which is designated as the target feature, the other as the object feature of the mating pair.

The use of a vector loop based analysis method requires additional information to be available when constructing the simulation model. Kinematic constraint of the simulation model is a necessary condition for analysis in vector loop based systems, the exact constraint scheme must therefore be available. The other reason for the increased data requirement is that these systems often treat the assembly of each pair of mating features (assembly location) as an entirely separate assembly operation. One advantage of this approach is that it is unnecessary to specify which mating pair is the primary, secondary, etc location. Several of the software platforms are capable of automatically applying a constraint scheme to each individual pair of mating features based on the type of joint involved (e.g. plane to plane or pin in hole etc). However, manual intervention is frequently required to attain kinematic constraint of the assembly, as vector loop based platforms rarely utilise the constraint redundancy and nominal position holding techniques common in Monte Carlo simulation based platforms. The manual intervention required when constraining a vector loop based simulation model has the advantage of permitting a specific constraint scheme to be applied to the simulation model as opposed to the automatic, but less than transparent, constraint scheme applied to many Monte Carlo simulation based models.

One area of simulation model construction that is very software specific is the order in which assembly features appear in the simulation model tree. Certain vector loop based platforms use the relative position of an assembly feature in the model tree to define the assembly feature precedence in the simulation model. The assembly features of whichever component part is closest to the base component in the model tree act as the target features in the assembly operation. Both of these requirements can be conveyed by means of an appropriately formatted assembly sequence diagram.

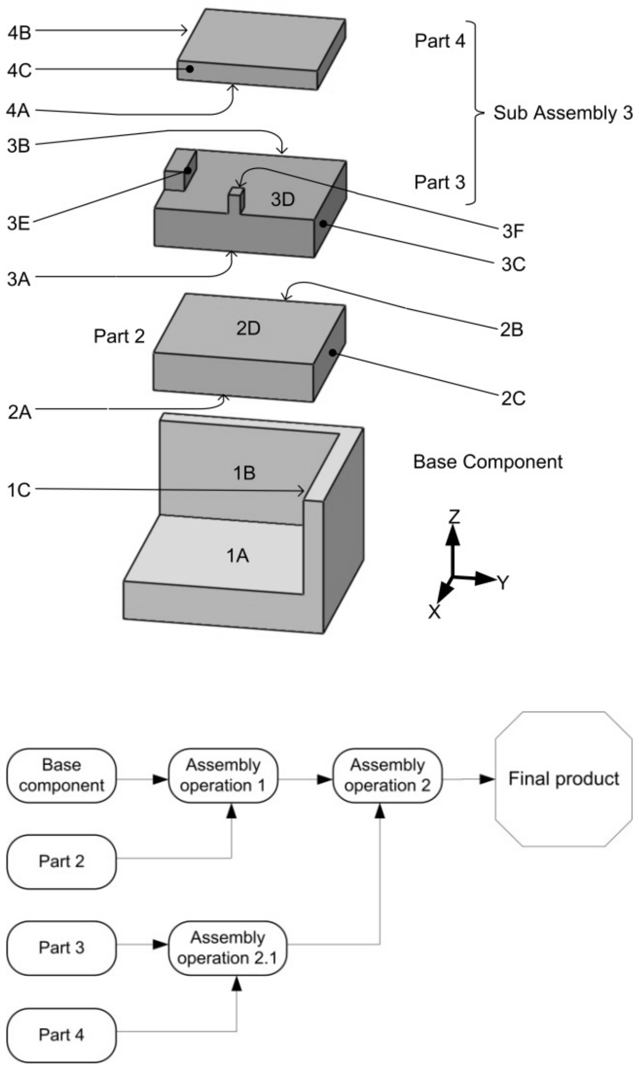

Figure 1. Exploded view of the assembly, showing the assembly features, and the assembly sequence diagram

4. Assembly Sequence Diagram

The main function of the assembly sequence diagram is to convey the assembly sequence. However, by appropriate formatting of the assembly sequence diagram the appropriate assembly feature precedence can be communicated simply and effectively. The preferred format is shown in Figure 1, where the assembly operations run horizontally across the top of the diagram and the component parts run vertically down the left side. Each new component part is added below the preceding part, when read from top to bottom, this will place the component parts in a suitable order to maintain the correct assembly feature precedence between component parts in the simulation model when using vector loop based software.

5. Basic Features of the Kinematic Constraint Map

The kinematic constraint map is based on the assembly sequence diagram shown in Figure 1. When constructing the kinematic constraint map the first stage, in a bottom up construction, is to add assembly features to each of the component parts of the assembly sequence diagram. The part icon used in the assembly sequence diagram is replaced by a bounding box for the assembly features of each part. Similarly, the icon for assembly operation 1 is replaced by an assembly operation bounding box that includes the Base Component and Part 2 complete with their assembly features (Figure 2). To differentiate between the two and to signify the change from icon to bounding box the line formats used for the part box and assembly operation box are changed to broken lines.

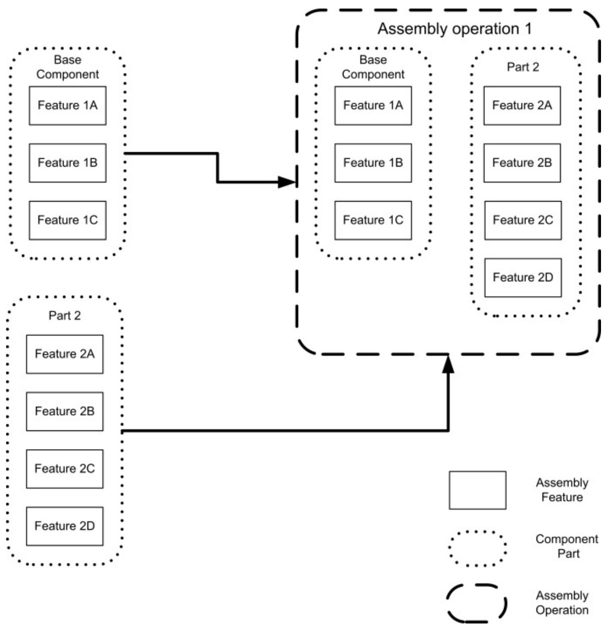

Figure 2. Assembly features for assembly operation 1

The next stage in constructing the kinematic constraint map is to apply the constraint scheme to the assembly operation. In a black and white environment the constraint scheme, which has been pre defined by the design engineer, is applied by means of specially formatted connecting lines (Figure 3). There are six different connectors, one for each degree of freedom constrained. Each degree of freedom is aligned to, and associated with, one of the principal axes of the assembly global co-ordinate system. The format of the connecting line (Table 1) indicates which of the translation (Tx, Ty, Tz) or rotation (Rx, Ry, Rz) degrees of freedom are constrained by each pair of mating assembly features. When colour is available, the connecting lines may also be colour coded to assist identification. The arrowhead on each connecting line, points towards the target feature in each pair of mating features. This serves two important purposes; firstly, it identifies the target feature in each mating pair of features and secondly it allows the constraint propagation chain to be examined for inconsistencies in the flow of constraint such as loops or retrograde links.

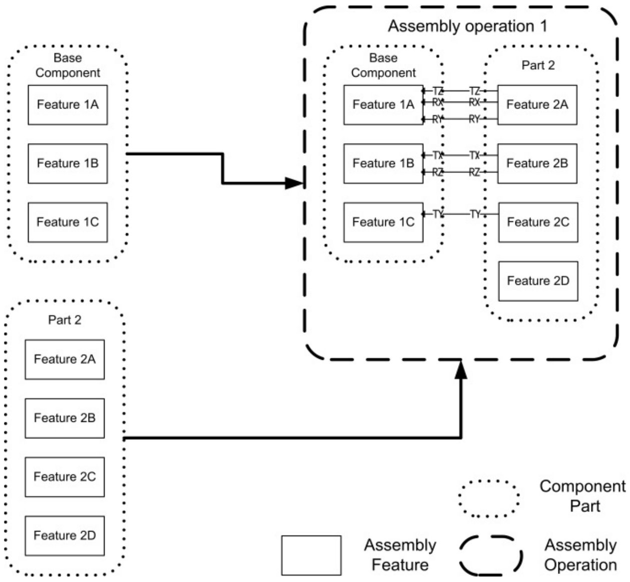

Figure 3. Kinematic constraint map for assembly operation 1

Table 1. Connecting Line Format and Degree of Freedom Constrained

Line Format	Degree of freedom constrained
—TX——TX——TX—▶	Translation along X axis
—TY——TY——TY—▶	Translation along Y axis
—TZ——TZ——TZ—▶	Translation along Z axis
—RX——RX——RX—▶	Rotation about X axis
—RY——RY——RY—▶	Rotation about Y axis
—RZ——RZ——RZ—▶	Rotation about Z axis

The inclusion of a second assembly operation in the assembly process (Figure 4) brings into play the concept of the intermediate product, bounding box. This is atemporary feature used during the construction of the kinematic constraint map. The component parts and their associated assembly features contained within the intermediate product, bounding box have been assembled, either directly or indirectly to the base component of the assembly in the preceding assembly operations. Thus, any assembly feature contained within the intermediate product bounding box will be a target feature for any subsequent assembly operations..The size and content of the intermediate product bounding box will change with each successive assembly operation until the last component is assembled when it becomes redundant and is removed from the kinematic constraint map. Figure 4 also illustrates how the presence of a sub assembly in the assembly process is represented in the kinematic constraint map. Part 4 is assembled to part 3 in assembly operation 2.1. The assembly operation is designated 2.1 to indicate that it is a subsidiary assembly operation of assembly operation 2. Sub assembly 1 which results from assembly operation 2.1 is then assembled to the intermediate product in assembly operation 2 to form the final product. The subsidiary assembly operation 2.1 is represented in the kinematic constraint map in exactly the same manner as a normal assembly operation. However the product of the assembly operation 2.1 is contained within a sub assembly bounding box as can be seen in assembly operation 2 (Figure 4). The sub assembly bounding box has two functions; firstly it denotes that parts 3 and 4 were added simultaneously to the assembly as a sub assembly rather than sequentially as individual component parts. Secondly as the sub assembly is assembled to and located from the intermediate product, any assembly feature within the sub assembly bounding box is a potential object assembly feature in assembly operation 2.

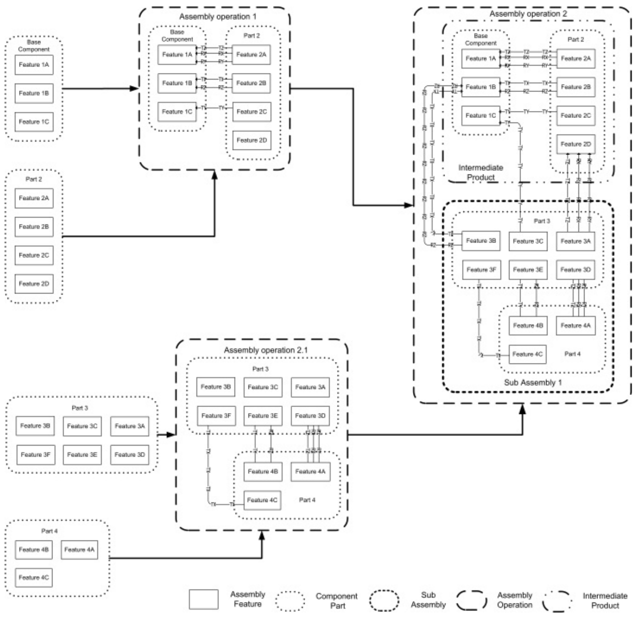

Figure 4. Kinematic constraint map for assembly operations 1 & 2

Figure 5. Turnbuckle

Consideration must be given to the choice of base component for a sub assembly as the constraint scheme applied to the "sub" assembly when it is the final product of its own assembly sequence may be different to that applied when it is only a component part of a larger product. Consider a turnbuckle consisting of a central barrel into either end of which is screwed an eye bolt (Figure 5). When assembling the turnbuckles one obvious method would be to clamp the barrel and screw in the eye bolts, one at each end. This would make the barrel the base component of the assembly (Figure 6). However, when the turnbuckle is part of a larger assembly it is almost certain that one of the two eye bolts would be assembled to the intermediate product. In which case, the eye bolt that is assembled to the intermediate product, in this instance eye bolt 2, would locate the barrel and not the other way round see (Figure 7). If the barrel remainedas the base component of the turnbuckle sub assembly, the overall assembly would contain two components that were not located from another component, the base component of the parent assembly and the barrel of the turnbuckle sub assembly. This is not permitted under the rules formulated by Mathieu and Marguet [41]. The situation can be avoided by ensuring that the base component of any sub assembly is one that is involved in an assembly operation to the overall assembly.

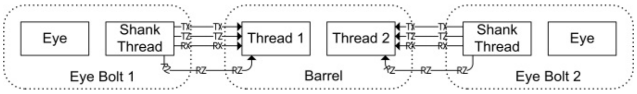

Figure 6. Constraint scheme of the turnbuckle as a final product

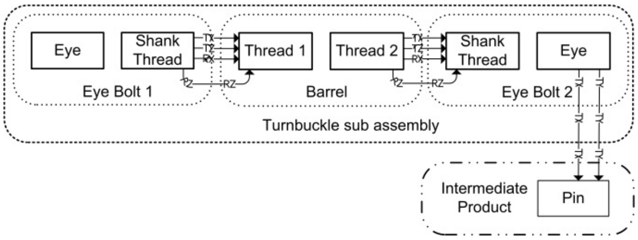

Figure 7. Constraint scheme of the turnbuckle as a component sub assembly in a larger assembly

5.1. Abridged form of the KCM

The kinematic constraint map in Figure 4 shows the assembly of four component parts into a product. A complex assembly such as an internal combustion engine may contain hundreds if not thousands of component parts and would produce a highly complex and expansive KCM. Inspection of Figure 4 shows that all the component parts are repeated three times. Inspection of assembly operation 2 will show that it actually contains all the information from the preceding assembly operations, in this instance assembly operation 1 and assembly operation 2.1. The only information that this final panel of the KCM (assembly operation 2) does not convey in an unambiguous manner is the assembly sequence. Thus by using the assembly sequence diagram in conjunction with the final panel of the unabridged KCM (Figure 8) the same information can be communicated but in a more compact form. It will be noted that the intermediate product bounding box shown in Figure 4 is absent. This is because Figure 8 represents the finished product after the assembly operation has taken place while Figure 4 represents the assembly before assembly operation 2 takes place.

6. Secondary KCM Functions

The primary function of a KCM is to communicate the constraint scheme of an assembly. A KCM also has several useful secondary functions. One of these is the ability to check a constraint scheme for under and/or over constraint in a simple but effective manner and identify which degree of freedom is improperly constrained. Consider Part 2 in Figure 8, the part bounding box is intersected by nine connectors representing constrained degrees of freedom. At first sight, this would suggest that Part 2 is over constrained. However, of the nine connectors six are outgoing to the Base Component and three are incoming from Part 3. An outgoing connector is one where the feature to which it is attached is acting as an object feature in the assembly operation. Similarly, an incoming connector is one that is attached to a target feature. Each connector will have an outgoing and an incoming end. The six outgoing connectors from Part 2 to the base component indicate that Part 2 is the object part in the assembly operation with the base component.

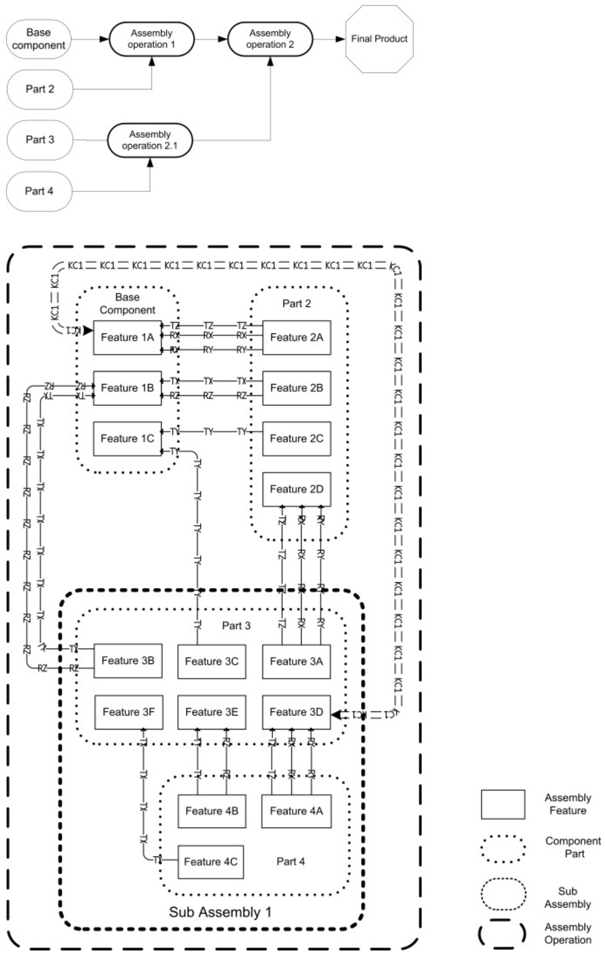

Figure 8. Assembly sequence diagram and abbreviated kinematic constraint map

The assembly sequence diagram identifies the operation as assembly operation 1. Each of the six connectors represents a different degree of freedom indicating that assembly operation 1 constrains all six degrees of freedom and thus Part 2 is kinematically constrained to the base component. The three incoming connectors to Part 2 are linked to Part 3. The assembly sequence diagram indicates that Part 3 and Part 4 are added to the assembly during assembly operation 2 and that Part 2 has previously been assembled to the base component. Let us therefore consider the part bounding box enclosing Part 3. Six different outgoing connectors intersect the bounding box indicating that all six degrees of freedom have been constrained and Part 3 is kinematically constrained to the base component and part 2 of the assembly. The same information can be derived from the full KCM (Figure 4) without the need to refer to the assembly sequence diagram. The presence of the intermediate product bounding box indicates that all the enclosed components have already been assembled. As above, six different connectors intersect the Part 3 bounding box and in this instance the same six connectors intersect the intermediate product bounding box indicating that Part 3 is kinematically constrained to the intermediate product. The same process can be used to check the degree of constraint between sub assembly 1 and the intermediate product. In Figure 4 six different connector lines intersect both the sub assembly and intermediate product bounding boxes. This indicates that all six degrees of freedom are constrained and sub assembly 1 is kinematically constrained to the intermediate product.

Another useful secondary function of a KCM is the ability to generate constraint propagation chains for any given degree of freedom. Consider the constraint of Feature 3D (Figure 8) along the Z axis (Tz). The constraint propagation chain flows from Feature 3D through the body of Part 3 to Feature 3A and thence by contact to Feature 2D of Part 2 Where it flows through the body of Part 2 to Feature 2A and is transferred by contact to Feature 1A on the Base Component. The constraint of Feature 3D in Tx, however, follows a completely different path via features 3B and 1B. The ability to trace constraint propagation chains can be useful when a component part of the assembly is subject to a late design change. Consider the key characteristic KC1 represented by the double broken connecting line between features 1A and 3D in Figure 6. If the key characteristic consists of a measurement along the Z axis, from the description of the constraint propagation chains given above, if part 2 of the assembly is modified it is likely that the key characteristic will be affected. Whereas if the key characteristic is a measurement along either the X or Y axes it is unlikely to be affected by any modification of Part 2.

Practical experience has shown that the ability to generate constraint propagation chains for individual degrees of freedom is advantageous when examining the constraint schema of complex kinematic assembly systems. Consider the manual drive train of a rear wheel drive motor car that is in gear and with the clutch engaged. All the component parts are either bolted or splined together or meshing gears. The only exception is the clutch where the friction plate is rigidly clamped between the pressure plate and flywheel. The one common factor is that all of these joints between the drive train components constrain rotation. Yet when the crankshaft turns the rear road wheels turn indicating that rotation of the drive train has not been constrained. One method of constraining the rotation of the drive train is to apply the hand brake. The rotational constraint propagation chain that began at the crankshaft and propagated via the clutch, gearbox, transmission shafts, rear axle and road wheels is extended via the brake disc and calliper through the suspension system to the body in white and on to the base component of the vehicle. When and only when, in this particular instance, the unbroken rotational constraint propagation chain reaches the base component is the rotation of the crankshaft constrained. The ease with which such propagation chains can be detected and traced is one of the advantages of KCM's compared with other liaison diagram based methods.

7. Application

Kinematic constraint mapping has been applied to both simple and complex assemblies and was found capable of accurately recording and communicating the constraint schema and assembly features of the parent assembly. This includes assembly systems that are both complex and conceptually challenging due to the presence of nested simulation models [46] with near identical constraint schema. The differences between the constraint schema while small were significant. The use of a kinematic constraint map allowed these differences to be readily discerned and communicated in an exact and unambiguous manner.

8. Conclusions

The unabridged version of the KCM is capable of unambiguously communicating the assembly sequence, assembly features (both target and object features) and the exact constraint scheme necessary to construct a DVA simulation model and requires only limited technical knowledge to extract this information from the KCM. The abridged version conveys the same information in a much more compact manner but requires greater technical knowledge to extract the information. It is, however, still suitable for deployment in a normal engineering environment. Visual examination of either version of the KCM is capable of detecting over or under constraint conditions whether occurring singularly or simultaneously. It is also possible to determine which degrees of freedom are under or over constrained even in complex kinematic assemblies where the means of constraint is distant from the component being constrained. The main benefit of a kinematic constraint map is that it preserves the original design intent to a greater extent and reduces the number of errors due to misinterpretation, assumption and guesswork regarding the assembly constraint schema. This allows the construction of a more realistic simulation model.

The examples given in this paper clearly show the value of the KCM method as a preparation aid when building a DVA model. In one document a KCM provides a concise and comprehensive graphical method to identify and record the physical constraints that govern the location and (where applicable) the motion of each component within a mechanical system. Once complete, the KCM contains all of the information listed below and this is sufficient to fully define the structure of the subsequent DVA model.

- The bounding boxes show what are internal constraints within a component (or sub assembly) or external constraints between components or sub assemblies.
- Constraint lines connecting features within the same bounding box (single component or sub assembly when sub assembly level dimension and datum schemes are specified) identify the internal constraints that govern the size and shape of that single component (or sub assembly)
- Constraint lines connecting features within different bounding box (between components) identify the connections and the external constraints that govern the location or motion of the components.
- The direction of the constraint lines and the order of the KCM layers show the assembly and the operation sequences for the components.
- The number and type of constraint lines crossing any bounding box show whether the component or sub assembly contained with the bounding box is fully, under or over constrained. One constraint of each type

(Tx, Ty, Tz, Rx, Ry&Rz) indicates full constraint. Less than one of each type shows under constraint, more than one of each type shows over constraint.

- The consistency and integrity of the proposed constraints is shown by achieving full constraint and the absence of unexpected constraint loops or constraint dead ends.

9. Areas for Further Work

The method described in this paper is applied to an assembly system that is aligned to a single global co-ordinate system. In the real world, even comparatively simple assembly systems may be aligned to a global co-ordinate system and one or more local co-ordinate systems. The method of plotting kinematic constraint maps therefore requires further development to allow it to record assembly systems with multiple co-ordinate systems.

The present method of plotting kinematic constraint maps utilises a bottom up approach to their construction. The popularity of the top down approach when assigning key characteristics and constraints, suggests that a top down method of constructing kinematic constraint maps may be beneficial.

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