4 Assembly Feature Selection for Jigless Assembly

4.1 Introduction

The focus of this research work has been the development of a process to select appropriate assembly features specifically to enable jigless assembly but which also caters for more conventional forms of assembly.

However, this assembly feature selection process must be part of and integrate into the wider AIM-FOR-JAM methodology, as the assembly features are governed and influenced by many other factors including assembly strategy and concept, manufacturing process capability, and allocation of tolerances and datums – as depicted in Figure 3.12. Indeed, each area of the AIM-FOR-JAM methodology entails a considerable body of previous knowledge and current research in itself. It is the relationships and links between the assembly features and the other factors that need to be determined and highlighted in this scope of work.

This chapter will describe in detail the assembly feature selection process that has been developed as part of the research.

The initial stage of this process must start with a redefinition of the term ‘assembly feature’. As stated in section 3.2.1.5, ‘Physical Features – Feature Library for Jigless Assembly’, there has been no agreement on what is the most useful definition of a ‘feature’. This situation depends greatly on the perspective of the interested party. For example, designers might see ‘features’ being physical areas of a part, such as surfaces, edges, holes, etc, whereas manufacturers may see ‘features’ as being areas of a part that need to be removed, such as slots, pockets, holes, etc. To enable the selection of features for jigless assembly, the definition of assembly features needs to be clarified and adapted for this use.

Once it is understood what is meant by ‘assembly feature’ in this context the selection process can begin. The selection must take into account all the factors described previously and then provide the best assembly features to use by following a coherent, repeatable and accountable process.

4.2 Assembly Features Definition

In order to define assembly features, the assembly process needs to be understood. There are many complex and often conflicting operations that are undertaken at assembly and these need to be broken down into further detail.

At assembly, the parts are joined to one another after having being held and located by either tools or other parts or a combination of both. In accordance with the definitions stated in Chapter 2, fixtures are used to hold and support a part, jigs are used to locate the part and tooling refers to any ancillary or detail tools, such as clamps, step gauges, etc.

Another important function at assembly is the measurement of the parts that are being assembled. This can either be done passively whereby the tooling is certificated and so the measurement is implicit in the assembly and any measurement of the finished assembly is for inspection purposes only, or, actively whereby the parts/tools are measured in-process, or, a combination of the above.

Once the parts have been fixed and located, using the selected measurement techniques, joining of the parts can be completed. Within the aerospace industry this commonly involves fastening of the parts using rivets or bolts. Although, other forms of joining are increasing in acceptance and use, such as welding, forming, adhesives, etc.

Hence, the following Table 4.1 shows the components and which functions within assembly they correspond with. It should also be noted that there are many more operations involved at assembly that are not directly relevant to this work and are therefore not included; these include such operations as assembly planning, assembly scheduling, ergonomics, etc.

		COMPONENT			
		Part	Jig	Fixture	Tool
FUNCTION	Location	✓	✓		
	Support	✓		✓	
	Clamping	✓			✓
	Fastening	✓	✓	✓	✓

Table 4.1 Components and their corresponding associated functions

These assembly functions whether it be for conventional assembly or jigless assembly would use assembly features to enable each specific function. As a jig is used to locate one part to another part, then the specific assembly features used to do this can be identified and it is these assembly features that can be chosen in such a way as to minimise the amount of tooling used. This identification process would also help to differentiate which assembly features of the part, jig, fixture or tooling are carrying out each specific assembly function alleviating the problem of isolating the origin of an assembly error.

Hence, the assembly features correspond to their respective assembly functions, namely :-

- Location Features
- Support Features
- Clamping Features
- Fastening Features

Not all assembly features will be present on an individual part, jig, fixture or tooling. For example, there may be no need for fastening features on a fixture.

Examples of the use of all the assembly feature types are illustrated in the following section. It should be noted that a particular assembly feature may appear in more than one assembly feature type, e.g. a planar surface can be used for location or support, either exclusively or in combinations of each function. It is dependent on the selection process as to how an assembly feature is identified and hence, what is its purpose.

As with more typical Feature Libraries, which aim not to have to add a new feature for each minor modification the Assembly Features would be stored as generic types, e.g. pads, bosses, G-Clamps, etc., and their Feature Attributes would be stored alongside the generic feature type, e.g. profile, diameter, size, etc. For instance, a 'pad' could be a square/round/diamond pad with certain dimensions/height.

In addition, most assembly features will be Pre-Defined in some kind of generic Feature Library. However, the users should still have the capability to define their own assembly features, for instance, a unique, special one-off assembly feature.

For further classification the Assembly Feature types have been divided into 'Hard' and 'Soft' features. Hard features would be product-specific, e.g. pads, holes, etc. Soft features would not be product-specific, e.g. Retro-Reflective Targets, Vacuum Features, etc. This classification would help to highlight the choices that can be made between product- and non-product-specific Assembly Features.

4.3 Feature Selection Process

Now that the definition of 'features' has been clarified in this context the process by which to select them can be described.

For the particular Assembly Concept under consideration, the Assembly Build Tree can be drawn. This will help to highlight the Assembly Key Characteristics that should be selected for the particular Assembly Concept. The Datum Flow Chain of the Assembly Concept can then be derived and illustrated.

As described in Chapter 3, the original concept of the Datum Flow Chain is solely concerned with the location of parts, jigs, fixtures and tools and the assembly features used to carry out these processes. However, Section 4.2 illustrated the other functions performed during assembly other than Location, namely, Support, Clamping and Fastening.

Hence, after the Datum Flow Chain of the given Assembly Concept has been derived, each component needs to be identified as either a part, jig, fixture or tool, in line with the definitions of Chapter 2. This is in order to specify the particular functions corresponding to each component of the Datum Flow Chain, as depicted in Table 4.1. For example, if a component is identified as a Fixture then it could be involved with the assembly functions of Support and/or Fastening.

Clearly, if jigless assembly has been achieved in the particular Assembly Concept then jigs will not appear in the Datum Flow Chain and the function of Location would have to be fulfilled by either the part itself, i.e. part-to-part assembly, or with the aid of some kind of measurement system, i.e. measurement-assisted assembly.

Once each component and its corresponding assembly function have been identified, the assembly features associated with those assembly functions can be selected.

The assembly features will be selected in the order listed previously, i.e. Location, Support, Clamping and Fastening Features. This is because in terms of jigless assembly the Location Features are evidently the most critical. After the selection of Location Features the priority follows a logical sequence, i.e. the components first have to be supported, then clamped and finally fastened.

The next sections describe in detail the process for selecting each of the different assembly features, beginning with Location Features.

4.3.1 Location Feature Selection

4.3.1.1 Kinematics

The function of Location is to position an object in space with reference to an axis system. Commonly, the axis system used is the Cartesian axes with orthogonal, mutually perpendicular axes in **x**, **y** and **z**. In engineering terms, the origin of these axes is referred to as the **datum**, i.e. 0, 0, 0 in x, y and z respectively. Hence, any position of the object can be determined by its co-ordinates with respect to the datum. This is shown in Figure 4.1 below.

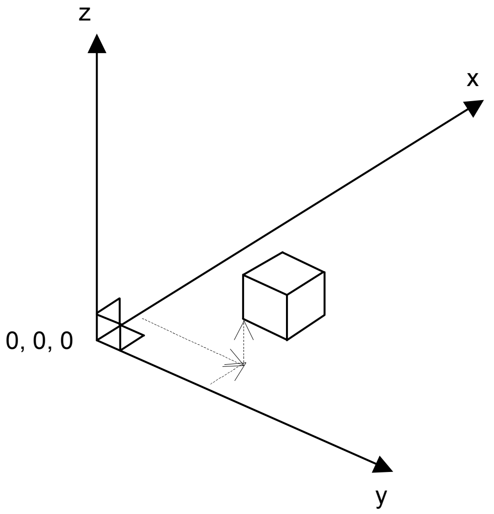


Figure 4.1 Position of an object with respect to the datum in a Cartesian co-ordinate system

The object has six degrees of freedom in which it can move: three in translation and three in rotation, i.e. it can move along the x, y or z axes (in both directions), or it can rotate about the x, y, or z axes (clockwise and anti-clockwise). These six degrees of freedom will be denoted as T_x, T_y and T_z for the translations and R_x, R_y and R_z for the rotations. This is shown in Figure 4.2 below.

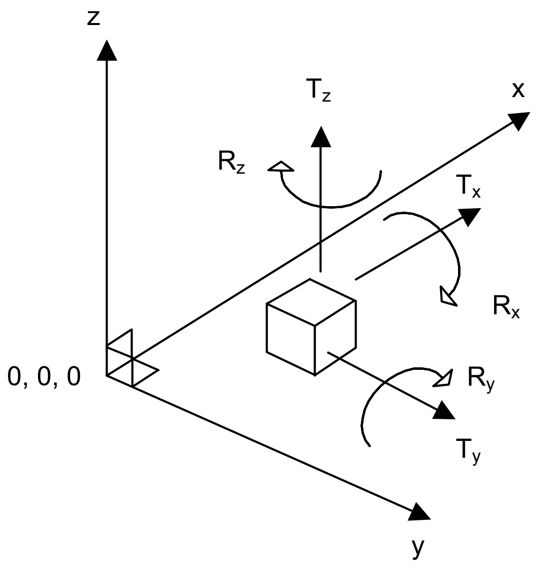


Figure 4.2 Six Degrees of Freedom of an object

For the position of the object to be fixed, its location must be **constrained** in the six degrees of freedom – T_x, T_y, T_z, R_x, R_y and R_z. If the object is static then as long as it is considered perfectly rigid the degrees of freedom will be constrained. If the object is dynamic then the object will need one or more other objects to prevent movement in each of the degrees of freedom to be constrained. In aerospace manufacture and assembly this function is fulfilled by a jig.

From a pure kinematics viewpoint, each of the degrees of freedom should be constrained by a '**single point of contact**'. However, a single point of contact would induce unacceptable stresses as the area of applied force would be so minute. Therefore, in reality, 'semi-kinematic' design principles are employed so that a small surface area, such as a pad or plate, represents the 'single point of contact' and is used to constrain one or more of the degrees of freedom.

If one or more of the six degrees of freedom is not constrained then the object will be able to move in that degree of freedom and the object is said to be **under-constrained**. Its position will not be fixed until all the remaining degrees of freedom have been constrained.

If the object is constrained in the six degrees of freedom, the addition of any other objects preventing the object from moving will cause it to be **over-constrained**. This is because the additional objects will be competing to constrain the same degrees of freedom and it is not be possible to determine which degrees of freedom are actually being constrained and hence, the actual position of the object.

The aim in selecting the location features is to constrain all of the six degrees of freedom of an object so that no degrees of freedom remain unconstrained and that the object is not over-constrained. Additional features may be added to the assembly but these should not be location features and as stated previously, serve only for strength or support.

Practically, this may not be easy to achieve as the six degrees of freedom will be ‘used up’ very quickly in constraining a large and complex structure such as an aerospace assembly. Also, all objects have some degree of flexibility and it is necessary to support or clamp these objects without affecting their location, which may be difficult due to factors such as induced or machined-in stresses.

4.3.1.2 Kinematic Location Feature Pairs

When the location features are selected, they need to be considered in pairs of location features. By its very definition, an assembly is where parts are brought together to be joined in some way. Therefore, an object’s degrees of freedom are dependent on the other object or objects providing the constraint.

This is illustrated in the simple example below, Figure 4.3, where two cubes have been located beside each other so that the face of one cube is flush with the corresponding face of the other cube. Referring to Figure 4.2, the translation in the x-axis has been constrained since if both faces are to remain flush then each cube cannot move in either direction of the x-axis with respect to the other. Similarly, the rotations about the y- and z-axes have been constrained for the same reason. This leaves the translations in the y- and z-axes and the rotation in the x-axis unconstrained: the faces of the cubes can translate and rotate in these axes whilst still remaining flush. One or more other objects would have to be added to constrain the three remaining degrees of freedom. In this example, it is the particular face of each cube that has been selected as the pair of Kinematic Location Features.

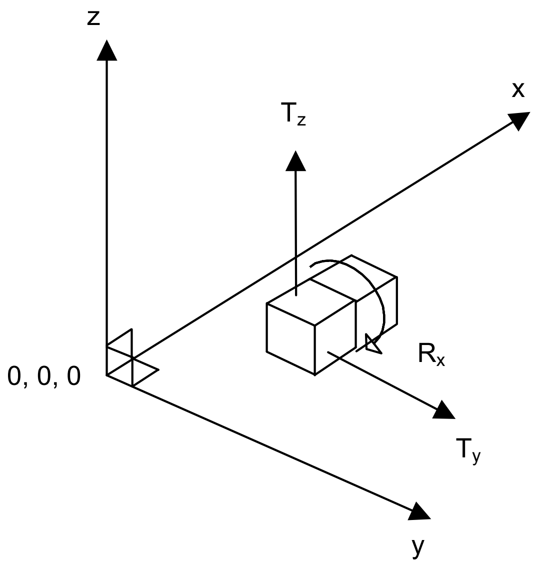


Figure 4.3 Example of Constraint Provided by a Kinematic Location Feature Pair

In practice, the Kinematic Location Feature Pairs will be chosen in turn. Once a Location Feature has been selected for a particular component then an appropriate corresponding Location Feature must be selected for the mating component or components. The process to do this is described forthwith.

4.3.1.3 Principal Mate Feature Pairs

The first operation to be carried out when locating an object using one or more other objects is the placement of these other objects on the object to be constrained. This is an everyday occurrence where, for example, a pen is placed on a table or a chair is placed on the floor.

The specific Kinematic Location Feature Pairs used to carry this out, i.e. the edge of the pen and the surface of the table or the surfaces of the chair legs and the surface of the floor, have been denoted as **Principal Mate Feature Pairs** because they are the first mating features used to begin constraining the degrees of freedom and therefore, locating an object.

It is these Principal Mate Feature Pairs, then, that are the first of the Kinematic Location Feature Pairs to be selected.

4.3.1.3.1 '3-2-1' Design Principle

The most basic examples of Principal Mate Features that could be selected, as introduced previously, are the **point**, the **edge** and the **plane** (or surface). This will be familiar to tool designers as the '**3-2-1**' design principle where a plane is first selected to constrain three degrees of freedom, then an edge is selected to constrain two further degrees of freedom and finally a point (or small surface area) is selected to constrain the remaining degree of freedom. The name '3-2-1' deriving from the fact that it takes three points to construct a plane, two points to construct an edge and leaving the remaining one point.

This is illustrated in Figure 4.4, below, where the 'red' plane is constraining the translations in the x-axis and the rotations in the y- and z- axes, the 'green' edge is constraining the translations in the y- and z- axes and finally, the 'blue' point is constraining the rotation in the x-axis.

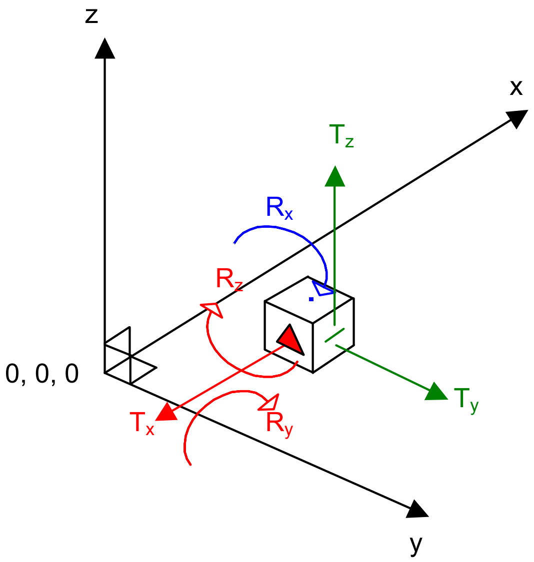


Figure 4.4 '3-2-1' Design Principle

4.3.1.3.2 *Combinations of Basic Principal Mate Feature Pairs*

All of the possible combinations of the basic Principal Mate Feature Pairs made between a point, an edge and a plane are displayed in Table 4.2, below.

COMPONENT A		COMPONENT B
Point	to	Point
Edge	to	Point
Edge	to	Edge
Plane	to	Point
Plane	to	Edge
Plane	to	Plane

Table 4.2 Combinations of Basic Principal Mate Feature Pairs

As previously stated in Section 4.3.1.1, Point Location Features are not used in practice because of the unacceptable high stresses they induce. Therefore, the Point-to-Point, Edge-to-Point and Plane-to-Point Principal Mate Feature Pairs can be discounted. This leaves the Edge-to-Edge, Plane-to-Edge and Plane-to-Plane as Basic Principal Mate Feature Pairs. The following diagrams are examples of these Basic Principal Mate Feature Pairs.

4.3.1.3.3 *Edge-to-Edge Principal Mate Feature Pair*

The example below, Figure 4.5, shows a typical structure of a Wing Leading Edge Skin. The area highlighted by the red box indicates the critical function of the structure, namely, the designed aerodynamic profile of the Wing Leading Edge. This must be achieved by the correct location of the alignment of the Edge of the Wing Leading Edge and the Edge of the Skin, in order to avoid any ‘Steps or Gaps’ that would interfere with the required aerodynamic profile.

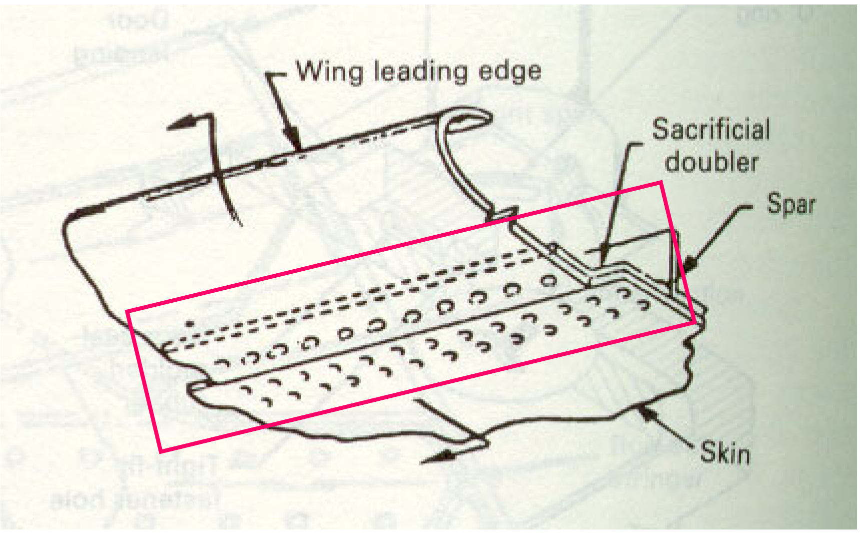
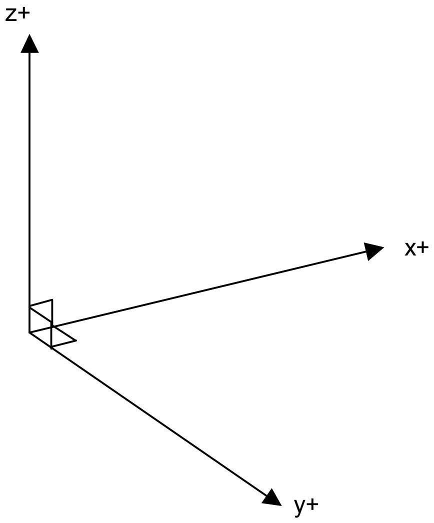


Figure 4.5 Example of an Edge-to-Edge Principal Mate Feature Pair (Diagram from Niu, 1988)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by this particular Edge-to-Edge Principal Mate Feature Pair in this axis system will be:-

- **T_y, T_z, R_x, R_y** and **R_z**

4.3.1.3.4 Plane-to-Edge Principal Mate Feature Pair

The next example, Figure 4.6, shows a typical Fixed Leading Edge structure of a Wing Leading Edge. The area highlighted by the red box indicates the assembly of the Support Strut to the Leading Edge Panel and Door Support.

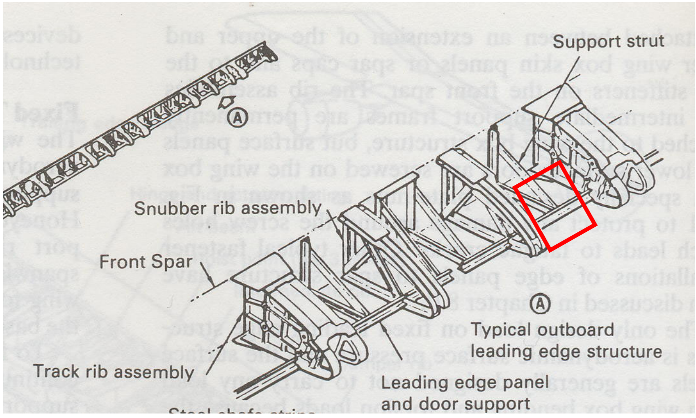
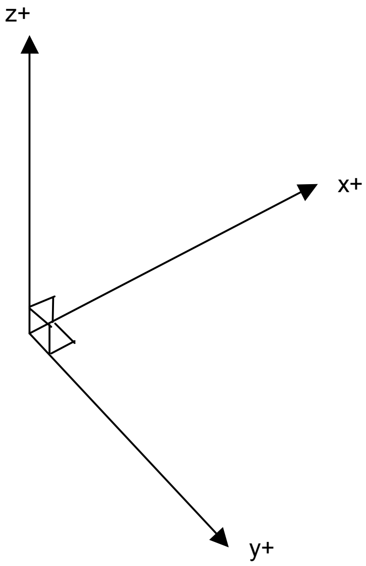


Figure 4.6 Example of a Plane-to-Edge Principal Mate Feature Pair (Diagram from Niu, 1988)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by this particular Plane-to-Edge Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{T_y}$, $\mathbf{R_x}$ and $\mathbf{R_z}$

4.3.1.3.5 Plane-to-Plane Principal Mate Feature Pair

The following example, Figure 4.7, shows a typical structure of two Skin Panels for a Fuselage section. The area highlighted by the red box indicates the assembly of the Top Skin Panel onto the Bottom Skin Panel.

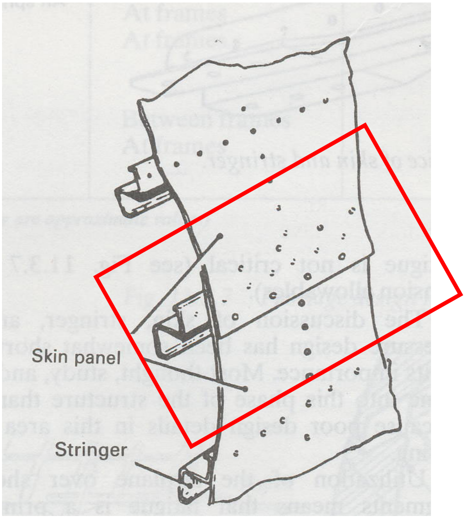
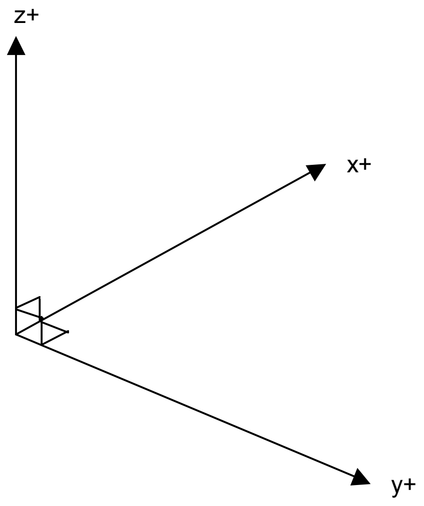


Figure 4.7 Example of a Plane-to-Plane Principal Mate Feature Pair (Diagram from Niu, 1988)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by this particular Edge-to-Edge Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{R}_x$ and $\mathbf{R}_z$

4.3.1.3.6 More Complex Principal Mate Feature Pairs

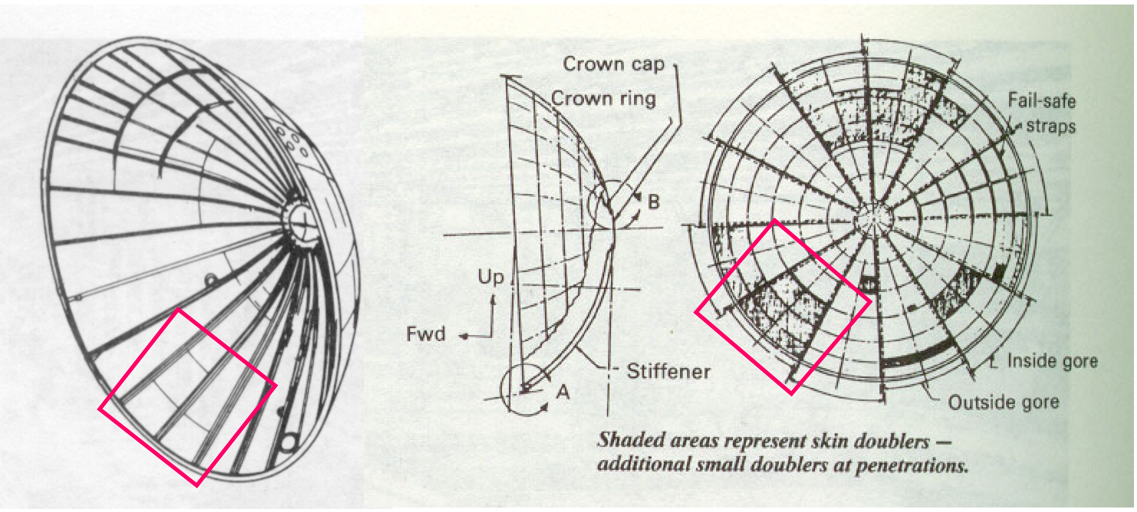
The most common Principal Mate Feature Pair is the Plane-to-Plane Principal Mate Feature Pairs, since no matter how complex the geometry of a product is, a flat surface is usually required to locate the product on to another object, which also usually has a flat surface. Hence, the Plane-to-Plane Principal Mate Feature Pair will be the most widely selected and chosen.

However, it is apparent that not all products, if not most, are constructed of entirely flat, orthogonal surfaces or edges. These products may have surfaces or edges that have one or more axes of curvature for the purposes of functionality or aesthetics. This is especially true with aerospace products as the aerodynamic requirements of the structure drive the geometry of the outer surface.

Figures 4.8 to 4.11, below, illustrate examples of actual structures with more complex Principal Mate Feature Pairs. Here, the structures are constructed from more complex geometry and their Principal Mate Feature Pairs must be evaluated on a case-by-case basis.

4.3.1.3.7 Typical Dome Pressure Bulkhead

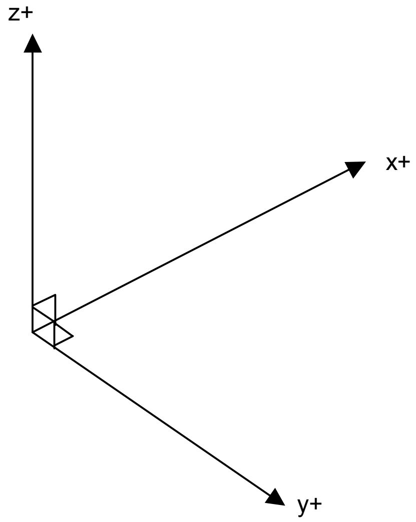
The example below, Figure 4.8, shows a typical structure of a Dome Pressure Bulkhead; these are found at the rear of the fuselage of most commercial aircraft to withstand the pressurisation of the fuselage. The area highlighted by the red box indicates a shaded area that represents the Skin Doublers used to reinforce the structure in certain areas. The correct location of the Skin Doubler with respect to the Dome Pressure Bulkhead structure will be considered by firstly evaluating the Principal Mate Feature Pair for this assembly. In this case, the Principal Mate Feature Pair will be double-curved surfaces of the back face of the Skin Doubler and the front face of the Dome Pressure Bulkhead.



Shaded areas represent skin doublers — additional small doublers at penetrations.

Figure 4.8 Typical Dome Pressure Bulkhead (Diagram from Niu, 1988)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by the double-curved surfaces of the back face of the Skin Doubler and the front face of the Dome Pressure Bulkhead Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{T_x}$, $\mathbf{T_y}$, $\mathbf{T_z}$, $\mathbf{R_y}$ and $\mathbf{R_z}$

4.3.1.3.8 Airbus A340-500/600 Main Landing Gear Door

This example, Figure 4.9 below, shows an Airbus A340-500/600 Main Landing Gear Door. The objects highlighted by the red box indicate Brackets that are assembled to the Main Landing Gear Door. In this case, the Principal Mate Feature Pair will be single-curved surfaces of the back face of the Brackets and the front face of the Main Landing Gear Door.

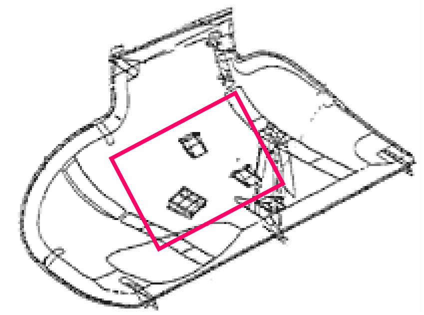
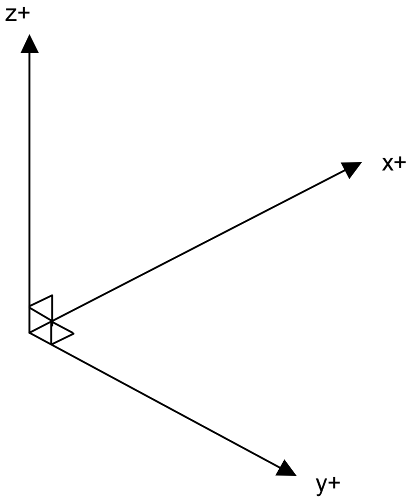


Figure 4.9 Airbus A340-500/600 Main Landing Gear Door (Diagram from SAAB Aerospace, 2002)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by the single-curved surfaces of the back face of the Brackets and the front face of the Main Landing Gear Door Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{T_y}$, $\mathbf{T_z}$, $\mathbf{R_x}$, $\mathbf{R_y}$ and $\mathbf{R_z}$

4.3.1.3.9 Airbus A340-500/600 Pylons

So far, all of the examples of Principal Mate Feature Pairs have left unconstrained at least one of the degrees of freedom. This means that once the object had been located to the other object in the assembly using the Principal Mate Feature Pair, an additional Location Feature could be used to constrain the remaining degree or degrees of freedom.

The following example, shown in Figure 4.10 below, is the first assembly where all of the degrees of freedom are constrained by the Principal Mate Feature Pair. This is important because any other additional Location Features used to locate the components will, by definition, over-constrain the assembly. Therefore, in order for this not to happen, the components must be located correctly using only the Principal Mate Feature Pairs.

The example is that of an Airbus A340-500/600 Pylon. The components highlighted by the red box indicate the Forward Structure of the Pylon that is assembled to the Aft Structure of the Pylon. In this case, the Principal Mate Feature Pair will be complex-curved surfaces of the underside surface of the Forward Pylon Structure and the Top surface of the Aft Pylon Structure.

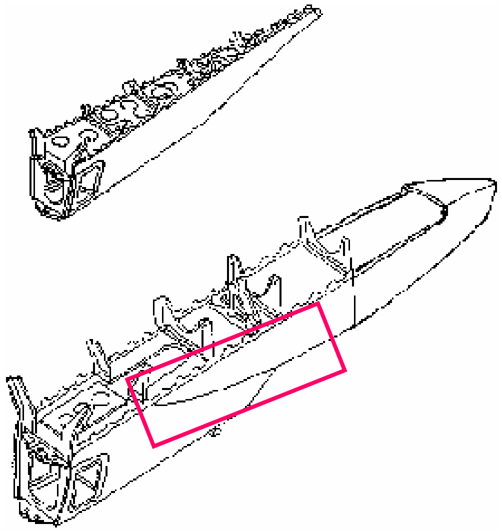
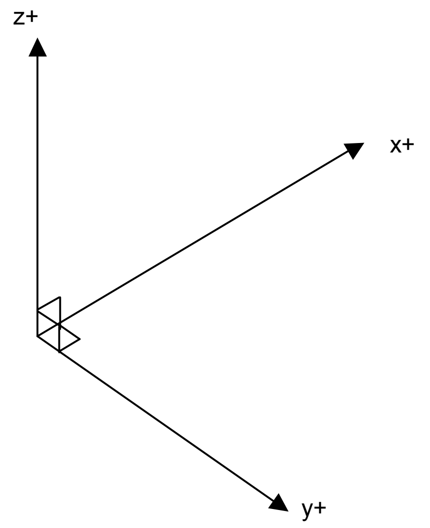


Figure 4.10 Airbus A340-500/600 Pylons (Diagram from SAAB Aerospace, 2002)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by the complex-curved surfaces of the underside surface of the Forward Pylon Structure and the Top surface of the Aft Pylon Structure Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{T_x}$, $\mathbf{T_y}$, $\mathbf{T_z}$, $\mathbf{R_x}$, $\mathbf{R_y}$ and $\mathbf{R_z}$

4.3.1.3.10 Boeing 747 Cockpit Structural Framework

The following assembly is another example of where all of the degrees of freedom are constrained by the Principal Mate Feature Pair. The example, shown below in Figure 4.11, is a Boeing 747 Cockpit Structural Framework. The components highlighted by the red box indicate the Frames that are assembled to the Cockpit Structural Framework. In this case, the Principal Mate Feature Pair will be complex-curved surfaces of the bottom surfaces of the Frames and the top surface of the Cockpit Structural Framework.

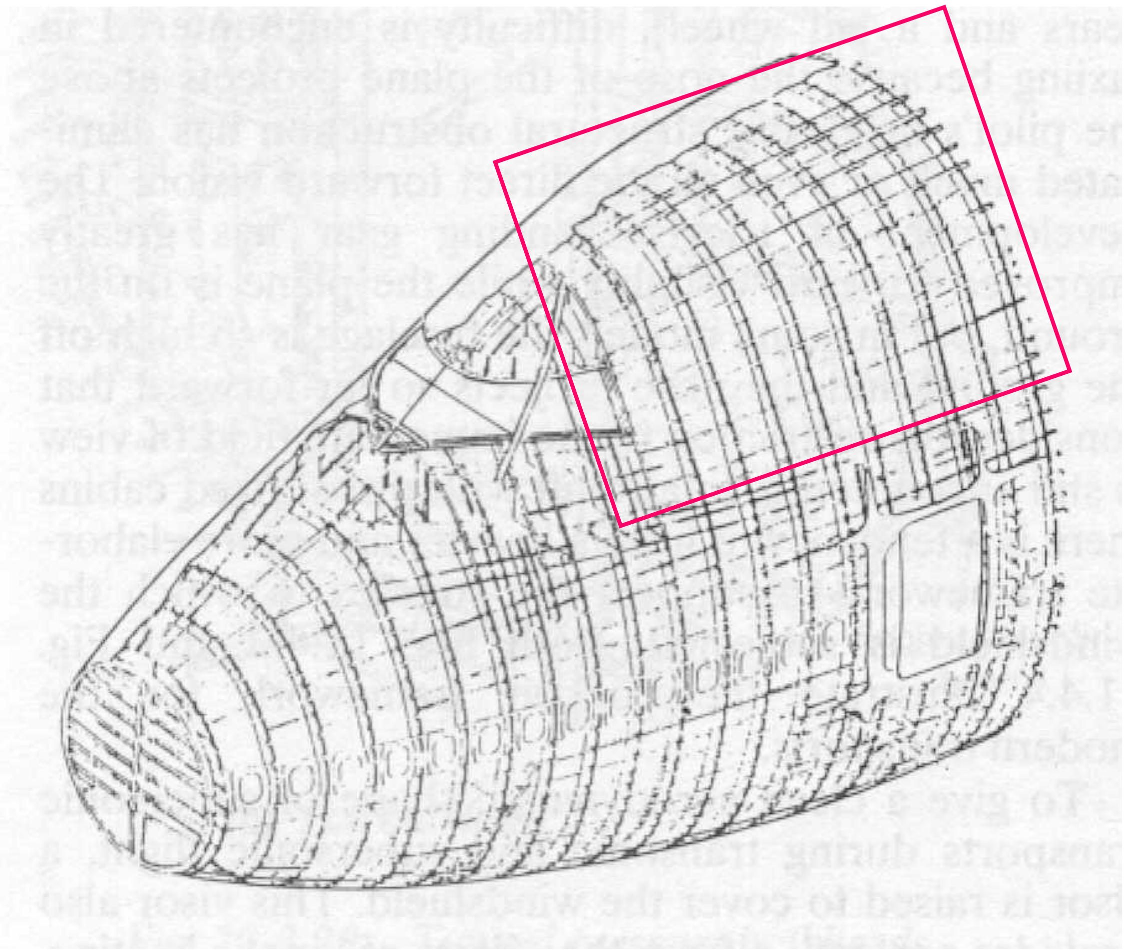
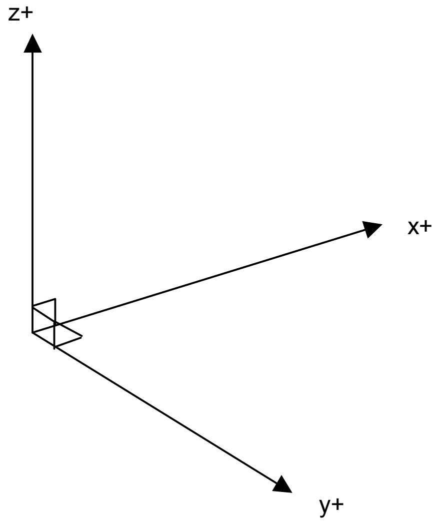


Figure 4.11 Boeing 747 Cockpit Structural Framework (Niu, 1988)

If an axis system is used whereby the x-axis is positive diagonally up the page, the y-axis is positive diagonally down the page and the z-axis is positive in the Up direction the axis system will look like:-



The degrees of freedom constrained by the complex-curved surfaces of the bottom surfaces of the Frames and the top surface of the Cockpit Structural Framework Principal Mate Feature Pair in this axis system will be:-

- $\mathbf{T_x}$, $\mathbf{T_y}$, $\mathbf{T_z}$, $\mathbf{R_x}$, $\mathbf{R_y}$ and $\mathbf{R_z}$

4.3.1.4 Location Feature Pairs

Once the Principal Mate Feature Pairs have been identified and the corresponding Degrees of Freedom they constrain, any other, additional Location Feature Pairs can be selected to constrain the remaining degrees of freedom.

The main difference in the selection process of the Principal Mate Feature Pairs compared to the Location Feature Pairs is whereas the Principal Mate Feature Pairs are identified due to the inherent nature of the assembly of two objects, the Location Feature Pairs can be selected from any number using one or more criteria.

The following sub-sections describe the process developed to select these Location Feature Pairs.

4.3.1.4.1 Assembly Concept Choice

The first point that must be noted is the selection of the Location Features will be dependant on the choice of assembly concept. For a given assembly concept, different Location Features could be selected. For example, a particular metrology apparatus could use one of a whole range of appropriate types of metrology targets. Each Location Feature will have individual and different properties but their applicability is restricted to the system that they were intended for.

To illustrate this point – the choice of assembly concept could have been made to be either a (i) 'conventional' assembly using jigs, fixtures and tools; (ii) a 'part-to-part' assembly using part-integrated Location Features and supporting fixtures; or (iii) a 'measurement-assisted' assembly using metrology apparatus with metrological Location Features and adjustable fixtures. Options (i) and (ii) would only involve 'Hard', physical Location Features that are specific to the product, whereas option (iii) would only involve 'Soft', non-contact Location Features that are not specific to the product.

Of course, there is no reason why a combination of all three, assembly concepts could not be used for different stages of a particular assembly. The examples merely serve to demonstrate the fact that the choice of assembly concept will drive the selection of the Location Features by limiting the type of Location Feature available to use.

4.3.1.4.2 Goal in Selecting Location Feature Pairs

Once this fact has been established, the selection of the Location Features Pairs can begin.

From an assembly point of view, the purpose of the Location Feature Pairs is to constrain any remaining degrees of freedom of an assembly between two objects. If the premise is taken that 'the best form of assembly is no assembly at all' because no errors or additional operations will be introduced, then the best Location Feature Pairs will be those that constrain the most degrees of freedom. However, there are many other factors influencing the selection of the Location Feature Pairs including the Design and

Manufacturing effort of each, individual Location Feature and the associated Cost of producing the Location Feature.

The following Table 4.3 shows the list of factors involved in the selection of Location Feature Pairs. The list is not exhaustive but it typifies how many factors are involved, indeed, each of one these factors could be a major subject of research in itself. However, for the purposes of this particular research a simple methodology is required to organise all of these factors into some sort of order to be able to select the 'best' Location Feature Pair. The next sub-sections will explore this methodology in more detail.

	Degrees of Freedom Constrained	**Design Criteria**	**Manufacturing Criteria**	**Cost of Location Feature Pair**	**Accuracy of Location Feature Pair**
Location Feature Pair	1 2 3 4 5 6	Material Loads Stress Fatigue Weight	Material Behaviour Manufacturing Processes - Casting - Forming - Shaping - Removal - Joining Machines Available - Process Capability (Part & Feature)	Design Costs + Manufacturing Costs	Tolerances

Table 4.3 Factors Involved in Selection of Location Feature Pairs

4.3.1.4.3 Design Criteria for Selecting Location Feature Pairs

It is preferable that the Location Feature Pairs are selected as early as possible in the product's development so that the design analysis and manufacturing preparation can be undertaken to the fullest extent. However, the sooner this is done the less information there will be on the choices made for the product's design and manufacture.

As the product gathers maturity then greater and more detailed analysis will be carried out on the design. The basic process typically follows the order used in the Design Criteria of Table 4.3 – for a particular component, its material will be the first choice made, after which representative load cases can be applied, from these load cases the stress concentrations can be worked out, along with fatigue conditions and finally, the weight of the component can be estimated after the analysis has been completed. Obviously, this is a vast simplification of the design process but essentially all components must go through the same process.

As the process is continually evolving, if the selection of the Location Feature Pairs is to be made at the earliest possible opportunity, then the best that can be done is the creation of a database cataloguing the design properties of different Location Feature Pairs analysed using the Design Criteria listed in Table 4.3. In this way, generic models can be made available for particular Location Feature Pairs that could be modified to suit changing conditions. The most effective way to do this is though applying Finite Element Analysis on the Location Feature Pairs as this provides the quickest and most accurate approximation compared to actually carrying out experiments on each specific Location Feature Pair.

An attempt to start this has been included in Appendix A, ‘Effect of Assembly Features on Structures – FE Modelling’, completed by Dr. Randolph Odi, a member of the JAM Project Research team at Cranfield. This effort resulted from the need to ascertain the effect of using different assembly features on a particular assembly, namely the JAM Demonstrator Structure described in Chapter 6. This was a major piece of work and yet it only considers a small number of Location Feature Pairs under limited load cases. A more thorough and comprehensive analysis would have to be completed on all Location Feature Pairs if the selection process were to be adopted in reality.

Nevertheless, the general conclusions that the work draws are that any integral Location Features will act as significant stress raisers and perhaps unsurprisingly, the more ‘complex’ a Location Feature Pair the higher its induced stress will be. However, the results do serve to qualify and quantify the levels of stress for the particular Location Feature Pairs considered.

The work also underscores the fact that if 'Soft', non-contact Location Features were used in the assembly of a product then these stress implications would not apply. This would point to a major benefit towards using these types of Location Features that are not specific to a product, as in the case of 'Hard', physical Location Features that are specific to the product. Although, of course, there are many other considerations involved in the adoption of 'Soft', non-contact Location Features, such as the acquisition cost of the metrology equipment or operator skill/training.

4.3.1.4.4 Manufacturing Criteria for Selecting Location Feature Pairs

In common with the Design Criteria, the first consideration in the Manufacturing Criteria for selecting Location Feature Pairs is the choice of material for the particular component. Different materials will exhibit different behaviour for certain manufacturing processes such as castability, forgeability, workability, machinability and weldability. For example, some materials can be processed at room temperature but others require elevated temperatures; some materials are soft and ductile, whereas others are hard, brittle and abrasive.

The next consideration must be the shape, size and thickness of the component to be processed. Figure 4.12, below, shows the minimum section size or dimensions that can be satisfactorily produced for a typical, thin-section web using different processes.

It can clearly be seen that some processes are able to achieve smaller dimensions for certain materials.

Each of these processes can produce a range of surface finishes and tolerances. This is summarised in Figure 4.13, below.

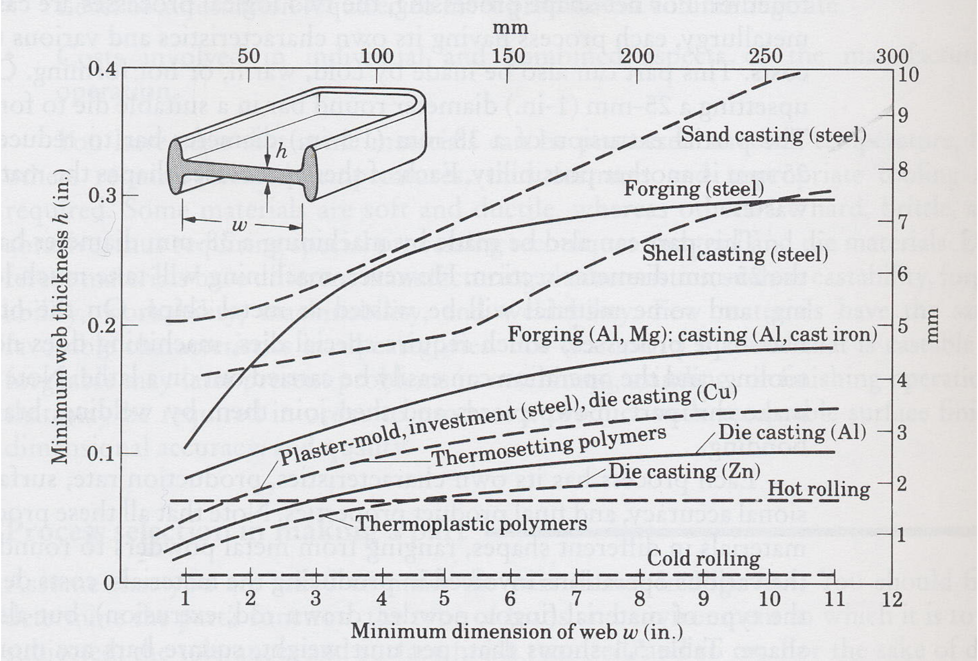


Figure 4.12 Process Capabilities for Minimum Part Dimensions (Kalpakjian, 1995)

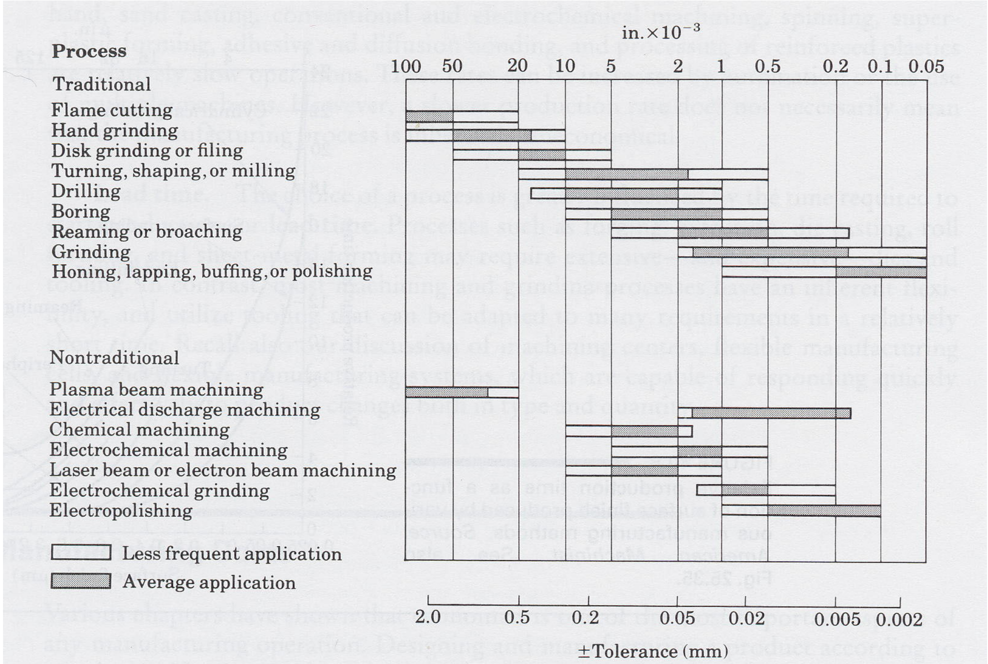


Figure 4.13 Tolerance Capability of Various Processes (Kalpakjian, 1995)

Figure 4.14, below, shows the relationship between the relative cost of a manufacturing process and the tolerance required: the closer the tolerance, the higher the cost of manufacturing will be. Figure 4.15 shows a similar relationship in that the finer the Surface Finish required of a particular process, the longer the manufacturing time, thereby increasing the cost.

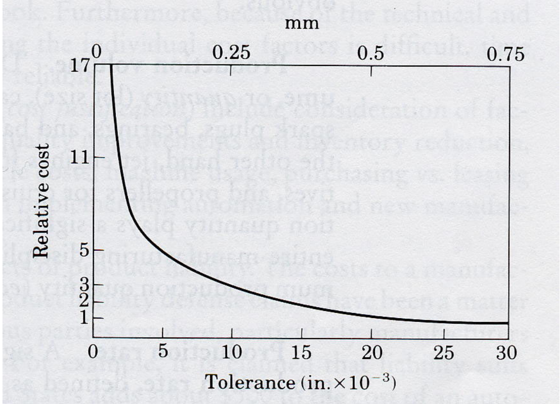


Figure 4.14 Relationship Between Relative Cost and Tolerance (Kalpakjian, 1995)

Illustrating this point, in machining aircraft structural members made of titanium alloys as much as sixty percent of the cost of machining the part is consumed in the final machining pass in order to hold proper tolerances and surface finishes (Kalpakjian, 1995).

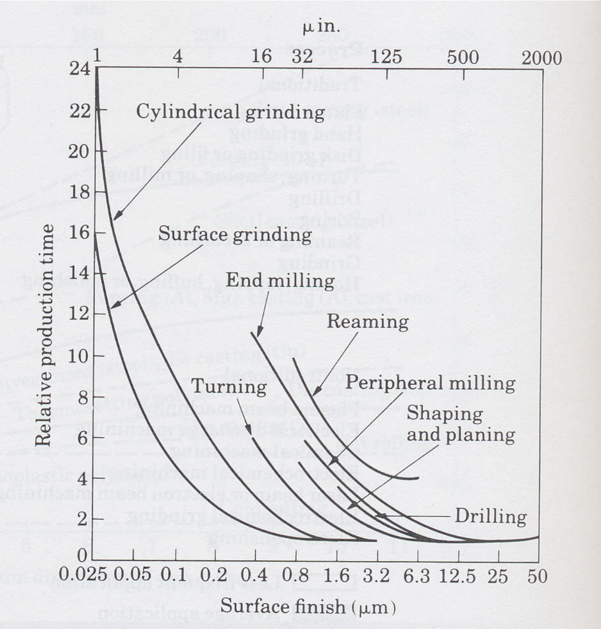


Figure 4.15 Relative Production Time as a Function of Surface Finish Produced by Various Manufacturing Methods (Kalpakjian, 1995)

4.3.1.4.5 Cost of Location Feature Pairs

The preceding sections have illustrated that there is a trade-off in selecting the Location Feature Pairs. Section 4.3.1.4.2 stated that the best Location Feature Pairs would be those that constrain the most Degrees of Freedom. However, these Location Feature Pairs would involve greater complexity and require higher tolerances and surface finish. Section 4.3.1.4.3 concluded that these Location Features will act as significant stress raisers and Section 4.3.1.4.4 has shown that they will be more costly to produce than Location Features with less complexity and requiring slacker tolerances and surface finish.

The optimum solution will therefore be somewhere in the middle between highly constraining Location Feature Pairs and simple, relatively inaccurate Location Feature Pairs.

Hence, there needs to be further criteria by which to select the Location Feature Pairs. The two, prime candidates would evidently be *(i) the total Cost of producing the*

Location Feature Pairs in both Design and Manufacturing and *(ii) the Accuracy achievable by various Location Feature Pairs*.

The second criteria will be covered in the following section. This section will cover the first criteria, i.e. the total Cost of producing the Location Feature Pairs.

The total Cost of producing the Location Feature Pairs is clearly a very, important factor in their selection. Consequently, a method is required to evaluate this Cost in order that one set of Location Feature Pairs can be compared with another.

The phrase 'total Cost' is emphasized because historically, Costing activities have concentrated upon the cost of the manufacturing processes required to produce the Location Features. For a Jigless Assembly environment, the costs incurred by the extra design analysis required due to the use of more varied and atypical Location Features makes the design costs important. However, this extra design analysis necessary to create a database cataloguing the design properties of different Location Feature Pairs could be completed as a 'one-off' activity, e.g. a non-recurring cost. An example of how much a one-off activity, such as this, would cost is discussed in Chapter 5, specifically concerning the JAM Demonstrator Structure. Although it should be noted that the extra design costs for the JAM Demonstrator Structure assume that the newly, selected Location Feature Pairs would not incur any serious complications that would require redesigning the component. In practice, part of the database cataloguing the design properties of different Location Feature Pairs would describe when particular Location Feature Pairs would be suitable for certain situations in terms of load cases, allowable stress limits and fatigue conditions.

The bulk of the cost in producing a Location Feature Pair would remain in its manufacture. As described in the Literature Review of Chapter 2, the current state-of-the-art in commercial Cost Engineering systems already have the facility to interrogate standard Feature Databases and predict the manufacturing cost.

The next steps would be to make these Cost Engineering systems more flexible so that their architecture could handle the unconventional design, manufacturing and assembly methods being described in this research study. This would involve progressing from the widely accepted Expert Systems of today to the evolving Knowledge Based Systems that are just beginning to be implemented within industry.

An ideal architecture is illustrated below, Figure 4.16, and the subject is explored further in Chapter 6.

Briefly, Figure 4.16 illustrates an architecture where Design Data, such as the product's requirements, is input into the Knowledge Based System. This data is then used by the Knowledge Based System though programmed rules within its Knowledge Base to create a Geometrical Definition of the product. The Design Data would also be used by the Feature-Based Cost Tool, along with input from the Knowledge Based System, to evaluate the total production costs. These costs would then help to drive the Capacity Scheduling tool as the times and costs of all the processes involved in the production would have been estimated. Finally, the Capacity Scheduling tool could serve as input for Discrete Event Simulators to simulate the entire production processes in order to assess such issues as process flow, logistics, operator interfaces, etc.

The evaluation of the total production costs by the Feature-Based Cost Tool could then be fed back into the Knowledge Based System for the comparison of different Assembly Concepts and Location Feature Pairs.

Hence, the relative production costs of alternative Location Feature Pairs could be quickly and easily evaluated using the Feature-Based Cost Tool in conjunction with the Knowledge Based System.

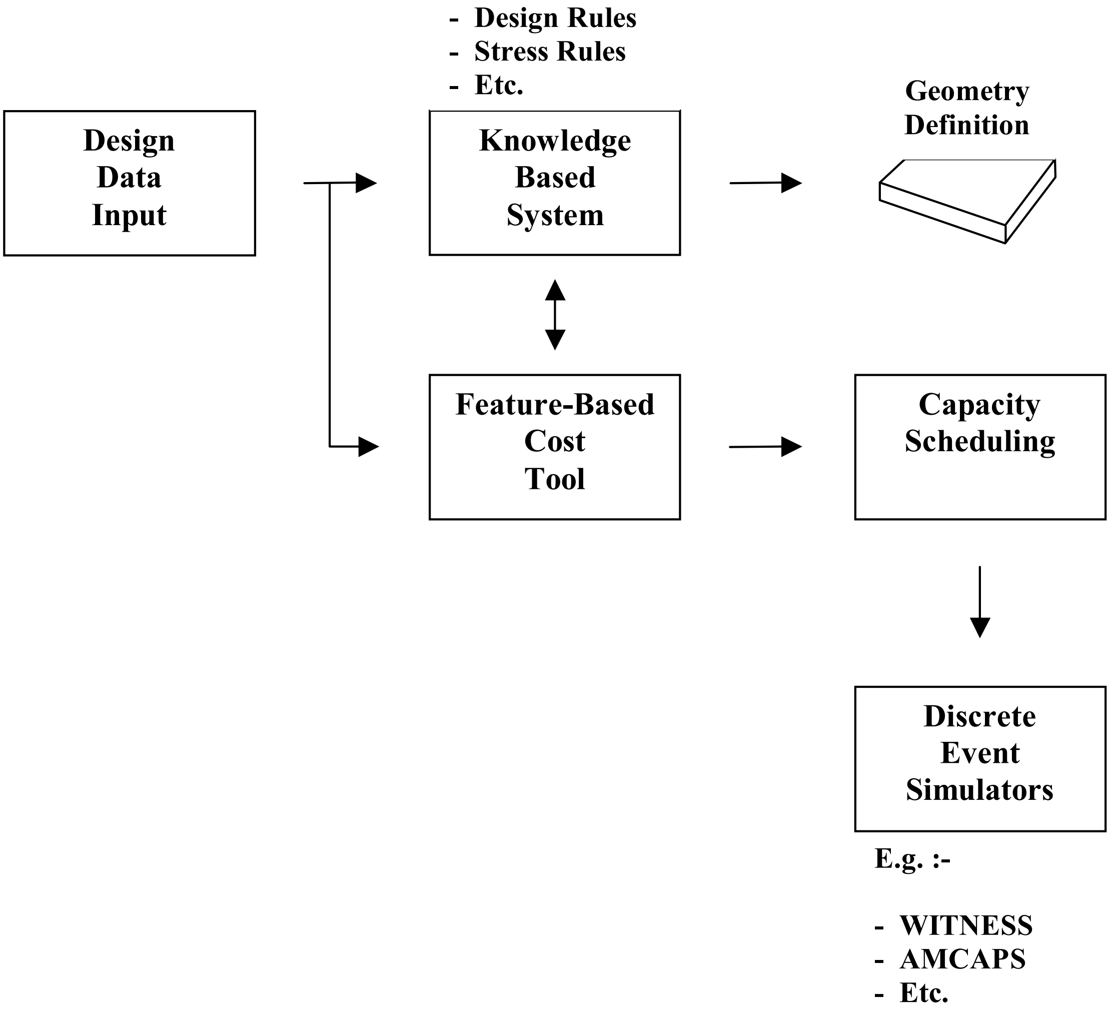


Figure 4.16 Ideal Architecture for Knowledge Based System and Feature Based Cost Tool

4.3.1.4.6 Accuracy of Location Feature Pairs

The second further criteria by which to select the Location Feature Pairs, in addition to the total cost of production, is their achievable accuracy. This criterion has major importance because it is essential to know how accurate is a particular Location Feature Pair. It would be unacceptable for a Location Feature Pair to be able to be produced cheaply but not to have the required accuracy to constrain all of the remaining degrees of freedom in an assembly.

Accuracy is measured in the form of tolerance, i.e. the actual deviation of a dimension from its designed nominal. As illustrated in Figure 4.14, there is an inverse relationship between tolerance and relative cost whereby it is very expensive to produce a tight tolerance but becomes more and more cheap to produce a looser tolerance.

Therefore, like the total cost of production, a method is required to evaluate how accurate different Location Feature Pairs are. With this information, different Location Feature Pairs can then be compared against the total production cost they incur and the accuracy to which they can achieve.

More accurate Location Feature Pairs would be preferable than less accurate choices as they would be more likely to constrain all of the degrees of freedom they were intended to, due to their decreased amount of deviation and variation. However, more accurate Location Feature Pairs would be more costly to produce.

Furthermore, the selected Location Feature Pairs would not be operating in isolation; there would be a variety of Location Feature Pairs for a given assembly. Hence, the method to evaluate the accuracy of particular Location Feature Pairs must take into account the cumulative, three-dimensional effects of the assembly.

Typically, individual, detail parts are allocated linear tolerances, i.e. a +/- deviation from the nominal dimension. However, these tolerances only operate in two dimensions. For a three-dimensional assembly, GD&T must be used because this system of tolerancing inherently adheres to a three-dimensional environment.

Using GD&T, the collective accuracy of all the Location Feature Pairs within the assembly can then be predicted. As discussed in the Literature Review, commercial applications are available to simulate the variation in the assembly caused by the deviations of the Location Feature Pairs from their nominal dimensions.

The most widely known and industrially used commercial applications, such as Valisys/eM-Tolmate, VSA, etc., employ Monte Carlo simulation techniques to replicate the real physical assembly before it goes into production. The disadvantages of these particular applications are that they need a highly defined Geometrical Model of the assembly in order to be able to perform the Monte Carlo simulations. By this time, a great deal of the design and manufacturing choices will have been selected and the product will already be quite mature in its development. It will therefore be very difficult to make any changes to the selections made.

To reverse this situation the selection of the Location Feature Pairs needs to be made as early as possible although this would mean that the detailed geometry of the assembly would not be available for simulation. The method to evaluate the accuracy of the Location Feature Pairs within the assembly must therefore be simple and not require any geometry.

The method used for this purpose has previously been described in Chapter 3 and is called 'Error Budgeting'. The reason the Error Budgeting tool is so powerful is because it does not require the complete geometry of the assembly, as it calculates the accuracy of each feature-to-feature link for all the Location Feature Pairs using GD&T symbols and terminology.

Error Budgeting can be applied to all types of assembly, with either Hard or Soft Location Features. If Hard Location Features are employed then the GD&T tolerances allocated to the component are used to calculate the accuracy of the structure. If Soft Location Features are employed the measurement error of the metrology targets are used for the calculation of accuracy.

An example of an Error Budget applied to a particular assembly is presented in Chapter 5. The Error Budget has been calculated for the JAM Demonstrator Structure and illustrates its use.

4.3.2 Selection of Other Assembly Feature Types

Once the Location Features have been selected, the remaining types of assembly features defined in Section 4.2 can be selected. Their selection will not be covered in very great detail here because like the Location Features, each one of the assembly feature types is a large subject of its own.

Accordingly, a short description of the issues concerning the selection of the remaining assembly feature types is given below.

4.3.2.1 Support Feature Selection

Referring to Table 4.1, the components associated with Support are Parts and Fixtures. Indeed, Support Features and their selection are encompassed within the wider field of Fixture Design. Along with Jigless Assembly, there is a concurrent area of study and research into ‘Fixtureless Assembly’, which involves the assembly of Parts without the use of Fixtures (for example, Walczyk et al, 2000).

The main issues of concern in the selection of Support Features are the strength required by the Support Features to support the Part and in conjunction, how many Support Features are necessary to adequately support the whole Part.

The required strength of the Support Features will be dictated by the weight of the Part that they are designed to support. This will tend to drive the attributes of the Support Features in terms of material and dimensions.

How many Support Features are necessary will also be determined by the Part. The number of Support Features could be chosen through experience, experimentation or analysis. Generally, the more Support Features there are the better, but they will be more expensive to produce and calibrate.

For the selection of Location Features, it was assumed that all components were rigid otherwise Kinematic Principles would not be strictly applicable, as flexible components would not be entirely constrained. In reality, nothing is totally rigid and everything has some amount of flexibility. Therefore, the Support Features must be in place to negate as much of the flexibility of a Part as possible.

Care must also be taken for the Support Features to only provide support rather than inadvertently providing location – in order for the Part not to be over-constrained. Commonly, this is achieved by the use of ‘Screw Jacks’ or similar, adjustable features so that after the Part has been located using the Location Features, the Support Features can be adjusted to ‘just’ support the part without imparting any location.

4.3.2.2 Clamping Feature Selection

Again referring to Table 4.1, the components associated with Clamping are Parts and Tools. There are numerous types of clamps. In fact, any tool that holds a Part in position whilst other operations are carried out can be classified as a clamp. As for the Location Features, Clamping Features can either be ‘Hard’, i.e. product-specific, or ‘Soft’, non product-specific features. Most Clamping Features will be Hard as the clamping relies on the physical shape of the Part itself. There are a small number of Soft Clamping Features, such as Suction Cups or the features enabling the clamping by some non-physical method like vacuum or electromagnetic clamping.

Similar to the Support Features, the major issues for the selection of Clamping Features will be the force required to clamp the Part and the number or configuration of Clamping Features to do this.

The Clamping Features will have to be able to withstand the force of any operations carried out on the Part, such as drilling, riveting or bolting. Different Clamping Features will have different Clamping force capabilities due to their shape or material. These various Clamping Features will also impart the Clamping Forces to the Part in various ways, which will need to be considered.

Again, the Clamping Features have to clamp the Part without providing additional Location to the Part. This may be difficult as enough Clamping Force has to be applied to the Part to clamp it firmly but too much Clamping Force will cause deformation of the Part and hence, distort the location of the part. The configuration and arrangement of the Clamping Features is also important in providing enough Clamping Force without unnecessary deformation.

Experience, experimentation or analysis will once more aid the tool designer and/or manufacturer to select the appropriate Clamps using suitable Clamping Features for the particular part and assembly.

4.3.2.3 Fastening Feature Selection

The final operation in assembly that needs to be performed is some sort of fastening or joining operation, once all the parts have been located, supported and clamped together. Therefore, Table 4.1 illustrates that all components are involved with fastening – Parts, Jigs, Fixtures and Tools.

There are many types of fastening methods depending on the particular ‘fit, form and function’ of the assembly. The fastening can be carried out as one operation or as a series of operations. The assembly can also be performed manually or automated by a machine.

The general types of fastening methods that can be used on both metallic materials and composite materials, include mechanical fastening (screws, rivets, bolts, etc.), welding, brazing, soldering, bonding, and stitching or stapling. There are a few generic fastening methods that are restricted to metallics, such as seaming, crimping and shrink or press fitting. Each type of fastening method has its own advantages and disadvantages.

The type of fastening method will determine whether the fastening is a one stage process, e.g. welding, or whether the fastening requires multiple stages, e.g. mechanical fastening. For all types of fastening methods, the process parameters and functional properties need to be considered. For the multiple stage processes, the prerequisite processes will also have to be investigated. For example, mechanical fastening requires the drilling of holes for the screws, rivets or bolt to be inserted in; this is an additional operation which either has to be done prior to assembly or at assembly.

Historically, all fastening has been carried out manually. However, manual labour is expensive and imprecise. Hence, automated fastening processes are becoming more and more widespread. This is especially true in aerospace as traditionally the usual type of fastening methods have been with many thousands of bolts and rivets, which are more economical to produce with automated processes.

There are, in addition, many more issues that must be evaluated in the fastening of assemblies that are not covered here.

4.3.3 Schematic of Assembly Feature Selection Process

The Assembly Feature Selection Process to enable jigless assembly described in the preceding sections can be summarised in the following schematic (Figure 4.17):

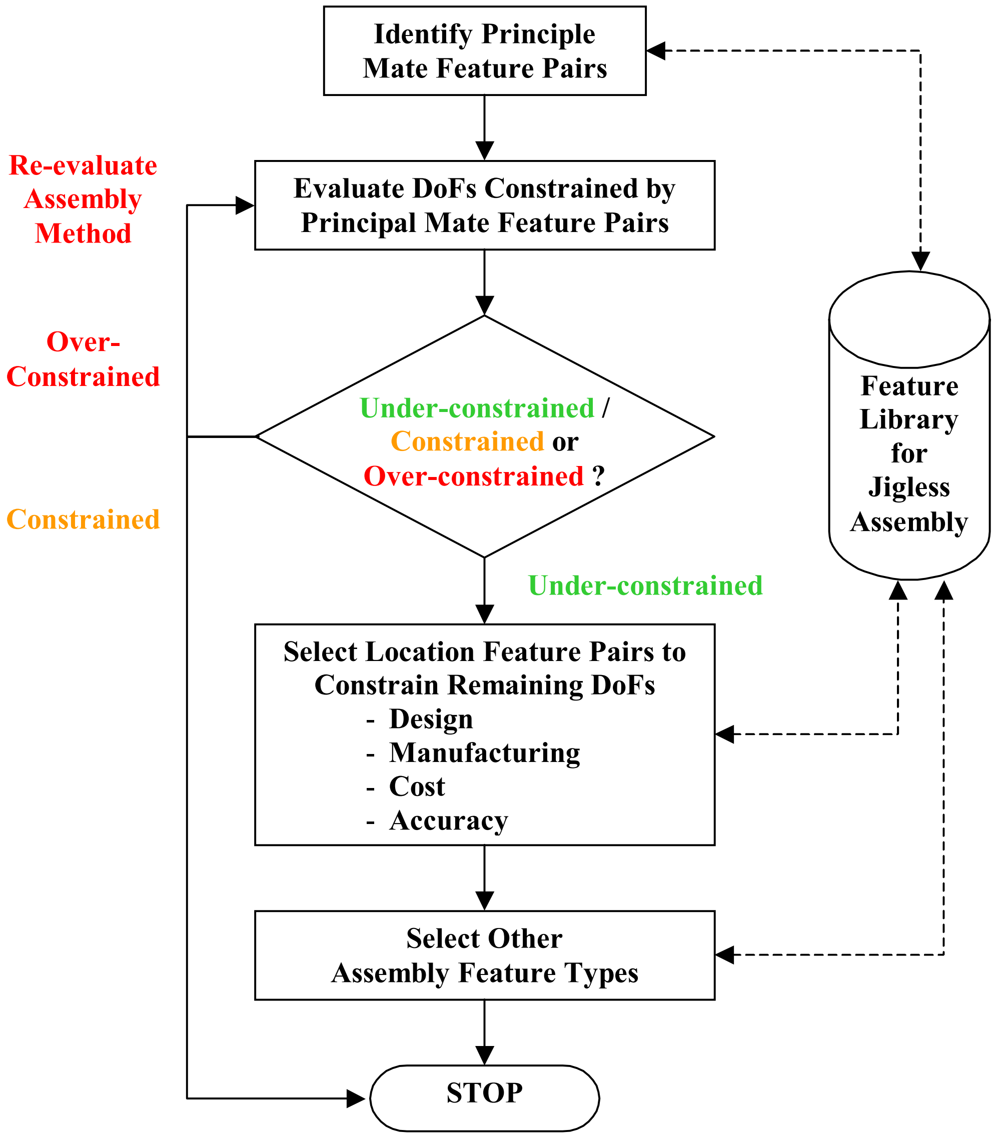


Figure 4.17 Schematic of the Assembly Feature Selection Process to enable jigless assembly

4.4 Feature Library for Jigless Assembly

In the preceding sections a process to select appropriate assembly features specifically to enable jigless assembly, but which also caters for more conventional forms of assembly, has been described.

Throughout this description reference has been made to example assembly features that would be selected from a 'Feature Library for Jigless Assembly'. This library would contain generic, pre-defined assembly features associated with specific attributes, as well as, the ability to add extra, user-defined assembly features.

The assembly features, particularly the Location Features, would then be selected using the feature selection process to obtain the most appropriate assembly features.

A Feature Library for Jigless Assembly and more conventional forms of assembly has been included as Appendix B, 'Assembly Feature Library'. The Feature Library contains examples of each of the four assembly feature types, i.e. Location, Support, Clamping and Fastening Features.

The list of examples is intended to be comprehensive but is by no means exhaustive. It does, however, display more types of unconventional assembly features than typical Features Libraries.

With specific reference to the Location Features, there has been no attempt to illustrate combinations of Location Feature Pairs as the list would have been extremely long. Nonetheless, the assembly feature selection process could be used to select the best Location Features Pairs amongst these examples.