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## The Use of Virtual Fixtures, Jigs and Gauges in Dimensional Variation Analysis, Simulation Models

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### Abstract

This paper describes the use and deployment of, virtual fixtures, jigs and gauges to locate, align and measure features in simulation models used in the dimensional variation analysis (DVA) of assembly systems. The particular example chosen in this paper is a McPherson strut suspension. The correct use of virtual fixtures, jigs and gauges can significantly improve the accuracy and realism of the simulation model and thus the DVA output. In kinematic assembly systems, the use of virtual fixture, jigs and gauges is often essential to produce a working simulation model.

**Keywords;** Dimensional variation analysis, Dimensional variation behaviour, Virtual fixtures, Virtual jigs, Virtual gauges.

### Introduction

At the heart of the dimensional variation analysis, (DVA) process is the simulation model [1]. The simulation model is a 3D computer model that, as the name suggests, is intended to simulate the real world behaviour of the assembly system. The simulation model consists of three main layers; the first of these is the CAD geometry. The CAD geometry supplies the nominal size and shape of the component parts in the assembly. Those features of the nominal parts involved in the assembly process are then overlaid with assembly features. The assembly features introduce the variation in size and shape of the component parts due to the manufacturing process and any associated tolerances applied to the component parts. The final layer in the simulation model is the assembly operations. The assembly operations mimic the assembly of the component parts into the final product. This is achieved by mating an assembly feature on one component part with its corresponding assembly feature on

an adjacent component part. The mating of the two assembly features constrains one or more degrees of freedom to mimic the assembly process. The analysis process consists of applying assembly level measurements to the simulation model that characterise the assembly characteristics or attributes of interest and analysing the simulation model using appropriate DVA software.

In a simple static assembly, the default orientation of the component parts supplied by the CAD geometry may be sufficient to analyse the assembly. However, in a large and complex kinematic assembly system with one or more movement ranges the default orientation of the component parts provided by the CAD geometry is unlikely to be sufficient to allow analysis. One method of dealing with movement ranges in kinematic systems is to divide the movement range into a series of incremental steps, each of which is analysed separately. In the case of vector loop based DVA software each incremental step in the movement range becomes a separate configuration of the simulation model and it is only necessary to realign the simulation model to each configuration to permit analysis. This raises the question as to what method will be used to align the component parts of the simulation model into the various assembly configurations required without the need for a complete rebuild of the CAD and simulation models.

Where the assembly is particularly large it may not be viable to construct a simulation model of the entire assembly system. To conserve resources and reduce analysis times the simulation model may consist of only part of the overall assembly. In such circumstances, a method must be devised of locating the simulation model relative to the parent assembly and of mimicking any relevant dimensional variation behaviour of those component parts excluded from the simulation model. To be considered effective a simulation model must be capable of measuring and evaluating the effects of variation on the chosen system attributes or key characteristics. If no appropriate CAD geometry exists to support the necessary measurement features a means of incorporating such geometry into the simulation model must be devised. The method chosen must be capable of accommodating any changes in size or orientation of the required measurement feature in kinematic systems as they progress through their movement ranges.

This paper proposes methods whereby virtual constructs are incorporated into the simulation model of an assembly or partial assembly to enable the location in space of the assembly, the alignment of the component parts into specific configurations and the measurement of the desired system attributes or characteristics where no suitable geometry is present.

### **Related work**

Rosenberg [2] first proposed the concept of virtual fixtures in connection with the telemanipulation of robotic devices. Rosenberg's virtual fixture was a metaphor used to explain the use of abstract sensory information overlaid on top of reflected sensory feedback from a remote environment. In Rosenberg's work, much of the abstract sensory information was haptic feedback but this work established the concept that virtual fixtures could be used to guide and align objects in a virtual workspace. He

also noted that while virtual fixtures could be functionally equivalent to real world fixtures, due to their virtual nature, they could occupy the same physical space as other objects in the workspace. Thus, the location and configuration of a virtual fixture is not compromised by the presence of other objects in the workspace. This early work has been developed to produce the modern surgical virtual fixture used in robotically assisted cardiac surgery [3]. These are extremely complex 3D, real time constructs with multi modal feedback systems. While the virtual fixtures used in DVA simulation models are generally less complex, the surgical virtual fixture amply demonstrates the potential of the concept.

Ikonomov [4] described the use of virtual gauges to extend the range of measurements that could be made using co-ordinate measuring machines (CMM's). Ikonomov et al. concluded that the use of virtual gauges closely resembles real gauge measurements and was in accordance with the requirements of the ISO tolerance system. Indeed one of the most significant current uses of virtual gauges is in the definition of geometric dimensions and tolerances (GD&T) [5] in standards such as ASME Y14.5 [6].

### **Definition and description of virtual fixtures, jigs and gauges**

Virtual fixtures, jigs and gauges are virtual constructs that are added to the simulation model of an assembly under investigation. The basic construction of the virtual constructs is similar and it is only the use to which they are put that distinguishes between virtual fixtures, jigs and gauges. A virtual fixture is a construct that is used to locate an assembly in space. A virtual jig is a construct used to align the component parts of an assembly into a specific configuration and a virtual gauge is a construct that enables any form of measurement. These constructs consist of features of size, mathematical features or more commonly a combination of the two.

### **Virtual fixtures**

A virtual fixture operates in a similar manner to a real world fixture in that it locates one or more component parts in space relative to a predefined co-ordinate system. Since the component parts are located from the virtual fixture the virtual fixture usually forms the base component of the simulation model. In such cases the co-ordinate system of the virtual fixture will form the global co-ordinate system of the simulation model. As virtual fixtures are most commonly used where only part of the parent assembly is being simulated the global origin of the virtual fixture may be at some considerable distance from the CAD geometry of the virtual fixture. It is important to maintain the same relationship between the global origin and any assembly features of the virtual fixture as exists between the global origin and the same assembly features in the parent assembly. Another important function of the virtual fixture is to mimic the dimensional variation behaviour of component parts that are not present in the simulation model of a partial system. Consider the virtual fixture shown in Figure 1. In this instance, the virtual fixture mimics the dimensional variation behaviour of the body in white, which is not present in the model.

The virtual fixture locates the upper end of the shock absorber, the steering rack and the inboard end of the suspension arm in space. This is achieved by means of features of size (holes, surfaces etc) contained within the virtual fixture. As the locations are features of size, geometric dimensions and tolerances can be applied to them to mimic the dimensional variation behaviour of the body in white. The appearance of the solid geometry that makes up the remainder of the virtual fixture is largely unimportant provided it does not interfere with, in this instance, the suspension system. However, the geometry of the virtual fixture does perform an important function, particularly so when vector loop based analysis software is employed in that it allows closure of the vector loops without which analysis cannot take place. In this instance the virtual fixture locates the components of the suspension system and mimics both the geometric variation and constraint behaviour of the absent body in white.

### **Virtual jigs**

Virtual jigs are frequently used in conjunction with kinematic assembly systems. A kinematic system has, by definition, one or more continuous movement ranges. One method of simulating the behaviour of such systems is to divide each movement range into a series of incremental steps each of which is represented by a different configuration of the simulation model. Virtual jigs are then used to align the simulation model into each of the configurations. Consider the suspension system shown in Figure 1. This has two movement ranges, suspension travel and the steering lock. The ride height of the system is set by means of the suspension virtual jig. This consists of a series of mathematical planes set parallel to the ground surface. The planes are, in this instance, attached to the virtual fixture, which acts as a carrier for the mathematical features. This is permissible as the virtual fixture is the base component of the assembly and thus the only component that does not move relative to the global origin of the assembly. A mathematical point attached to the outboard end of the stub axle is then assembled in turn to each of the planar features to set the ride height. Kinematic systems are by definition under constrained, a secondary function of the virtual jig is to supply some of the additional constraint required to achieve kinematic constraint of the system. This is particularly important where a vector loop based simulation is employed as kinematic constraint is a necessary condition for simulation. The second virtual jig shown in Figure 1 is the steering jig this is similar in nature to the first jig in that it consists of a series of mathematical planes attached in this instance to the steering rack. In this instance, the mathematical planes are assembled to a feature of size, namely the end face of the boss on the virtual fixture through which the steering rack passes. If any tolerances are applied to the face of the boss they will prevent the virtual jig from exactly aligning the system to the required configuration. Virtual jigs can also be used to align sub assemblies where one of the parameters is implicitly defined [7]. In such circumstances, the resultant virtual jig tends to be both large and highly complex.

### **Virtual gauges**

A virtual gauge is any construct that enables measurement within the simulation model. A virtual gauge is usually employed to provide a measurement feature when no suitable CAD geometry exists. Consider the suspension system shown in Figure 1. To determine the effect of variation on the caster angle of this system it necessary to measure the angle between the vertical plane (ZY) and the steering axis when viewed from the side of the vehicle. The first problem in achieving this is that there is no suitable geometry linking the upper and lower pivot points of the McPherson strut and thus no suitable measurement feature. In an attempt to resolve this issue a mathematical line feature was added to the CAD geometry as a measurement feature. For convenience, the line feature was attached to the suspension knuckle, which acted as a carrier. Construction of the simulation model entailed constraining the measurement feature to the upper and lower pivot points of the steering axis to ensure that the measurement feature accurately followed any movement of these points. However, this resulted in a significant over constraint of the suspension knuckle in the simulation model precluding analysis by vector loop based DVA software. To allow analysis the constraints were removed. However, visual inspection of the simulation model in various configurations raised doubts as to the validity and accuracy of this approach. To resolve the issue a long needle like component part was constructed. This acted as a carrier for a mathematical line feature and a mathematical point feature at one end. The line feature was co-incident with the centre line of the needle geometry. The component was added to the simulation model, the point feature was assembled to the upper pivot point of the McPherson strut in the simulation model and the three translational degrees of freedom constrained. The line feature was assembled to the lower pivot point of the strut and rotation about  $\theta$ , and translation perpendicular to  $\theta$ , the line feature were constrained. The needle like component and the mathematical features it carried formed the virtual gauge, which was kinematically constrained in the simulation model without over constraining the simulation model (Figure 1). This approach was able to accommodate the changes in size and orientation of the steering axis in the various simulation model configurations.

When constructing the solid geometry of a virtual gauge, simplicity is the key as it rarely plays a role in the measurement process. Consider the needle shaped virtual gauge described previously. Despite the solid geometry being a simple cylinder that tapers to a point at one end the solid geometry is unnecessarily complex. A superior version of the gauge would consist of a short cylinder with a mathematical line co-incident with the centre line and extending a considerable distance beyond the ends of the cylindrical solid geometry. The needle shaped version has the disadvantage that when attempting to select the mathematical point at the pointed end, the point feature is co-incident with both the end of the mathematical line and the vertex of the tapered solid geometry, which may cause considerable uncertainty as to which of the three features, has been selected. The vertex of the tapered solid geometry is a feature of size and as such may be subject to geometric dimensions and tolerances. If selected inadvertently it may cause a significant error in the measurement. For this reason, all tolerances applied to features of size in a virtual gauge should be set to zero unless explicitly specified to the contrary.

Where suitable CAD geometry does exist, the measurement features may be added directly to the extant geometry provided it does not cause over constraint of the simulation model. Consider measurement of the toe-in of the suspension system shown in Figure 2 by using the difference in distance from the longitudinal centre plane of the vehicle to a point on the leading and trailing flanges of the wheel. In this instance, the measurement feature consists of a mathematical line attached to the wheel rim, which commences at the leading flange, passes through the wheel centre and terminates at the trailing flange. Due to the effect of the camber angle on the system the measurement feature must be horizontal if it is to give an accurate measurement. When the measurement feature was added to the wheel CAD geometry it was set horizontal but subsequent assembly operations have influenced this alignment and it is not reliable (Figure 2). Fortunately, the wheel rim is inherently under constrained and free to rotate about the stub axle. Since kinematic constraint is a necessary condition for analysis in a vector loop based DVA simulation, constraint of the rotational degree of freedom can be used to align the toe-in measurement feature without over constraining the simulation model. This can be achieved by assembling the linear measurement feature to the appropriate planar feature of the virtual suspension jig. This ensures that the measurement feature is both horizontal and passes through the spin axis of the wheel

In this particular instance the measurement feature functions as both a virtual jig; in that it is used to align the wheel rim to the horizontal, and as a virtual gauge in that, it enables measurement of the toe-in. If, however, the measurement feature, or the virtual suspension jig, were excluded from the simulation model for any reason it would be necessary to constrain the rotation of the wheel by some other means. For this reason it is considered preferable to use a virtual gauge that has its own dedicated solid geometry (Figure 3) rather than rely on the solid geometry of an extant component part of the assembly. The advantages are that no modification to the constraint scheme of the parent assembly is required regardless of whether the dedicated solid geometry of the gauge is present or not. Secondly the virtual gauge and dedicated solid geometry is entirely self contained and could be reused as part of a toolbox of ready made virtual gauges. The virtual gauge shown in Figure 3 consists of a sub assembly of four component parts. The four component parts are the base, which sits on the ground plane, The upper section which incorporates the horizontal blade, the vertical blade and the central pin. The central pin is assembled to a point on the outboard end of the stub axle, which sets the height of the virtual gauge and ensures that both the horizontal and vertical blades are co-incident with the wheel centre. The vertical and horizontal blades are each assembled to the wheel rim by means of two point contacts. In the case of the horizontal blade this causes the entire virtual gauge to rotate about the vertical axis until the horizontal blade makes contact with the wheel rim. This has the advantage of ensuring that the vertical blade remains perpendicular to the face of the wheel rim. The vertical blade pivots about its centre to align to the wheel rim without affecting the alignment of the rest of the virtual gauge. In this particular instance the vertical blade is used to provide a measurement feature to enable measurement of the camber angle while the horizontal blade is used in the measurement of the toe in or steering angle. One advantage of using the more

complex sub assembly for a virtual gauge is that once it is assembled to the suspension system it is self-adjusting regardless of how the simulation model is subsequently configured.

The design of the virtual gauge while more complex than strictly necessary does allow it to be reused on any suspension system of approximately the same physical size. The additional complexity of the design also means that the virtual gauge more closely resembles a real world artefact and thus its use is more intuitive than a minimalist design.

## **Validation**

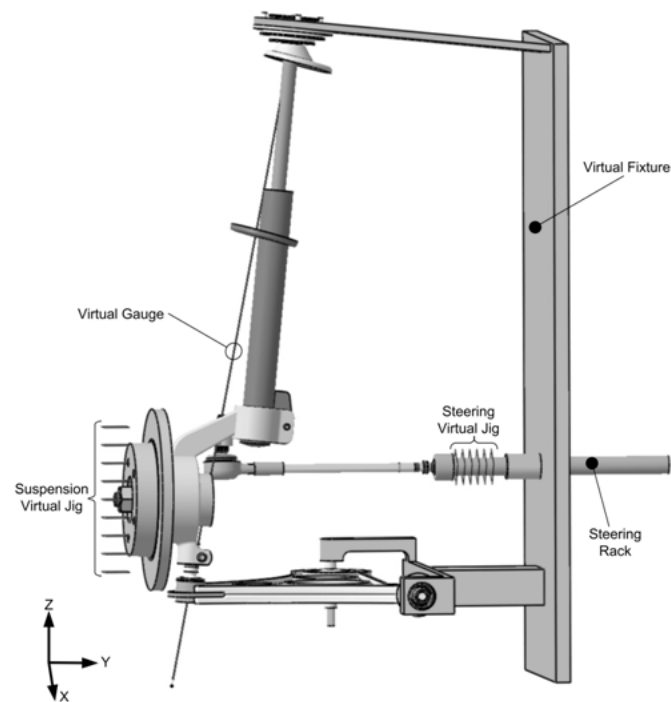
The validation of the use of virtual fixtures, jigs and gauges is largely empirical in nature. If the simulation model in which the virtual constructs are deployed exhibits the same dimensional variation behaviour as the full assembly and can be aligned into the desired configuration(s) without compromising the assembly constraint scheme while permitting accurate measurement of the desired system attributes then the virtual fixtures, jigs and gauges deployed are considered to be valid.

Consider the McPherson strut suspension system shown in Figure 1. If the complete vehicle were modelled then the suspension system would, in this instance, make contact with the body in white at the upper and lower mounting points and the steering rack. It is only at these points that variation can propagate between the suspension system and the body in white. Thus provided that the virtual fixture contains the same assembly features, tolerances and is aligned to the same global coordinate system the dimensional variation behaviour of the virtual fixture will be indistinguishable from that of the body in white regardless of the overall size and shape of the virtual fixture.

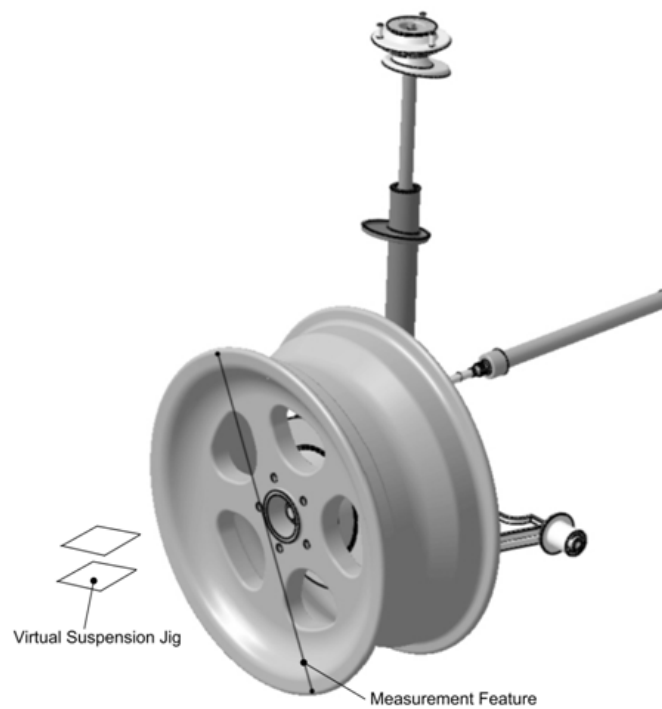
In the real world when the driver turns the steering wheel to go round a corner, the motion is transmitted via various components to the steering rack. Depending on the input from the steering wheel the steering rack will either move to the left or right. The virtual steering jig shown in Figure 1 produces exactly the same result in that the position of the steering rack can be set to any desired position to the left or right of its default position.

Virtual gauges are simpler to validate as they contain a measurement feature. Consider the virtual gauge shown in Figure 1. The virtual gauge was added to the simulation model to enable measurement of the castor angle of the suspension system. The virtual gauge performed two functions; it introduced a measurement feature that linked the upper and lower pivot points of the McPherson strut, which defined the steering axis of the suspension system. Once defined the inclination of the steering axis to the vertical when viewed from the side of the vehicle could be measured to give the castor angle [8]. The positioning of the virtual gauge and its ability to follow changes in the orientation of the suspension system can be validated by the simple expedient of including two check measurements in each configuration of the simulation model. These measurements simply measure the distance between the measurement feature of the virtual gauge and the upper and lower pivot points of the McPherson strut which should be zero.

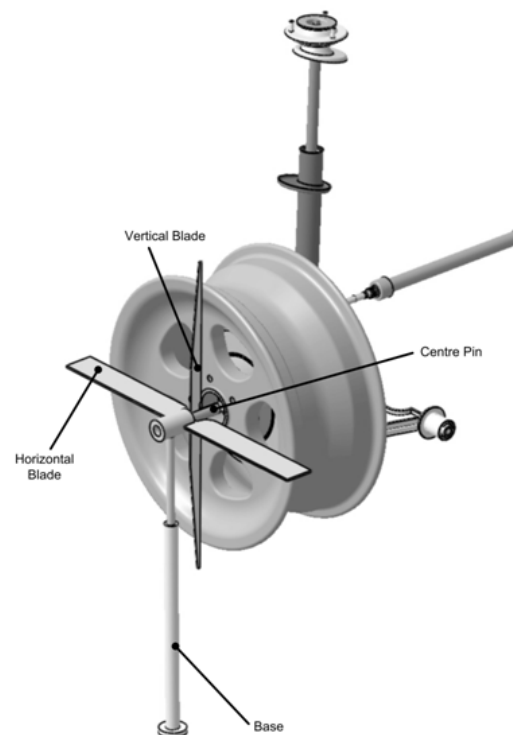




**Figure 1** Examples of virtual fixtures, jigs and gauges as applied to a McPherson strut suspension system.



**Figure 2** Measurement feature attached to the wheel rim



**Figure 3** Virtual gauge with dedicated solid geometry

## Conclusions

The maximum benefit from the deployment of virtual fixture jigs and gauges is obtained when simulating complex kinematic systems with multiple movement ranges. Little or no benefit may result from utilising virtual fixtures and jigs in the simulation of simple static assemblies. Virtual gauges may be used to advantage in any type of assembly where there is no suitable solid geometry to provide measurement features in the simulation model. This is particularly so if the measurement feature is subject to changes in size and orientation.

Virtual fixtures often constitute the base component of a simulation model as their function is to locate assembly components in space. The location and orientation of the virtual fixture co-ordinate system is thus of importance as it may constitute the global co-ordinate system for the entire simulation model. Virtual fixtures frequently contain features of size as these can be used to mimic the dimensional variation behaviour of components that have been excluded from the simulation model on grounds of size or complexity.

The mathematical features of a virtual jig may be attached directly to an existing component part as they are used to align inherently under constrained parts to a fixed configuration. The unconstrained degrees of freedom are available to effect alignment of the simulation model. The preferred format for a virtual gauge consists of limited but dedicated solid geometry that acts as a carrier for one or more mathematical features. The mathematical feature(s) acting as the measurement feature(s) in the

simulation model. Where virtual gauges contain features of size care must be taken to ensure that these do not act as unintentional sources of variation in the simulation model. This format of virtual gauge prevents the simulation model becoming over constrained and the self contained nature of the virtual gauges also has the potential for reuse in other simulations

### Further Work

Many of the designs used for the virtual constructs have been unnecessarily complex and reflected real world practices. This is especially so with regard to virtual gauges. The possibilities of reducing design complexity while retaining functionality needs to be explored further with a view to producing minimalistic but fully functional virtual gauges. The impact such minimalist designs would have on the re-use of virtual gauges also needs to be investigated.

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