Methodology for High Accuracy Installation of Sustainable Jigs and Fixtures

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Abstract
The ability to accurately measure the components of jigs and fixtures during their installation determines the state of their precision, especially for large size products and applications. This matter is crucial in mass customisation where small batches of products and components with high variety in design are manufactured. Product quality should be in harmony with rapid changeover philosophy as compromising quality for speed is not forgivable for sensitive components and assemblies such as those seen in the aerospace industry. It is necessary for the installation of the jigs and fixtures to be highly accurate in order to minimise the use of tolerance budget due to variations in jigs and fixture positioning. Major overhead costs for jigs and fixtures particularly in the aerospace industry led to the development of the concept of flexible and reconfigurable jigs and fixtures. Reusability of reconfigurable jigs and fixtures makes them attractive for sustainable solutions as their components can be reused for several variant of a product or assembly. The main drawbacks of this type of jigs and fixtures have been their poor accuracy and reliability. In this paper accurate positioning of the key components of sustainable jigs and fixtures is investigated. The factors affecting the performance of the jigs and fixtures are reviewed from the installation stage. The paper introduces a methodology for minimising uncertainties in positioning of the holds and clamps for flexible jigs and fixtures.

Keywords:
Sustainable Jig, Jig installation, Calibration Uncertainty, Jig Monitoring, Metrology, Reusable Jig

1 INTRODUCTION

Factors such as quality and reliability have long converted to implicit characteristics of the new products. Recent market trends have forced manufacturing industries to move towards mass customisation in their products and service range. Increased variation in the design of new products is followed by a second wave of variation with higher amplitude at subassemblies and component level.

State of the art manufacturing systems and technologies have provided more flexibility, enabling designers to think more freely. For instance new large volume measurement systems, developed in the past few years, are capable of measuring several decametre distances. Such technologies facilitate the verification of large size components that used to be manufactured from several assembled components.

The manufacturing of large size products requires specialist jigs and fixtures in order for their components to be held in the desired orientation during build and assembly. This requires major overhead cost that can only be justified by mass production in some cases or otherwise the cost of finished products can be very high. This issue contradicts with the market trends where customers are constantly looking for higher value for their money. In a typical product the variation in the product creates a more sustainable business as it can fulfil the needs of a relatively larger market.

Flexible and reconfigurable jigs and fixture that can be formed in different shapes to support different variation of products is a key solution for the above challenges. The concept of flexible jig existed for several years in the research domain [1]. However, they are not fully utilised to a great extent in real production facilities especially for large size product manufacturers, such as aerospace. This is due to the challenges related to their initial installation, poor calibration, and repeatability that often exceed the tolerance requirement. The manufacturing of these jigs and fixtures from high quality key components as well as their integration with large volume metrology systems can reduce the above limitations.

This paper covers metrology issues related to the installation and calibration of flexible jigs and fixtures as well as their monitoring during service.

2 RELATED WORK

2.1 Manufacturing and assembly of large scale parts

Typically prior to precision manufacturing of mechanical parts it is essential to move the raw material to the machine bench, proceed with rough cutting then fine alignment and clamping. At this stage the part is ready for machining of its high precision key features. However, this is not always possible for large size and/or heavy components. Large scale products refer to those with components that are not economically possible to handle or move around in the factory for fabrication and assembly purposes [2]. The manufacturing and assembly processes of these parts encompass movement of the machines and systems to the desired location and orientation with respect to these parts. Such parts are normally held in their positions using large size jigs and fixtures. If these parts are produced in small batch sizes that is the case for aerospace industries, high overhead cost per product will occur. There have been many attempts to design and manufacture jigs and fixtures so that they can hold a number of variants of components [3, 4]. However, this approach is not feasible for parts with sensitive or key features due to their high accuracy requirements.

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Adjustable, reconfigurable jigs and fixtures produce lower repeatability over time compared to fixed ones. Fixed jigs have permanent topology achieved through their permanent joints that are welded or riveted. Mechanical failure of these jigs and fixtures for example due to fatigue and plastic deformation is a main cause of terminating their service and sending them for recycling. With small batch manufacturing requirements it is now common to retire a conforming jig as their service life depends on the life of products. In other words soon after the cease of manufacturing a part's variant, the associated jigs and fixtures become redundant. Even if the jigs are still in working order, they have to be scrapped and sent for recycling. This method brings the burden of high energy consumption for recycling. Even for the fixed jigs and fixtures the drift in the large size parts and jig can affect the accuracy of a large size assembly [5]. Several methods for analysing jig rigidity have been developed [6] to evaluate the impact of vibration on large size jigs. In any case a more sustainable manufacturing can only be achieved by alternative solutions.

Figure 1: Typical components of large scale jig (image courtesy of Electroimpact http://www.electroimpact.com/G150TFIX/gallery.asp)

Extensive lead time to manufacture is another major drawback for fixed jigs and fixtures. These jigs should be ordered well in advance of any manufacturing processes. This can create additional complexity in production planning and product time to market.

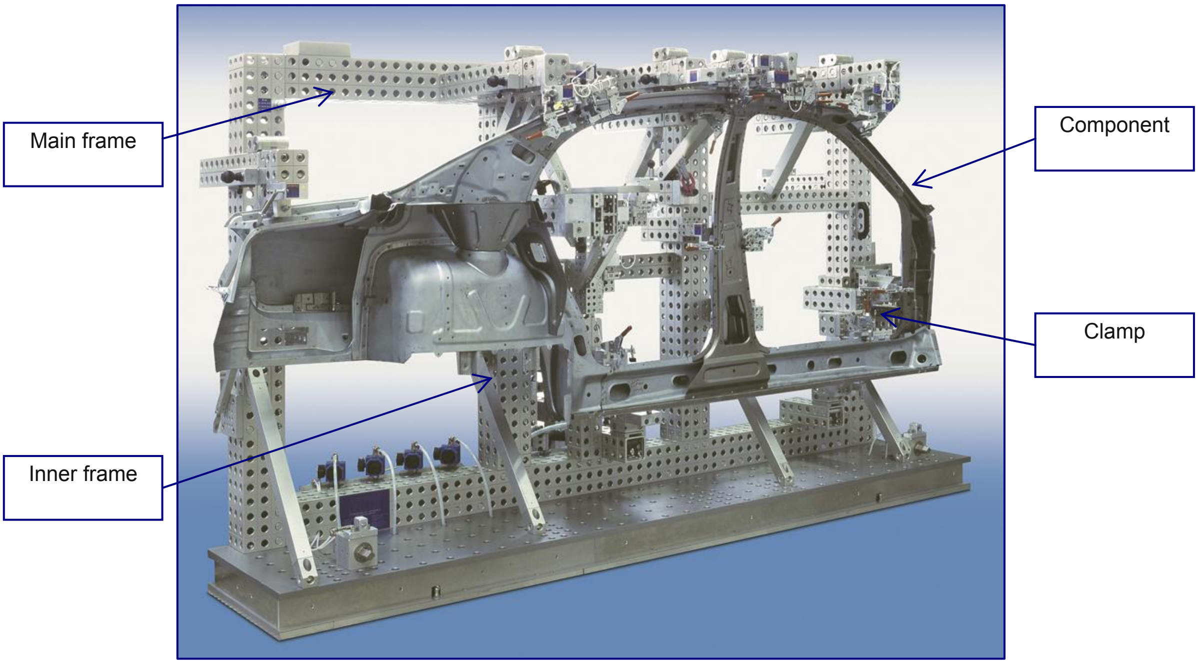
Regardless of their type, large scale jigs have a number of common elements including one main frame, one or a number of inner frames, potentially one or a number of moving mechanisms, and smaller components such as clamps, bushings, pickups and adjustable screws (Figure 1).

2.2 Flexible jigs and fixtures

The concept of flexible jigs and fixtures is developed for increased sustainability, rapid changeover as well as low cost. It is now possible to use off the shelf modules and clamps for jigs and fixtures design and assembly. Depending on the requirement only a handful of specialised components for the jigs and fixtures might be needed to be custom designed and manufactured. In this concept the majority of bulk components, joints at the attachments are used in for a specific application. Once the product design variant is fully manufactured it is then possible to disassemble the above components and reassemble them in a new topology to suite the next design variant. This cycle can be repeated over a large number of times resulting in reduced overhead cost for jigs and fixtures. Needless to mention the other factors such as disassembly time, resetting time, operators' time should be considered for evaluating the real cost benefit of using this type of jigs and fixtures. This approach best reduces the cost of jigs and fixtures for the assembly and component ranges that are fairly close in design.

Depending on the level of variations in the components and the type of work required on each a different percentage of the flexible jigs need to be rearranged. This matter is crucial to be considered at design stage in order to increase the benefit of using this type of jigs and fixtures. For example, when possible, the location and 3D positioning of pickups and clamps on different variants of the component or even totally different parts should be in close proximity to increase compatibility and inter-changeability of sub-systems of jigs and fixtures. Having a collection of the key components of the jigs can guarantee the availability of the desired jigs in a short time. In addition to this the storage of the jigs required less space as it is possible to dismantle all the modules that are typically in the form of scaffolding and place them next to each other. Flexible jigs are currently utilised in some of the automotive companies (Figure 2) as their accuracy level is sufficient for this sector. Despite the above benefits there are not many flexible jigs in operation in large size manufacturing facilities such as aerospace factories. Accuracy and uncertainty of positioning pins, repeatability of the clamps and drift of the jig structure are all contributing to the fact that these jigs cannot meet the tolerance requirements of the power generation and aerospace industries. These jigs have high potentials for utilisation in the above industries once their accuracy problems are resolved.

Figure 2: Fixture with reconfigurable components for automotive industry (image courtesy of Witte http://www.horst-witte.de/en/)



There has been a number of new developments in large volume metrology systems and technologies. Modern laser based metrology systems and technologies are now capable of measuring large size products up to several decametres with acceptable accuracy. These systems can be used to accurately position mountings of the key components of the jig during its installation and initial setup.

The installation of jigs and fixtures typically starts form its base or main frame then large components and gradually to the smaller components such as pickups and clamps. Metrology systems can be used for the installation of flexible jig main frame and its inner frames to guarantee the correct positioning of each and every component. Table 1 shows a few of these large scale measurement systems. For technological review of these systems see [7]. Laser tracker systems capable of measuring reference points, are among the most suitable measurement systems for this purpose. The instrument tracks a Spherically Mounted Retroreflector (SMR) target the position of which can be registered in three dimensional space. SMR can be contacted directly with the target object to provide geometrical positional information or can be used within a mechanically repeatable SMR nest known as Laser tracker target or in short target from this point on. Laser trackers like any other measurement instrument have a level of uncertainty that need to be accounted for during the jig installation process. Also the line of sight issues between the laser tracker and its target point should be considered and if necessary multiple tracker positions should be used. In real measurement activity the result must be accompanied with a statement of uncertainty. Such statement characterises the dispersion of the values that are reasonably attributed to the measurand [8]. This issue is the same for the installation and later verification of any jig or fixture. This knowledge clarifies the jig capability of a given positioning and assembly task. In other word it indicates if a jig can meet the tolerance requirements for its related processes.

2.3 Comparison of jig philosophies

There are a large number of different shape and design jigs and fixtures in different companies for various manufacturing and assembly applications. Some of these jigs and fixtures are readily available in standard forms, while some are designed and manufactured specific to particular parts and tasks. The latter can be very expensive based on the complexity and scale of the products [9].

Regardless of cost and purpose a manufacturing or assembly process can be performed using with no jig, with fixed frame jigs, or with reconfigurable or flexible jigs. Table 2 provides a comparison of these methods with their typical applications.

Fixed frame jigs are typically for heavy duty applications. They are more suitable for applications with a large number of products that can relax the overhead cost of the jig.

There are several advantages in the application of flexible jigs and fixtures for the manufacturing and assembly of large and complex products. In particular for research and development work, as well as for cases where low volume products are manufactured flexible jig and fixture can be very beneficial. In addition to time and money saving benefits the possibility of having a flexible jig gives more freedom to the design, manufacturing and assembly processes due to the low direct and recurrent cost of changing the overall topology of the jig. Reconfigurability and reusability of flexible jig is a main advantage for this type of jig compared to conventional jigs. This is particularly important as it is in line with the industry direction in terms of green manufacturing by recycling components from a used system, reducing project costs with regards to expenses for tooling of associated items.

Table 1: Examples of large volume/portable measurement instruments for jig verification

Instrument	Auxiliary components	Measurement type		Image
		Contact	Non-contact	
Laser Tracker	SMR probe	✓		
	T-probe	✓		
Laser Radar	Spherical targets		✓	
Photogrammetry	Targets	✓		
	Light projection		✓	
Articulated Arm CMM	Laser based scanning head		✓	
	Contact probe	✓		

3 FLEXIBLE JIG INSTALLATION

The issues and concerns that need to be considered in the jig installation procedure are described in this section. The installation of the jig components in the right position can be a challenging especially when the positioning tolerances are tights. Flexible jigs should also be monitored in order to exploit and compare their rigidity with that of the conventional ones.

Stage by stage measurement instruction for the jig installation based on the results of an initial jig setup in the simulation software environment and practical experiment of a large size jig with dimensions of *5m x 4m x3m* is given in a generic description. This is regardless of whether the jig is in first time installation or it is a change of an existing jig topology into a new shape, for holding a different component.

Depending on the complexity a typical large size jig has between three to five levels of frames. Apart from the base level with normally one main frame, at each level there can be one or several frames. These frames are interrelated with reference to the jig datum in order to facilitate the positioning and functionality required. In an automated, fixed platform, robotic systems carry out several tasks such as part positioning, machining and assembly. The robot working datum therefore is linked with the working frame of the jig. Careful consideration of jig datuming strategy and its subsequent installation can secure achieving the desired tolerance.

3.1 Measurement assisted flexible jig installation

There are several stages for the installation of flexible jigs that can be carried out in first simulation and then real world. The use of simulation exercise can reduce the number of potential errors and rework during this process. The process of measurement assisted installation is similar to tracking objects to position that is common for large size assemblies. In this approach the components of the jig are roughly positioned, within 1mm tolerance from the target position, at first. Then when all of the jig components are attached into their designated positions, within 0.1mm to 0.15mm tolerance, they are tightened using the appropriate torque. The typical stages of metrology assisted flexible jig installation are given below:

1. setting initial reference frames in the factory
2. measurement of initial reference frame
3. installation of base or main frame in its position
4. installation of inner frames offline
5. installation of holding and positioning brackets
6. installation of clamps, bushings and pickups in their rough position on inner frames and main frame
7. installation of inner frame on the base frame
8. fine adjustment and fastening of key locating components
9. verification of reference frames and clamps
10. in service monitoring of key positions on the jig

These stages are related to the complete installation of the jig from the scratch. Needless to mention that in case of slight change in design variation some of the following operations will be omitted.

Table 2: A brief comparison between different jig philosophies

	Typical characteristic	**Fixed frame**	**Flexible jig**	**Jig-less**
	Application	*Large volume production*	*Low volume production*	*Prototyping*
Pros	Uniqueness	Repeatable	Reconfigurable	Cost effectiveness
	Durability	Very high	High	Low
	Rigidity	Very high	Uncertainty rigidity	Low
Cons	Weight	Heavy	Medium	Low
	Portability	Non-portable	Difficult component positioning in each setup	Difficult to program
	Cost	Very high	Medium	Low
	Manufacturing time	Long	Medium	Short

3.2 Algorithm for flexible jig installation

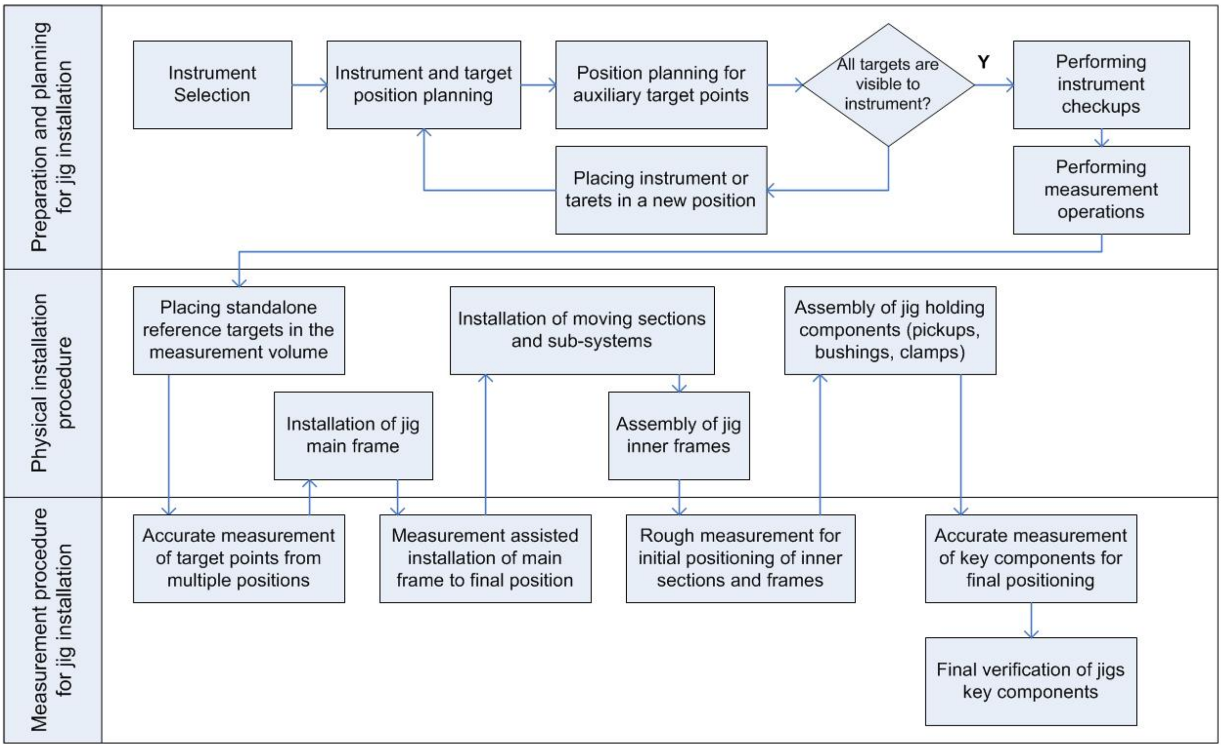
The installation processes for flexible jigs take the following main stages:

1. the installation of main frame of the jig
2. the assembly of moving units and sub-systems
3. the installation of the jig inner frames on the jig assembly
4. the assembly of pickups and clamps on the jig.

The main frame is the backbone of the jig that is typically fixed for a large number of jig topology and design variations.

Therefore it does not change in shape as regularly as the inner frame or the smaller elements of the jig such as bushings, pickups and clamps. Careful consideration of the manufacturing process can reduce the necessity of rearranging larger elements of the jig components resulting in further time and money saving. Figure 3 in three separate groups of activities shows the processes of flexible jig installation. In this process it is assumed that the standard parts of the jig are selected from the available, off the shelf sections and components. Then in advance of the physical installation a number of tests and trials are carried out to plan the jig installation in such a way that the uncertainty of measurement is reduced. Once the acceptable level of uncertainty is achieved the physical installation can take place.

Figure 3: Measurement assisted installation procedure for flexible jig



In jig installation process it might be required to use multiple measurement system or a measurement system from several locations to cover the complete set of key points for jig installation. This should include the auxiliary target reference points that are placed on the factory floor and wall for stability and drift check during the jig service.

During the localisation of the key points on the jig the uncertainty of the measurement instrument should be taken into account. As a rule of thumb the accuracy of the jig positioning for each key location should be in an order 10 times better than the required tolerance. In other word if the tolerance on the component is specified as 0.1mm the accuracy of the jig positioning should be at least 0.01mm. The best practice approaches for the flexible jig installation are given below:

1. A planned position for the initial reference points on the factory wall and floor is preferred in order to minimise uncertainty of the measurement.
2. The instrument position should be verified on regular bases using the initial reference points.
3. On each large section of the jig several SMR nests can be attached for better tracking and repeatability.
4. Where the large components of the jig have bend or twist the level measurement should be focussed on the central section of the beams to reduce angular positioning error.
5. The reference points on the inner frames should be selected as distant as possible for creating frame coordinate systems. This can result in smaller uncertainty when in the inner frame coordinate system.

4 UNCERTAINTY

Uncertainty if defined by GUM [8] as the result of the evaluation aimed at characterising the range within which the true value of a measured object is estimated to lie, generally with a given confidence. The Uncertainty here is reviewed from two aspects, the first is related to the measurement process and the second is related to the uncertainty of jig positioning. Measurement uncertainty has a number of contributing factors such as variation in environmental conditions such as dust, gravity temperature, air pressure and humidity, systematic errors within the measurement instrument and its related software, operators' skill, wear of contact probes or SMR. Based on GUM [8] definition a measurement result should be accompanied by its statement of uncertainty. Detailed discussion of these sources of errors is out of the scope of this paper. There have been a number of studies to establish the true uncertainty of some of the measurement instruments [10, 11].

The measurement results of key points on jigs and fixtures should therefore include the related confidence level. In addition to the initial uncertainty rising from the measurement instrument, the jigs and fixtures have other contributing sources of uncertainty. Forces applied to the jig frame due to weight of the product and also by manufacturing processes can potentially create elastic deformation in the jig frame. This matter becomes more complex for jigs that have integrated and automated moving sections.

Careful consideration of the sources of uncertainty at the jig design stage can reduce the risk of overusing the tolerance budget in a given scenario. There is a direct relation between the level of accuracy and cost of jigs and fixtures. However, the overall cost of manufacturing should be considered. The parts that have high number of first pass have longer life. In other words the parts that have quality characteristics closer to their mean values seldom fail during their use. The move towards six sigma [] approach is imperative in the installation and then monitoring of reconfigurable and flexible jigs and fixtures for high precision and sensitive parts.

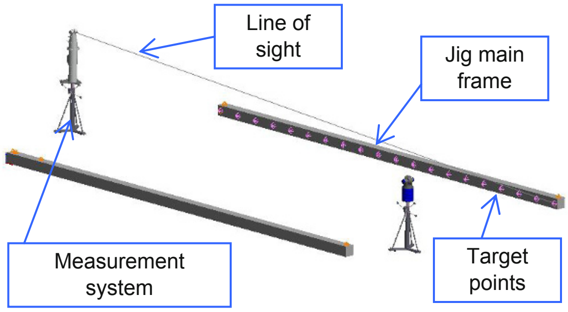
5 DISCUSSION

Flexible jigs are suitable for assembly and minor machining of a number of parts with different design and geometry. In particular when the design variations between these parts are small this type of jigs proves to be a cost-effective and fast solution. This is because it is possible to adopt the jig to a new product or component variant with minor reconfiguration of the jig. However, when the design of the desired part and assembly is totally different or with different dimensions a complete rearrangement of the jig components may be required. Therefore in designing a new topology for the jig the closeness of the design variant of the parts and sub-assemblies should be considered in order to minimise the time and cost of jig installation and reconfiguration by maximising the reuse of the existing components in the current configuration.

There are a number of ways in which a flexible jig can be assembled simply due to its flexibility. The selection of the right components in the right installation order can maximise time and cost savings. In this selection procedure the potential reuse of the jig for future products should be taken into account. In the case of constant product variation it is important to plan and design jig topology in a collective approach where the mine frame of the jig that is more time consuming and costly can be reused without disassembling for instance. The use of bespoke clamps, fasteners, bushings and other elements of the jig are key issues to the cost reduction.

Extensive use of simulation software and tools can reduce costs associated to rework and waste of jig material. The use of these software help plan for instance the line of sight check between the measurement instrument and its target point. Figure 4 shows the first stage of flexible jig installation in the measurement simulation software. As the jig is being built the benefit of simulation becomes more evident as it can highlight the line of sight issues and uncertainty level of an instrument with respect to the target measurement points.

Figure 4: Simulation for measurement assisted jig installation



Potential drift and deformation of jig component due to weight and forces related to the jig operation can be analysed in the simulation world well in advance of any financial commitment with regards to purchasing jig components. Furthermore such tools allow better planning for assembly and manufacturing operations as they can reveal the strengths and weaknesses of the jig prior to its physical setup.

The selection of the right measurement instrument is paramount for successful metrology assisted jig installation. A coherent metrology system with known uncertainty values in its measured results can determine jig accuracy and also expose the capability of the jig and its conformity for the required task within a given tolerance.

6 SUMMARY

Parts and assemblies should be designed in such a way to minimise the cost of jigs and fixtures by accommodating the use of standard components. If thought in advance the speed and cost of changeover of jigs and fixtures for the next variant of products can be increased. The design of jigs and fixtures in their turn can have strong implementation on the total cost, carbon footprint and their sustainability. It is often required to manufacture only a handful of a typical design or a product, subsystem or a component to satisfy variability of products and customer needs. For large scale products where the geometrical dimensions go beyond several meters jigs and fixtures can create major overhead. Furthermore, once the required number of parts is manufactured these jigs and fixtures become redundant. Conventional recycling of redundant jigs and fixtures is not economically viable or green. Therefore the answer should be found in increased flexibility of these jigs and fixtures.

The concept of flexible jigs and fixture has been around for the past two decades. However, their full potentials are not utilised due to uncertainties related to their accuracy and repeatability. High accuracy metrology systems are now available off the shelf that can be used from the initial installation of the jig and throughout its service. Then using the systems it is possible to reconfigure the jig elements accurately to a new topology in order to position components with different geometry, allowing the reusability of the jigs and fixtures for several times.

In this paper a generic algorithm is developed giving stage by stage approach for initial and installation of large scale flexible jigs and fixtures as well as their reconfigurations. The new concept of metrology assisted jig installation proved to be very beneficial for complex settings and installation of the jigs. The conformity of the jig when it is fully assembled can be guaranteed by careful consideration and selection of key points on the jig geometry. This method will be used in the manufacturing and assembly of large size components and products particularly in aerospace and power generation industries.

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