

Parallel Kinematic Assisted Automated Aircraft Assembly

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Abstract—Due to its high precision capability and high dynamic performance, Parallel Kinematic Machine (PKM) recently attracted lots of attention from aerospace enterprises for its potential to provide a flexible solution to automate aircraft assembly processes, in order to replacing the existing cumbersome processes for gaining the competitive edge. This work introduces an integrated method for high precision machining of large aero structures with a PKM based manufacturing system, ranging from development of the PKM solution with light weight supporting frame, machine transportation method in a large work area, dust extraction system design, cutting tool selection, to machining sequence design with in-process metrology support. Experiment results show that the new integrated solution is successful. This provides significant impetus for implementing the step change processes of aircraft assembly. The approach can be well applied to other large scale manufacturing, such as turbine blade machining.

Keywords—Parallel Kinematic Machine, automated aircraft assembly, large scale manufacturing.

I. INTRODUCTION

AIRCRAFT assembly is currently highly labour intensive and time consuming, and it accounts for about one third of the total manufacturing cost [1]. With 30% cost saving expected from the implementation of next generation machines, aerospace companies are looking for flexible manufacturing solutions to revolutionize their current manual assembly processes. Conventional large dedicated manufacturing systems are inflexible and rather expensive, and they are no longer sustainable in the competitive market today [2]. Industrial robots (serial robots) can offer the flexibility but are not able to meet the stringent requirements in speed and accuracy for high precision tasks. Current CNCs can provide the required high accuracy but have no flexibility to cope with large scale manufacturing tasks like aircraft assembly. Parallel kinematic machines (PKMs) or hybrid PKMs (HPKMs) are emerging technology which shows huge potential to fill the gap between robots and CNCs [3]. They have recently attracted much attention from universities to manufacturing industries [4, 5, 6]. (H)PKM has been identified as the key enabler for the next generation manufacturing systems [7] for their high

dynamics potential, high structural rigidity, high accuracy and zero error accumulating characteristics.

In the past 20 years, many different (H)PKM structures have been prototyped and a large number of related patents have been filed. However most research outcome are still remained in university laboratories [8], with very few being successfully implemented in practical machining operations. In addition, the knowledge support network is not well developed due to the novelty of the PKM technology. There is a greater perceived risk of adopting the new technology than for a conventional machine center, as industry is unfamiliar with tripod/hexapod structures and their implementation requirements for integration into existing manufacturing facilities [9, 10]. Under such context, this project investigates automation solution for aircraft assembly. One particular task is to explore the state-of-the-art PKM technology for the automated solution for machining the wing root end of a Lateral Wing Box (LWB). Present joining process of final wing assembly involves cumbersome manual fettling and shimming processes to remove clashes and fill in the gaps. To eliminate these time consuming operations, one step-change method for wing box assembly is to make the two mating interfaces 'perfectly' match, so that the two wing boxes can be easily joined together with no clash or gaps in between. However this has not been achieved due to the lack of cost-effective machining solutions. A number of forefront technologies have to be effectively integrated in order to solve the problem while meeting the stringent industrial requirements. This paper gives details of the proposed integrated methodology, which includes design, build, test and delivery of the PKM based assembly cell, as well as development of the associated metrology, cutting, probing and extraction solutions.

II. TASK DESCRIPTION AND ANALYSIS

Figure 1 shows the wing root end, which is the interface for joining the center wing box (CWB). The working area is composed of the end of the CFRP (Carbon Fiber Reinforced Plastic) spar and the metallic crown fittings (aluminum alloy). Since the rear spar root end was purposely oversized for machining it back to nominal size, it was decided to cut both the rear spar CFRP and the aluminum crown fittings to the required net size accurately and rapidly. Key machining specifications to achieve are $\pm 0.3\text{mm}$ over the entire root (with a size of $3.8\text{m} \times 1.3\text{m}$), $0.05\text{mm}/200\text{mm}$ waviness, 0.038mm cutter mismatch and surface finish $Ra < 3.2\mu\text{m}$.

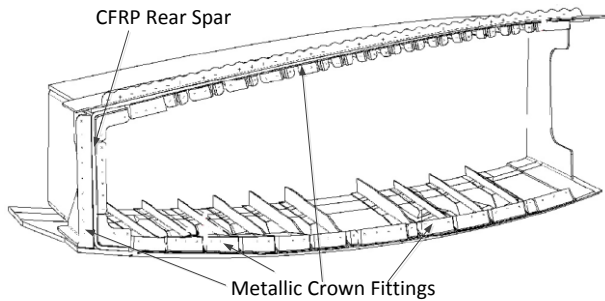


Figure 1 Root end of the Lateral Wing Box

Machining a large scale structure to such a high accuracy poses huge challenge to the manufacturing system under investigation. Through detailed task analysis, the following key points are to be considered.

1. The accuracy requirement dictates that the machine tool needs a very high stiffness and a high payload capacity. Large volume metrology systems, such as laser tracker or indoor GPS are needed to warrant the positioning accuracy of every step in the machining processes.
2. Machine tool needs to be agile for a number of high precision manufacturing/assembly tasks in aerospace. For the required stiffness and flexibility, a newly developed Exechon PKM, as shown in **Figure 2**, is selected for this task given its superior dynamic capability [11, 12].
3. Due to the large scale of the task, the machine tool has to be transportable, to cover the large working area. Omni Move from Kuka is selected as the transportation vehicle as it can be easily adjusted in a constrained space and has a high payload capacity.
4. Cutting tools and machining process parameters have to be carefully decided to meet the surface integrity requirement while providing a satisfying productivity.
5. Effective collection of swarfs and dusts is required to meet the health and safety regulations in industry.

Apart from the harness of each individual technology mentioned above, the greatest challenge is how to integrate all these technologies efficiently and effectively. This paper is to introduce the implementation methodology for achieving this.



Figure 2 Physical model of the 5-DOF Exechon machine developed in Queen's University Belfast

III. LITERATURE REVIEW

In order to gain competitive advantages by reducing cost and improving quality; Boeing, Airbus and Bombardier are all seeking to deploy advanced flexible manufacturing systems to achieve flow-line production. The research on robot-based manufacturing for automated aircraft assembly (AAA) started about 20 years ago, and has received increased attention recently [2, 11, 13]. One example is the AWBA (automatic wing box assembly) demonstrator cell for automated wing box assembly, developed by Airbus UK [14]. With two separate robot systems, the cell can not only handle and position 6m high ribs precisely into spars with a positioning accuracy of $\pm 0.5\text{mm}$, but also drill and fasten the skins to the ribs. Another assembly system was presented by Webb et al. for automated riveting of fuselage panel assembly [15]. Summers [2] tested four types of commercial robots for their aerospace capability, and the tests included static and dynamic loading, temperature drift, resolution and accuracy. Their results showed that the $\pm 0.2\text{mm}$ absolute accuracy was not achievable even with calibrated kinematic model, and the positional accuracy would be seriously affected by the temperature changes. The main historical barrier to the adoption of serial robots in aerospace has been their low level of accuracy and repeatability compared to hard automation solutions. This has led to projects investigating the use of new machine architectures based on parallel kinematics. For instance, researchers at Nottingham University have conducted research in drilling small aero components using the Tricept model [15, 16]. Recently, Tianjin University in China proposed several new (H)PKMs for drilling and riveting panel assemblies [17].

A parallel manipulator (parallel kinematic machine, or a parallel robot) is a closed-loop kinematic chain mechanism of which the end-effector is connected to the base by several independent kinematic chains (legs) in parallel [18]. Combination of parallel manipulator and additional serial axes are referred to as hybrid systems. Comparing to a serial robot, PKM offers higher stiffness (external load shared by all legs), higher speed, higher accuracy, and higher force capabilities. Due to these advantages, PKMs has received wide applications, e.g., flight simulators, high precision positioning devices, pick & place manipulation, metrology and co-ordinate machine, reconfigurable tooling, and high speed machining. Research has shown that HPKMs can offer competitive advantages over conventional CNC machines [11], but only a few (such as Tricept, Z3 sprint head, and Index V100) have been successfully implemented in practical machining operations. There is still a long way to go before putting them into productive work, such as in large volume high precision manufacturing. The Tricept machine, invented by Kalle Neumann, is by far the most popular machine for high stiffness manufacturing, with more than 300 currently in production. Exechon Technology [11] is an innovative PKM solution developed by the same inventor, and it offers enhanced stiffness, accuracy and scalability capabilities over the old Tricept technology. For this reason, the Exechon PKM machine is employed in this work.

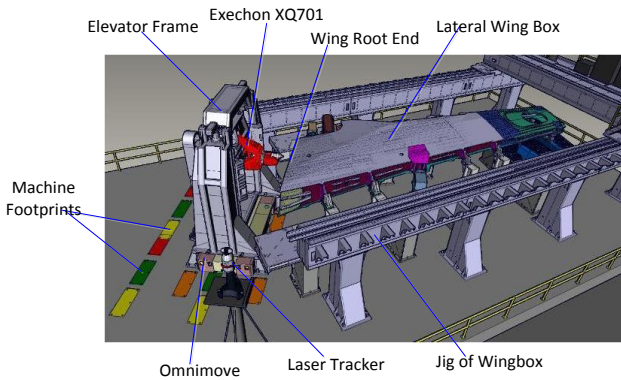


Figure 3 Designed workcell for automated machining of LWB

IV. IMPLEMENTATION METHODOLOGY

The task is to accurately and rapidly mill one layer off the CFRP spar end and the metallic fittings of the root end structure of a LWB to produce a flat surface to make ease of joining the LWB to CWB. Figure 3 shows the designed workcell based on the detailed task and technology analyses. The implementation technologies, including PKM solution, cutting solution, extraction system design, metrology solution and operation sequence design will be introduced in this section.

A. Parallel kinematic machine

The Exechon PKM is targeted on high precision machining [11]. Figure 2 shows the Exechon XQ701 machine developed by Queen’s University Belfast [19]. The Exechon machine has a hybrid structure in which a 2-DOF serial wrist is mounted on a 3-DOF triple-leg parallel architecture to provide 5-axis capability. As claimed by the Exechon Co., the machine can achieve 10µm repeatability, 50µm accuracy, and up to 80kg payload within a 2m x 2m x 0.7m work envelope. Its measured stiffness is 17N/µm in both X and Y directions and 35N/µm in Z direction.

To meet the height and width requirements of the task, the machine should be able to move vertically and horizontally to cover the whole work area. For achieving the elevation, a frame is designed with a motorized vertical lift as shown in Figure 4. It is operated by lead screws that ran between the top of the frame and lower frame base, one on each side. The PKM module has been mounted on liner bearings running from top to bottom of the PKM support frame. The screws were designed to operate in a master/slave configuration and are controlled by the overall control system for positioning the PKM. Feet were also designed and assembled under the frame to give clearance to Omni Move for lifting processes.

Finite element analysis results show that the stiffness of the frame is up to 0.2mm deflection at the bottom position with a lateral acceleration of 20m/s², 0.25mm deflection at the middle position with a lateral acceleration of 10m/s², and 0.3mm deflection at the top position with a lateral acceleration of 5m/s², as shown in Figure 5.

To enable the PKM to cover the width of the LWB, Omni Move, provided by Kuka, was selected for transportation of the machine. The Omni Move is a wireless remote-control

handling device, which can lift up the frame (with the PKM) and drive it to a designated location in all directions across a flat surface (floor). After one zone is completed the entire frame can be picked up and moved to the next zone. The position of the PKM solution is defined by mounting points on the floor, as shown in Figure 3. As a result, the task area has been divided into three zones A, B and C, corresponding to three designated locations for the PKM, as shown in Figure 6. Note that there are overlaps between any two adjacent zones for the PKM reachability and local probing purposes. Figure 7 shows the positions of the PKM relative to the LWB.

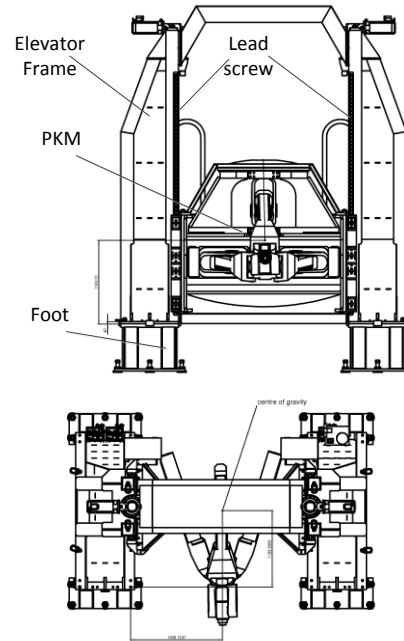


Figure 4 PKM Frame front view and top view

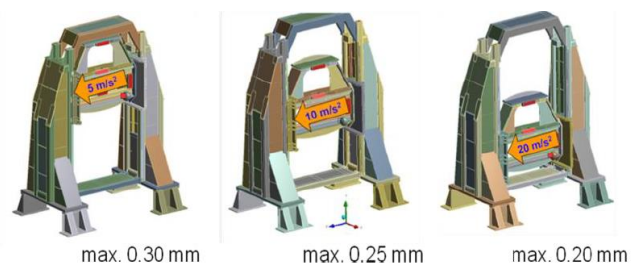


Figure 5 PKM damped oscillation

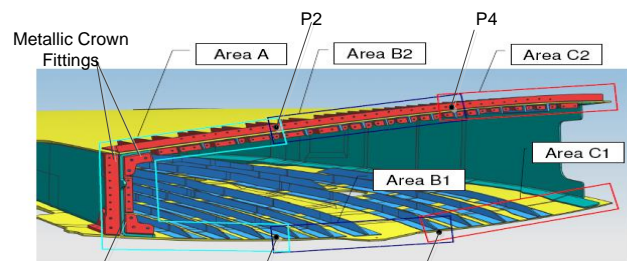


Figure 6 Working zones at the root end of the LWB

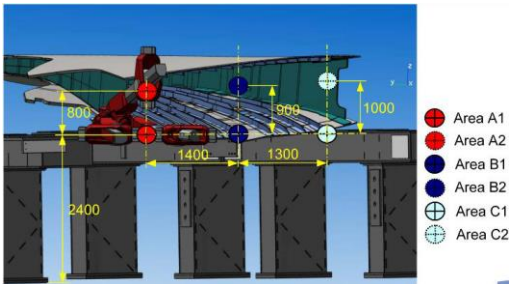


Figure 7 Zone positions for PKM relative to LWB

B. Extraction system design

As swarf and dust will be generated during the machining processes, two extraction systems, shown in **Figures 8 and 9**, have been designed for CFRP and aluminum alloy respectively to suit their corresponding spindle speed, cutters' size, chips shape, etc. Nederman extractor is employed. The CFRP cowl is sized according to the CFRP cutter ($\text{\O}40\text{mm}$ cut width), and has a seal to prevent the dust getting in to less protected areas around the spindle. The aluminum cutter cowl is designed to deal with large, potentially long chips that are generated during the cutting process. It is sized according to the aluminum cutter ($\text{\O}80\text{mm}$). To achieve 100% waste removal, the flow rate for both extraction systems needs to be greater than $500 \text{ M}^3/\text{hour}$ at 20 kPa. The readers are referred to [20] for more details.

C. Cutting tool

Ideally, the CFRP and metallic millings should be done in one go using only one cutter, however this will lead two major concerns.

- i. The cutter (fitted with carbide inserts) will wear out quickly as CFRP is very abrasive and the cut life of inserts for aluminium alloy will be shortened when exposed to CFRP. This may result in burnt CFRP and poor surface finish on the aluminium crown fittings.
- ii. The CFRP is susceptible to delamination and splintering.

For the above reasons the rear spar is to be cut separately from the aluminium fittings. Given the machining requirements of the CFRP spar and the metallic crown fittings of the wing root end, Sandvik Coromant Ltd in Sweden recommended two different sets of toolings for the two materials, i.e., carbide inserts for aluminium and Poly Crystalline Diamond (PCD) inserts for CFRP. As there is no permitted delimitation, burning or other adverse effects with the CFRP, CFRP machining is designed with two passes which meet at the centre line of the cutting surface. The first pass is to cut with the break out of the cutter just over the centreline of the CFRP and the second pass starts machining from the other side of the spar. This approach reduces the risk of CFRP delamination and splintering. The PCD offers good life and resilience to the abrasive CFRP. The size of the tooling is determined by the area and dimensions of the perceived material to be cut. The following tools have been selected: For CFRP milling, cutter: R590-04C3-11M; adapter: C6-391.02-32032; insert: R590-1105H-PS2-NL CD10 (Std. Edge). For the metallic milling, an inserted cutter (cutter: R590-080Q27A-11M; adapter: C6-391.05-27025A; insert: R590-110504H-NL H10) was selected.



Figure 8 Extraction hood for CFRP machining

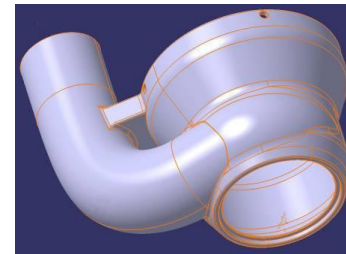


Figure 9 Extraction hood for milling aluminum alloy

D. Program for PKM solution

Offline programming (OLP) is required to validate all machining paths in a simulation environment before the physical machining takes place. OLP requires a software system capable of holding, interrogating and reviewing all geometries and features on the components to be machined. In addition, the software must be able to simulate the machining solution. The programmer can then select paths, tooling and processes in this virtual world, and generate new items (such as cutting tools) as appropriate. Once the OLP is completed the program can be exported in a form of machine code, which can be downloaded to the machine controller to drive the real machine. The process is valid providing the components are modeled within specified tolerances in the OLP generation. Search routines (using metrology and other sensing devices, such as probes) will allow the PKM solution to accurately adjust the real world discrepancies to the virtual. The Exechon PKM uses a kernel based programming system ILP (In Line Programming, provided by OptikosQ) with 100% accuracy. The ILP simulation is driven directly by the same machine code as with the real machine. The ILP will verify the perceived cutting process, check potential problems, and carry out machine optimizations before the actual machining processes take place.

E. Metrology (hardware + software)

In order for the PKM solution to "know" its position relative to the task area, and achieve the high positioning accuracy, a two-level operational metrology that consists of a large volume laser tracker (Leica) and a local probe (Renishaw RMP60), has been designed to locate the cut surfaces. The laser tracker is used to position the machine and wing box (task), while the probe is for minimizing the mismatch of the boundaries of adjacent cutting zones.

The LWB is set up with five drift nests (target Corner Cube Reflector receptacles) hot glued to the upper and lower wing surfaces. These target positions are tracked and recorded. Additionally the wing root end is scanned (as a by-product of the crown fitting processes) and made available as a position reference. The tracker will provide the position of the wing datum from the five measurements on the wing, and provide the TCP (tool centre point) of the PKM in relation to the wing reference frame.

To locate the TCP of the PKM, a SMR (surface mirror reflector) is mounted in the tool holder fit to the end of the PKM spindle. The machine moves the SMR to 10 pre-defined points which form a cross and the points' coordinates are captured by the laser tracker. The true TCP can then be calculated using an averaging process and best fit. The machine base frame (BES frame) can be represented in the wing frame through pre-defined algorithm in Spatial Analyser software.

To minimize the mismatch of zone boundaries, a touch probe (Renishaw RMP60) measures two points on a finished cut surface, which will be used as the reference for cutting the next zone. After moving or resetting the PKM to a new zone, the same points will be probed again to calibrate the relative position between the new working surface and the finished working surface. This will ensure the cut blends in to each other smoothly and remain compliant with industrial specifications.

Spatial Analyser (SA) software is selected to compare the digital mock-up (DMU) with the real LWB positions (through best fits, weighted). This provides the PKM with the correct offsets (δX , δY , δZ , $\delta \alpha$, $\delta \beta$, $\delta \gamma$) to be used by its CNC system. Therefore the PKM frame can be aligned to the LWB frame in all directions and rotations, eliminating the physical errors in installation phases of all the physical components.

F. Operation sequence

Based on the above consideration, the operation sequence of the automation solution is defined as follows.

1. Measure the positions of the five reflectors on the wing so as to locate the wing reference frame $\{W\}$.
2. Run the PKM machine to move the TCP through the predefined cross with 5 horizontal and 5 vertical points being measured by the laser tracker. The machine frame $\{BCS\}$ can then be constructed through the calibration algorithm in Spatial Analyser. The position of the machine frame relative to the wing frame ${}^W_B T$ is then obtained.
3. ${}^W_B T$ represented by three translations and three rotations (δX , δY , δZ , $\delta \alpha$, $\delta \beta$, $\delta \gamma$) will be input to Siemens 840D controller to align the machine coordinate system $\{BCS\}$ to the wing reference frame $\{W\}$.
4. Rear spar machining: To generate the program (ILP) for the rear spar. A RMP 60 probe is installed into the PKM to probe the inner/outer edges and faces of the rear spar and log the positions. The data is then loaded into the ILP and an accurate position (using the model of the spar in the DMU for reference) will be produced. Once the machining

program has been verified by the ILP, the physical machining will take place.

5. Crown fitting machining: To perform the root end cutting of the crown fittings, the PKM is installed in the relevant zones, following the order of Zone A, Zone B and Zone C. As shown in **Figure 6**, Zones B and C are further split into sub-zones B1/B2 and C1/C2 respectively for lower and upper covers per zone.
 - a. Zone A process: 1) Move the Exechon unit to Zone A and manually jog the Z-axis gantry with the Exechon unit to the required position. 2) Follow the process steps 2 and 3 to align the machine coordinate system to the wing frame. 3) With the measurement data, load and run the NC programme in ILP in test mode to verify the operations. The physical machining starts after the completion of verification, i.e., all errors adjusted to tolerance. 4) Once the machining process is over, the cutter will be replaced by the Renishaw Probe RMP60, and two points P1 and P2 (refer to **Figure 6**) will be probed on the machined surface close to the termination of Zone A and prior to Zone B, these points serve as the local reference to calibrate the depth of cut in Zone B.
 - b. Zone B1 process: Prior to the operation in Zone B1, the PKM is moved from position A to position B using Omni Move. Zone B1 is cut following the same process as Zone A, except that the points P1 and P2 need to be re-probed after moving the machine to a new position, and the measurements will be input to the ILP for further calibrating the NC program. This is to ensure a seamless cut between Zone A and Zone B1, and that Zone B1 is in the correct plane.
 - c. The remaining Zones B2, C1, and C2 should be processed in the same way as above.

V. TESTS AND RESULTS

Before machining the root end of the LWB, a number of tests were conducted on small scale aluminium coupons to validate the machine capability and the process feasibility. The PKM solution was transported to the LWB plinth and was set up for the PKM programs to reach the relevant zones of the root end LWB. As the machine unit (including the frame) is too heavy for the Omni Move, the PKM was moved using skates and tool movers. The PKM was then bolted down to the pre-drilled floor positions and finally levelled using adjusters (5 off per foot) to ensure that there was no twist in the PKM frame.

With the PKM solution in position and tracked with the tracker, the machining program was verified by ILP without the cutter and extraction hood installed. Then the cutter ($\varnothing 40\text{mm}$ R590 with PCD inserts) was installed and an offset was applied in the program to compensate the cutter's length. The program was run on the PKM solution without the spindle enabled. At key points throughout the program the cycle execution was halted, and the position of the cutter was measured to ensure

that it was within 1mm of the intended position, using a standard steel ruler. This gave confidence that the process has been translated to the real LWB correctly. The PKM was then reset to home position and the relevant extraction cowl was fitted to the spindle. All systems were enabled and the PKM solution set to proceed with the first pass cuts for the rear spar. Post test analysis showed the surface finish was satisfactory and was in accurate position (approximately 3mm depth removed), and therefore the cutting of the aluminium crown fittings would not be affected.

For the metallic cutting, the cut process was initiated from zone A. The depth of cut was set to approximately 2.0 mm (0.5 mm for finishing) referencing to the Crown Fitting scan data. The cut was performed as expected, with a normal cutting sound. No resonance or other unwanted artefact was perceived. **Figure 10** shows the root end before and after the cuts.



Figure 10 The root end before and after the machining



Figure 11 Root end measurements at +/-0.3 mm tolerance



Figure 12 Root end measurements at +/-35 µm tolerance

Once the crown fittings machining was completed, measurements were taken every 15 mm (condition of supply stated at least 20 mm) on each crown fitting [21]. As a result, 12,590 sample points arranged in a 15 x 15 mm grid were taken over the entire root end volume. The Spatial Analyzer analysis

was performed to check the results. As shown in **Figure 11**, the areas in green show that the machining tolerance of +/-0.3 mm has been met comprehensively across the 4 m span of the wing box root end. In order to understand exactly where error existed on the root end, the analysis was re-run with the tolerance being reduced to +/-35 µm. The graphical representation of this analysis is shown in **Figure 12**. The error range encountered was -0.0887 mm to 0.0416 mm, as shown in **Figure 11**. The trend of the error accumulated across the wing box was linear from Zone A to Zone C2. The maximum waviness of 0.007 mm over 200 mm also lay very comfortably within tolerance.

The swarf collection systems performed well, with no binding on the cutter of aluminium swarf or the like. The cyclonic separator was emptied after each zone as the volume was small. The extraction hood worked well, collecting most of the swarf, although some of the metallic swarf did escape but only limited to a few pieces. The CFRP hood extracted all CFRP dust.

The tooling provided satisfactory performance, and the inserts achieved good surface finish and reasonable insert life (1 set of carbide inserts worked for zone A +B1+ B2). The surface finish was measured using a Talysurf surface profiling instrument across the span of the entire root end. The maximum Ra was 1.4 µm, less than half of the target surface finishes (3.2 µm). Close inspection of the surface finish showed that the mismatch between passes on the root end was minimal (<3 µm). The mismatch between machining zones was less than 15 µm in average.

TABLE I summarizes the overall performance based on the measured results comparing to the task requirements. Conclusion was drawn that the integrated methodology has delivered a satisfactory solution.

TABLE I RESULTS OF ROOT END MACHINING

<i>Measurements</i>	Targeted	Achieved
Machining over root end span	+/-0.3mm	-0.0887mm +0.0416mm
Surface mismatch	38µm	15µm
Waviness over 200mm	+/- 0.05 mm	0.007mm
Surface finish	3.2µm	1.4µm

VI. CONCLUSION

This work introduces an integrated method of PKM based flexible manufacturing solution for automated aircraft assembly. It represents the state-of-the-art in aerospace automation, which combines a novel set of sub processes to deliver a step change in the current LWB root end manufacturing. The testing processes are proposed and a number of advanced techniques are disclosed. The proposed methodology has been validated through real industrial examples under the stringent industrial standard. The integrated methodology can be well applied to many other industrial

sectors, such as ship building and assembly of heavy machineries, and therefore could inspire more research into the challenging yet highly value-added area of flexible manufacturing.

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