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MEASUREMENT ASSISTED ASSEMBLY AND THE ROADMAP TO PART-TO-PART ASSEMBLY

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ABSTRACT

Cycle times and production costs remain high in aerospace assembly processes largely due to extensive reworking within the assembly jig. Other industries replaced these craft based processes with part-to-part assembly facilitated by interchangeable parts. Due to very demanding interface tolerances and large flexible components it has not been possible to achieve the required interchangeability tolerances for most aerospace structures. Measurement assisted assembly processes can however deliver many of the advantages of part-to-part assembly without requiring interchangeable parts. This paper reviews assembly concepts such as interface management, one-way assembly, interchangeability, part-to-part assembly, jigless assembly and determinate assembly. The relationship between these processes is then detailed and they are organized into a roadmap leading to part-to-part assembly.

KEYWORDS

Part-to-Part, Measurement Assisted Assembly, Interface management, Fettling, Shimming, One-Way Assembly, Determinate Assembly

1. INTRODUCTION

Traditionally the production of large aerospace assemblies has involved the inefficiency of craft production; craftsmen fettling or shimming parts to fit and carrying out a wide variety of highly skilled operations using general purpose tools. Reliance on monolithic jigs has also meant this approach has not resulted in flexibility since the jigs are highly inflexible, costly and have long lead times.

It could be said that the production of large aerospace assemblies combines the inefficiency of craft production with the inflexibility of the early forms of mass production. This is clearly an issue, but why is such an inefficient mode of production used? It is not due to a lack of competence, awareness of the issues or willingness to embrace new technologies; the aerospace industry benefits from access to many of the best minds in engineering and is well known for utilizing the latest technologies in many areas.

The root causes are the difficulties in maintaining very close tolerance requirements over large structures and the large number of different operations for relatively low production volumes. Issues related to maintaining high tolerances are the biggest challenges; the lightweight aero structure has flexible components; interfaces are often imprecise especially for composite components and it is very difficult to drill patterns of holes in different components which will match and lock the assembly into its correct overall form.

The traditional solution to these issues is to use a monolithic jig which holds flexible components to their correct final form as the assembly is built-up, interface gaps are then measured in the jig so that shims can be fitted and holes are drilled through the stack of components. It is then necessary to break the assembly apart to debur holes, clean and apply sealant before the final assembly takes place (Pickett et al. 1999 ; Muelaner and Maropoulos 2008). This process results in additional process steps, inflexibility due to reliance on monolithic jigs and inefficient craft based production due to high levels of reworking in-jig. Additionally, the variety of operations at low volumes combined with the high tolerances required makes it very difficult to automate processes. Further increasing the number of craft based processes required while maintaining close tolerances means that where automation is used, it is generally based on inflexible gantry systems.

There has in recent years been a great deal of interest in moving away from the inefficiencies of the traditional build process and concepts such as *Part-to-Part Assembly*, *One-Way Assembly*, *Predictive Shimming*, *Measurement Assisted Assembly* and *Determinate Assembly* are being discussed in the literature. The precise definition of these terms is not always clear and a key objective of this paper is therefore to provide clear definitions of some commonly used terms.

2. INTERFACE MANAGEMENT

Interface management involves processes which seek to ensure that any clashes and gaps between components are maintained within acceptable limits. It is therefore the key to ensuring the structural integrity of an assembly. Where interfaces cannot be managed through interchangeable components it often results in inefficient craft based in-assembly fitting processes.

The standard approach to interface management employed in high-volume manufacturing is to produce components to sufficiently tight tolerances to facilitate interchangeability while maintaining acceptable interface conditions. The alternative to interchangeability is to create bespoke interfaces by making adjustments to the form of components. Such adjustments may be additive (shimming) or subtractive (fettling). It should be noted that where bespoke interfaces are used to manage the interfaces it is still possible to have interchangeable parts within the assembly. For example a rib may be an interchangeable part but not be produced to interchangeability tolerances and shims then used to achieve interface management.

Bespoke interfaces, whether created by fettling or by shimming, may be produced using traditional in-assembly reworking processes or using measurement assisted *predictive* processes.

In the traditional approach components are pre-assembled, assembly tooling is often used at this stage to control the form of the assembly. Any gaps and clashes are measured in this pre-assembly condition, the assembly is broken apart, components are fettled or shims are produced and the structure is reassembled.

In *measurement assisted assembly* (MAA), or the *predictive* approach, components are measured pre-assembly and this measurement data is used to determine cutting paths for *predictive fettling* or the manufacture of *predictive shim*. The components and possibly also the shims can then be assembled as though they were interchangeable.

The various options for interface management are illustrated in the form of a Venn diagram in Figure 1.

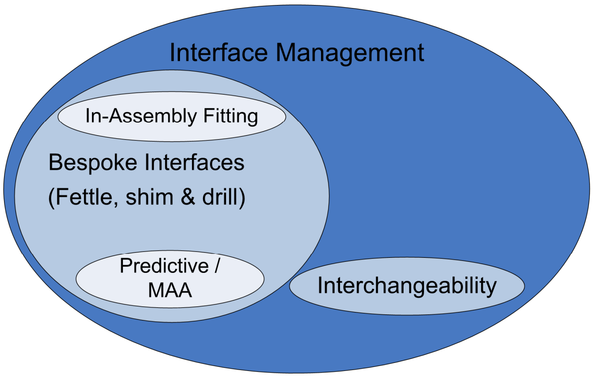

Figure 1 – Venn Diagram for Interface Management

The interface between components typically involves direct contact between the surfaces of components and also hole-to-hole interfaces into which fasteners are inserted to join components together. The above classification of interface management may be applied to hole-to-hole interfaces as well as to the interfaces between surfaces of components.

For example, in the case of an interchangeable assembly all holes are pre-drilled in components. In the traditional in-assembly fitting approach to producing bespoke interfaces first any fettling or shimming is completed and then holes are drilled through the stack of components. The pre-assembly generally then needs to be broken, deburred and cleared of swarf before sealant can be applied and the final assembly carried out.

Bespoke hole placements can also be produced using a predictive approach in which holes are first placed in one component prior to any assembly and to a tolerance insufficient for interchangeability. The hole positions can then be measured and holes in the second component placed. In the case of the second component holes must be located to interchangeability tolerances (Muelaner and

Maropoulos 2010). It may initially seem that this approach offers no advantage over full interchangeability since holes must be placed in the second component to interchangeability tolerances. The advantage is gained however when a large component is joined to one or more smaller components. It is then possible to place holes in the large component which requiring a high level of accuracy. The accurate holes are placed in the small components which is a relatively easy task.

2.1. INTERCHANGEABILITY (ICY)

Interchangeability (ICY) is the ability of components to fit to one another without requiring any reworking (interface management). An interchangeable part can therefore be taken from one assembly and placed into another assembly without changing the form of the part.

Low cost, high volume manufacturing typically depends on interchangeability but it is generally not possible to achieve the required tolerances for the majority of aircraft structure interfaces.

2.2. SHIMMING

Shimming involves adding additional ‘spacers’ or ‘packers’ normally referred to as shims to an assembly in order to fill gaps between components. As explained above, traditionally this involves measuring actual gaps in a pre-assembled structure using feeler gauges, producing shims and re-assembling with the shims in place. This traditional in-assembly fitting process may require a number of iterations before all gaps are within tolerance.

In the case of predictive shimming (Kayani and Gray 2009) components are measured before being assembled. In this state the interface surfaces are fully visible meaning that rather than simply determining gaps using feeler gauges, the full surface profile can be characterized using 3D scanning technology. It is then possible to produce shims which more fully conform to the surface profile of components.

The major advantage of this approach is that pre-assembly is not required and therefore one-way assembly is facilitated.

2.3. FETTLING

Traditionally fettling is carried out in-jig in a similar way to traditional shimming operations. It is however also possible to carry out predictive fettling in which components are measured and bespoke interfaces created before assembly.

Predictive fettling was used to maintain the interface between the wing box ribs and the upper cover on the Advanced Low Cost Aircraft Structures (ALCAS) lateral wing box demonstrator. In this process measurements of the cover profile were used to generate machining paths for the fettling of rib feet. The rib feet were then machined using a standard 6-axis industrial robot mounted on a gantry over the wing box. The accuracy of the robot was greatly increased through the application of closed loop control with feedback provided by a photogrammetry system.

In a traditional manual machining process high accuracy is achieved by initially cutting features oversized, measuring them and then using these measurements to guide the further removal of material in an iterative process. A similar but fully automated process was used in which the robot initially made roughing cuts of the rib feet, measurements were made and these were used to apply corrections to the finishing cut. The complete process is illustrated in Figure 2 (Muelaner et al. 2011).

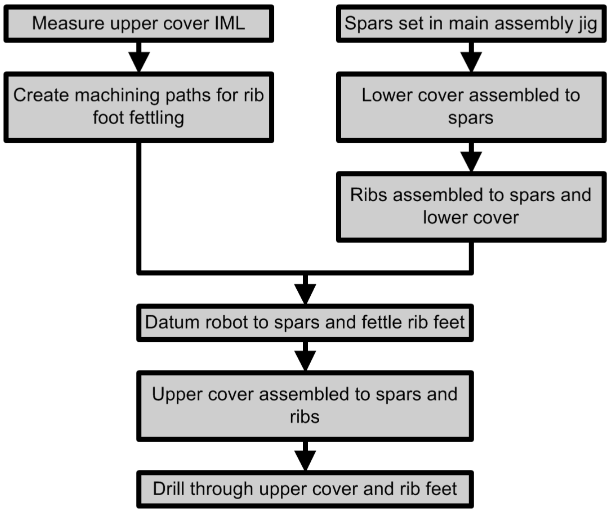

Figure 2 – ALCAS Rib Foot Fettling Process

The registration of point cloud data from multiple instrument locations (Mitra et al. 2004) may be important in enabling this type of predictive process.

2.4. DRILLING

Where interchangeability tolerances cannot be achieved it is necessary to place holes at bespoke positions in such a way that patterns of holes closely match so as to allow close fitting fasteners to pass through both components. The traditional way to achieve this is to drill through both components in the pre-assembly state.

There are a number of disadvantages to this approach, aerospace assemblies often contain thousands of holes and the drilling of these holes represents a significant percentage of the cost of building an airframe (Bullen 1997). By carrying out these operations within the capital intensive bottle neck to production - which is the main assembly jig

- the cost of drilling these holes is greatly increased. Furthermore, when a stack of components is drilled through it is often necessary to break the assembly to clean and debur before re-assembling, adding costly additional operations.

Orbital drilling (Kihlman 2005) may remove the need to break, clean and debur, and therefore facilitate a one-way assembly process. It will not however remove the need to drill through components or facilitate part-to-part assembly and therefore although some process steps are removed, drilling must still be carried out within the bottle neck of the jig.

Measurement assisted determinate assembly (MADA) has been proposed as a potential predictive approach to hole placement. In this approach holes are first placed in large components to relatively slack tolerances. The hole positions are then measured and bespoke holes are accurately placed to match in the smaller components, this is illustrated in Figure 3 (Muelaner and Maropoulos 2010).

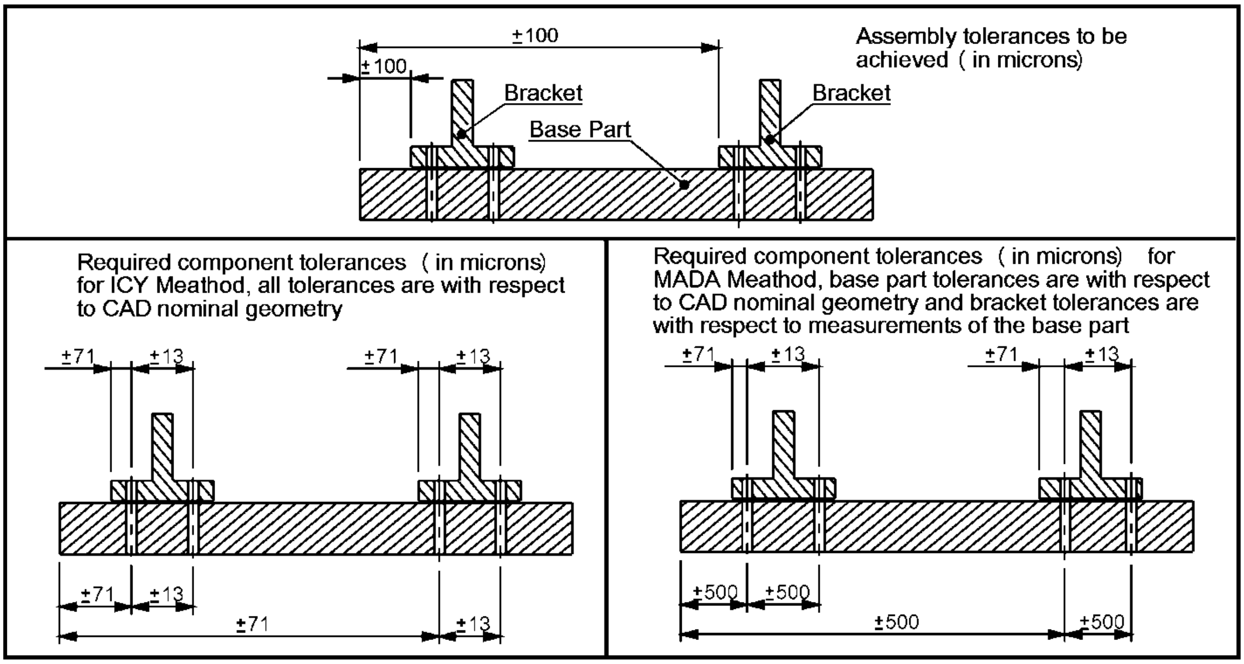

Figure 3 – MADA Predictive Hole Placement

3. PART-TO-PART ASSEMBLY

Part-to-part assembly is an assembly process where any interface management is conducted pre-assembly allowing a rapid one-way assembly process. Part-to-part assembly may therefore be seen as the key requirement for an efficient build process.

A full part-to-part assembly process would involve either interchangeable components or predictive fettling, shimming and hole placement being carried out prior to assembly. Currently part-to-part assembly is commonly achieved through interchangeability but achieving this using predictive processes is relatively unknown.

Figure 4 shows the Venn diagram used in section 2 with the interface management techniques which are compatible with part-to-part assembly clearly identified. It shows that both interchangeability and the use of predictive processes to produce bespoke interfaces are compatible with part-to-part assembly, while the use of in-assembly fitting processes to produce bespoke interfaces is not compatible with one-way assembly.

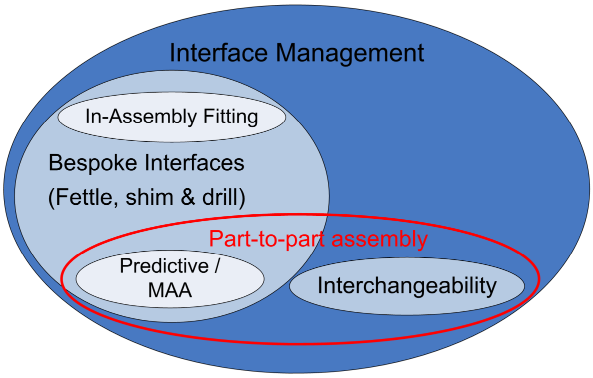

Figure 4 – Venn Diagram Showing Compatibility of Interface Management Techniques with Part-to-part assembly

4. ONE-WAY ASSEMBLY

One-way assembly is a process in which once parts are assembled they are not removed from the assembly; there is no requirement to pre-assemble, break and reassemble. **One way assembly is a precondition for part-to-part assembly**.

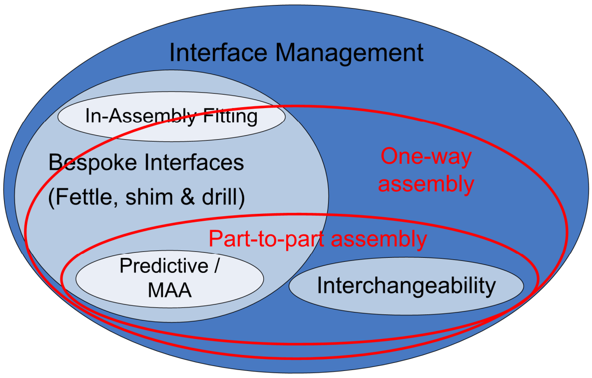

Figure 5 – Venn Diagram Showing One-Way Assembly in Relation to Part-to-Part Assembly and Interface Management

In order to achieve one-way assembly the following conditions must be met:-

- Preassembly to measure gaps before carrying out interface management must not be required and therefore any bespoke interfaces which may be required for interface management must involve a predictive measurement assisted process where component measurements are used to predict gaps.
- Any hole drilling operations must not require de-burring between components or the breaking apart of assemblies to remove swarf.
- There must be sufficient confidence that an assembly will be right first time that sealant can be applied the first time components are assembled.

The major difference between one-way assembly and part-to-part assembly is therefore that in a one-way assembly some drilling through of components in the assembly is permitted provided this does not require that the assembly is broken for cleaning and deburring.

5. MEASUREMENT ASSISTED ASSEMBLY

The term *measurement assisted assembly* (Kayani and Jamshidi 2007) is used to refer to any process where measurements are used to guide assembly operations. This includes but is not exclusive to *predictive* interface management processes in which measurements of remote parts' interfaces are used to fettle or shim another component either before or during assembly. It also includes the tracking into position of components using measurement and processes where automation operates under closed loop control with feedback from an external metrology system.

5.1. ASSEMBLE-MEASURE-MOVE

An *assemble-measure-move* (AMM) process is one in which a component is approximately positioned within an assembly, its position is then measured and it is moved into the correct position. This is generally an iterative process in which continuous feedback is used to track a component into position.

Generally this is not compatible with a fully part-to-part assembly process since once a component is located using an assemble-measure-move process it will then be necessary to drill through to fasten it in position. It is of course possible to envisage a process in which a component is fastened into position using an adjustable clamping arrangement but in practice for aerospace structures this is unlikely.

This technique is of interest because although it does not fully work within the goal of a part-to-part assembly process it does allow the accurate placement of components without requiring accurate assembly tooling. It is therefore a useful technique for certain difficult components within an assembly in order to reduce tooling complexity or as a get-out in a primarily determinate assembly. These techniques are used within final aircraft assembly at which stage the structure is largely interchangeable and determinate (explained below).

6. ASSEMBLY TOOLING

Assembly tooling is used to hold components and in the case of jigs to guide assembly machinery, during the assembly process. In the case of jigs and fixtures it incorporates highly accurate component locators allowing the tooling to determine the form of the emerging assembly. In the case of work holding it is the components themselves which determine the form of the assembly (*determinate assembly*) and therefore the tooling does not require any accurate locators. The various forms of assembly tooling and associated assembly methods are summarized in Figure 6 and described in detail below.

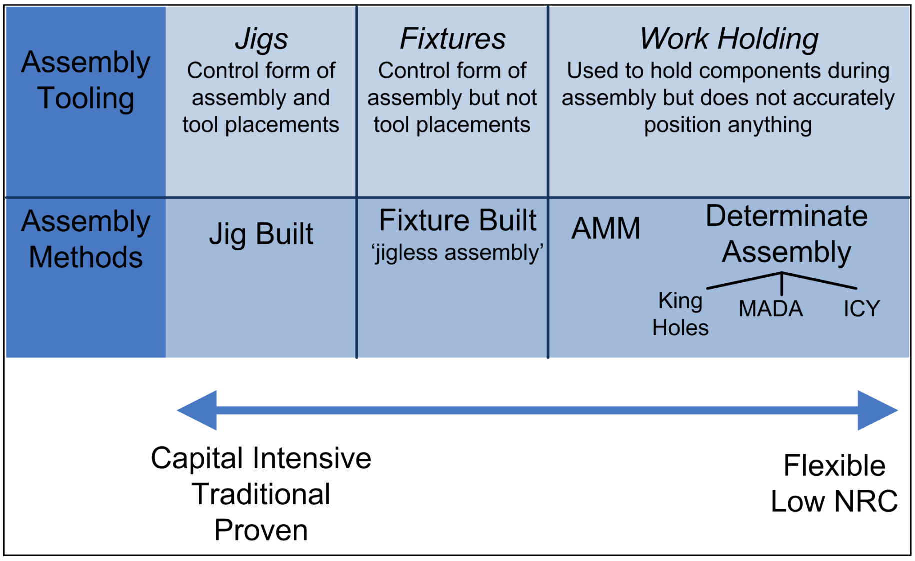

Figure 6 – Assembly Tooling and Associated Assembly Methods

6.1. JIGS AND JIG BUILT STRUCTURES

Traditionally aerospace structures are jig built; both overall form of the assembly and the position of assembly features such as holes are determined by the jig which controls component location and the positioning of assembly machinery. A jig is therefore a form of assembly tooling which comprises accurate locators for both components and assembly machinery.

It follows from these definitions that a *jigless assembly* is a process which does not meet all of these conditions. A process where fixtures are used to locate components therefore controlling the form of the assembly may be regarded as *jigless* provided the tooling does not also control machinery positioning.

6.2. FIXTURES AND JIGLESS ASSEMBLY

Jigless assembly within an assembly fixture follows essentially the same process as for a jig built structure. Components are still assembled within the tooling which controls the form of the assembly and in-assembly fitting processes are carried out.

The key difference is that an assembly fixture is generally very much simpler than an assembly jig since it is only required to locate components and not also locate machinery for fettling and drilling. These functions are instead generally carried out by automation such as dedicated drilling robots equipped with vision systems (Hogan et al. 2003 ; Calawa et al. 2004 ; Hempstead et al. 2006) or standard flexible robots with external metrology control (Summers 2005 ; Muelaner, Kayani et al. 2011).

Therefore in jigless assembly although a large number of operations continue to be carried out at late stages of the assembly process, these operations are completed more efficiently and the simpler tooling means that less capital is being tied up in these operations.

6.3. ASSEMBLE-MEASURE-MOVE USING WORK HOLDING TOOLING

As discussed above the assemble-measure-move technique is probably not suitable for the complete assembly of an airframe but is a useful technique for certain components. It is essentially a form of fixture built assembly in which the fixture is a robot operating under closed loop control from a large volume metrology instrument.

6.4. DETERMINATE ASSEMBLY (DA) USING WORK HOLDING TOOLING

A determinate assembly is one in which the final form of the assembly is determined by the form of its component parts. The location of components' interface features such as contacting faces and holes will therefore strongly influence the final form of the assembly. It is often assumed that a determinate assembly must be made up of interchangeable parts but this is not necessarily the case since determinate assembly can be achieved using, for example, measurement assisted determinate assembly, see below.

6.4.1. DETERMINATE ASSEMBLY WITH KING HOLES

King holes are holes which are placed specifically to facilitate determinate assembly. In this approach all of the holes which will finally be used to fasten components are not placed during component manufacture but just a few holes placed in the components to facilitate a determinate assembly. Once the components have been joined together using the king holes the actual structural holes are drilled through the component stack in the conventional way. If required then the assembly can be broken apart, cleaned, deburred and reassembled. The king holes can also be drilled under size so that once the other structural holes have been drilled and temporary fasteners fitted to them the king hole fasteners can be removed and full size holes drilled though to replace the king holes.

Determinate assembly using king holes is therefore an intermediate step towards the adoption of a fully part-to-part determinate assembly.

6.3.2. Measurement Assisted Determinate Assembly (MADA)

Measurement assisted determinate assembly is a process in which measurement assisted predictive processes are used to create bespoke interfaces. In general large components are measured and smaller bridging components are machined to interface with the less well dimensionally controlled larger components.

This allows all interface management to be carried out at the component manufacturing stage and for a fully part-to-part assembly process to then take place.

6.3.3. Determinate Assembly with Interchangeable Parts

Where sufficient tolerances can be achieved for fully interchangeable parts then this will lead to the minimum number of process steps and a fully part-to-part and determinate assembly. This is the ultimate goal for any assembly process.

6.4. COMPATIBILITY WITH PART-TO-PART

Any form of assembly tooling and associated method, from a traditional jig built approach to a fully determinate assembly, can be made to be compatible with one-way assembly if predictive fettling or shimming is combined with drilling techniques which do not require deburring or cleaning.

The only assembly methods which are fully compatible with part-to-part assembly are MADA and determinate assembly with interchangeable parts.

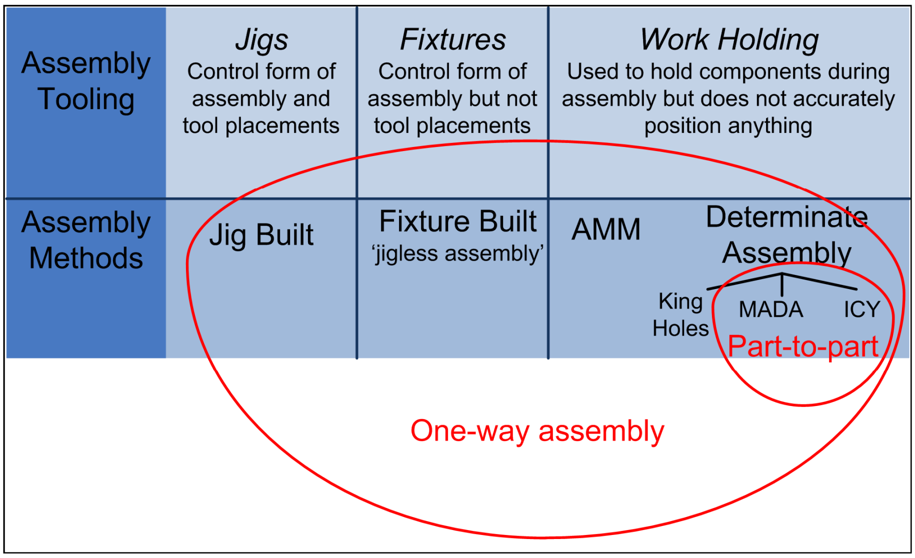

Figure 7 – Compatibility of Assembly Tooling and Associated Assembly Methods with One-Way and Part-to-Part Assembly

6.4. RECONFIGURABLE TOOLING

Reconfigurable tooling involves constructing assembly tooling from standard components which can be readily adjusted or rebuilt to accommodate design changes or new products (Kihlman 2002). This can be thought of as being similar to scaffolding. It solves the problems of inflexibility inherent in reliance on jig built and fixture built assembly processes. It does not however alleviate issues associated with interface management operations and in particular drilling being carried out at a late stage in assembly.

7. THE ROADMAP TO PART-TO-PART ASSEMBLY

Part-to-part assembly involves carrying the maximum possible number of operations during component manufacturing. This means that time is not spent working on components within the final assembly where a high level of capital expenditure is then tied up in these operations and a bottle neck to production exists.

It is the interfaces between component surfaces and mating holes which ultimately determine the form of any assembly, whether it has been built within an assembly jig or as a determinate assembly. Part-to-part assembly implies that all holes and interfacing surfaces have been processed to their final form before assembly takes place. It therefore follows that there is no point in using an assembly jig or fixture for a part-to-part assembly since it would have no influence on the form of the assembly once it was released from the jig. It is therefore possible to state that achieving true part-to-part assembly will require a determinate assembly.

There are two approaches identified as facilitating a fully part-to-part assembly process; MADA and determinate assembly using interchangeable parts. Since the king hole approach to determinate assembly involves the through drilling of holes during assembly it is not fully compatible with part-to-part, it could however act as an important intermediate step towards part-to-part assembly using MADA. Similarly predictive shimming and fettling processes may be initially developed within a jigless assembly process and act as intermediate steps towards part-to-part assembly using MADA.

The ultimate approach to part-to-part assembly through the determinate assembly of interchangeable parts will ultimately be facilitated through design for manufacture which allows reduced component tolerances and machine tool development which allows tighter tolerances to be produced.

Although processes and technologies such as reconfigurable tooling, assemble-measure-move and orbital drilling may bring important benefits in the short term they are not seen as directly contributing to the development of part-to-part assembly.

The way in which the various processes and technologies discussed do or do not contribute to the development of part-to-part assembly is illustrated in Figure 8

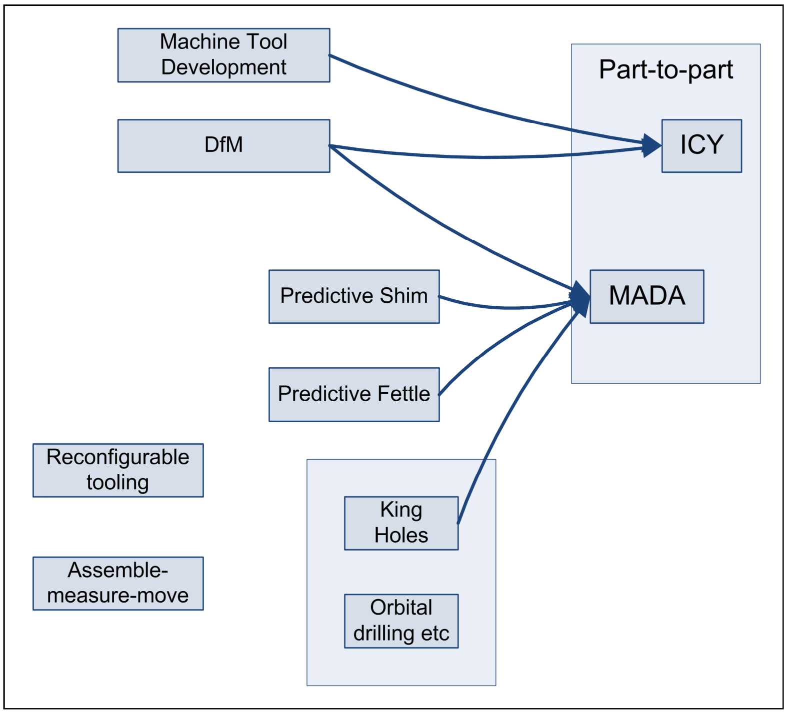

Figure 8 – The Roadmap to Part-to-Part Assembly

CONCLUSIONS

Concepts such as interface management, one-way assembly, interchangeability, part-to-part assembly, jigless assembly and determinate assembly have been explained. The relationship between these processes was detailed and it was shown that predictive shimming, predictive fettling, design for manufacture and the use of king holes will be of particular importance in enabling part-to-part assembly. These methods will have relevance to other industries beyond the aerospace applications discussed where bespoke interfaces are also required. Examples of such applications include steel fabrication, boat building and the construction of power generation machinery.

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