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ROBOTIC ASSEMBLY OF AERO-ENGINE COMPONENTS

The VITAL (EnVironmenTALly Friendly Aero Engines) project funded by the European Commission under Framework 6 aims to provide significant reductions in aero-engine fuel burn, noise and emissions through the development of innovative design and manufacturing techniques. One method of reducing the amount of fuel burnt, and hence CO₂ produced, is to reduce the weight of the engine. A significant proportion of an engine's weight is due to the large castings used to form the main non-rotating structures; the replacement of these with fabricated structures could provide a significant weight reduction.

This paper describes the design and implementation of a robotic assembly cell for complex aero-engine components. A series of experiments were performed to prove the feasibility of the automated assembly process. The results presented indicate that automated robotic assembly is feasible and cost effective.

1. INTRODUCTION

The VITAL (EnVironmenTALly Friendly Aero Engines) project funded by the European Commission under its Framework 6 Programme aims to provide significant reductions in fuel burn, emissions and noise through the development of innovative design and manufacturing techniques. One way to reduce the amount of fuel burnt, and hence CO₂ produced, is to reduce the weight of the engine. A significant proportion of which is due to the large castings used as the main structure of the engine, the replacement of these with fabricated structures consisting of small castings and sheet components could provide significant weight reductions. The use of sheet material has two advantages, it tends to have better structural properties compared to cast and so thinner sections can be used and no extra material is required to support the casting processing. However, the manual fabrication of such structures is slow and costly and is presently not economically viable. One way to reduce the cost is to automate the process. The use of conventional robotic assembly

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techniques for large and complex structures is limited by the geometric variability of the component parts caused by process limitations such as spring back and distortion from heat treatment and welding. This often results in a mismatch between the part's assumed and actual geometry making assembly difficult and inaccurate. These inaccuracies can be minimised by using metrology to find the true position of key features on the parts and then by performing a best fit assembly calculation parts can be placed in the optimum position relative to their counterparts.

The use of external metrology systems to improve the capability of robotic systems is not new especially in aerospace applications such as the assembly of wing structures (Rooks, 2001, Anderson, 2002, Kayani and Jamshidi,2007), airframe subassemblies (Eastwood et al., 2003, Webb et al., 2004) and fuselage skin panels (Webb et al., 2005, Jayaweera and Webb, 2007). These applications use metrology systems such as laser trackers, photogrammetry, laser radar, laser stripe scanners or vision systems to provide data for the assembly and manufacturing operations. Similar techniques have also been used in the automotive industry (Park and Mills 2002, Park et. Al. 2002) but to a lesser degree as the parts tend to be optimised for automated assembly and cycle times are much shorter limiting the amount of measurement and adjustment.

However, little work has been reported on the automated assembly of complex aero-engine structures. The research described in this paper describes an automated solution for the assembly of aero-engine structural components by integrating a standard industrial robot, non-contact metrology system, a mathematical processing toolbox and a cell control system.

2. METHODOLOGY

At the start of the VITAL project a number of different engine architectures were developed and representative parts designed for development and testing. Of these three representative parts were chosen to develop and prove the assembly methodology in the laboratory these were an inner and outer annulus and a vane structure as shown in Fig. 1. To prove the principle machined parts were used but in reality these would also be fabrications with distortions present from welding and metal deposition.

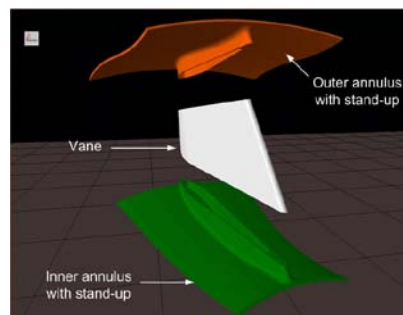


Fig. 1. Vane and Annulus Components

The overall assembly methodology developed is illustrated in Fig. 2. Before assembly the a robot mounted metrology system is used to locate the component and measure the position of assembly features relative to the robot to identify the actual and required position of the component before assembly and features on the counter-part.

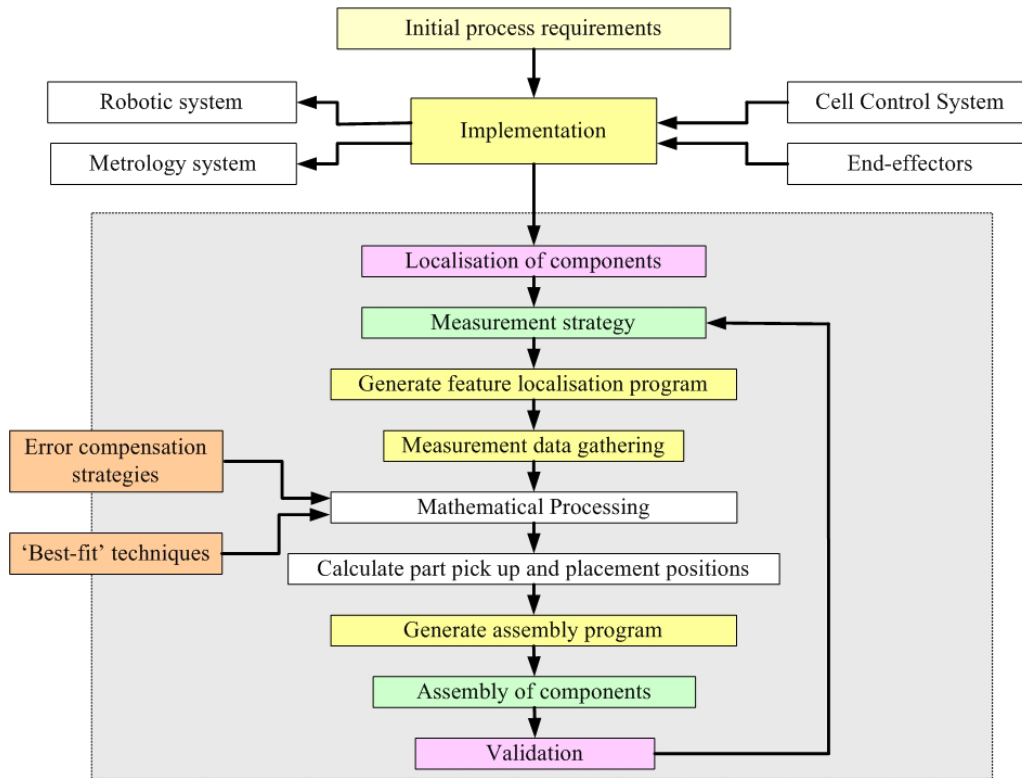


Fig. 2. Representation of the methodology through a flowchart

The acquired data is then processed through a mathematical algorithm to calculate the relative component positions required for optimal assembly. This gives the precise relationship between the TCP and the component relative to the robot base coordinate system which then used to generate the assembly programs by manipulating a pre-programmed robot path. This has the secondary effect of optimising the performance of the robot used since it and the part are locally calibrated to each other thus ensuring that the maximum repeatability and accuracy are achieved. This reduces the need for high cost high accuracy robots and expensive product specific fixtures.

If the part cannot be placed in the exact position required the software performs a ‘best-fit’ operation relative to features on the counterpart, along with an overall tolerance check, to ensure that the part can be assembled within the required specifications. The data can also be used to check for gross distortion of the components and to reject those outside the specification limits. Metrology data can also be stored and analysed to produce quality assurance and process verification information. The next section describes the design and implementation of robotic assembly cell.

3. CELL DEVELOPMENT

To prove the assembly methodology within the laboratory a cell was designed and constructed which consisted of an industrial robot, an end-effector for the handling of the components (vane and annulus with stand-up), a metrology system, a mathematical processing kernel and a cell control system. The complete system is shown in Fig. 3. Ethernet was chosen as the main data transfer protocol due to its capability to support the rapid transfer of large volumes of data. The cell is controlled through a master PC running customised software developed by the University of Nottingham. Each of the components is described in the following sections.

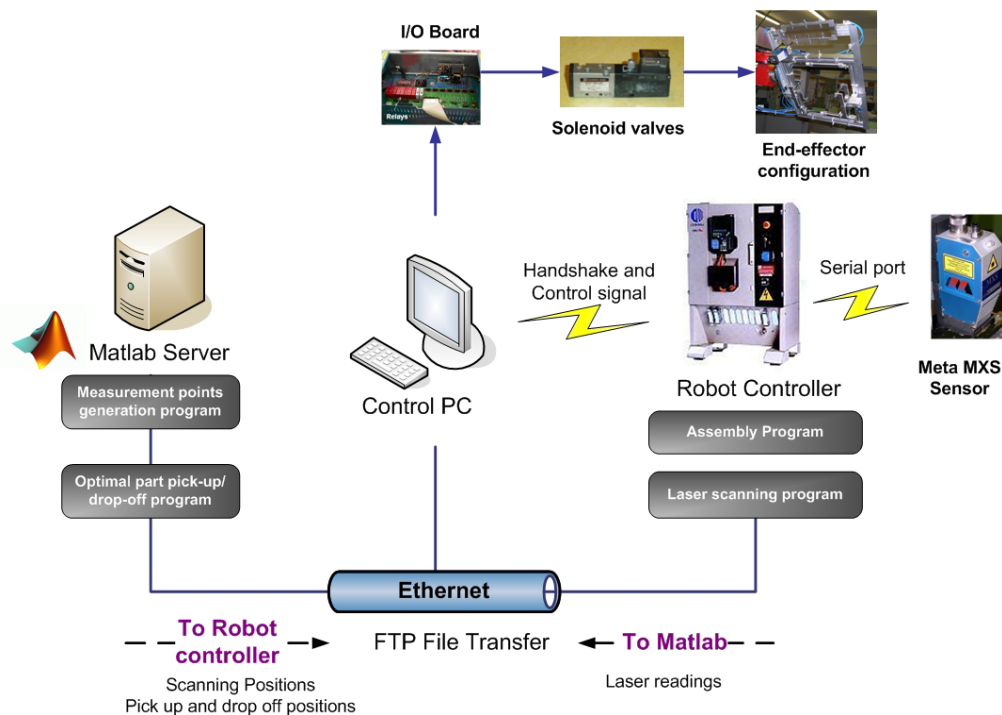


Fig. 3. Cell control architecture

Robotic System

A Comau S2 robot was chosen as it was representative of a small payload, large work volume and low cost robot. The Comau S2 robot has an articulated, six axis anthropomorphic structure, its maximum wrist load capacity is 78.45 N (8 kg) and the repeatability is quoted as ± 0.1 mm.

Metrology System

A Meta MXS laser cross-sensor was selected which uses a laser stripe to measure positional data and can be used for height, edge and hole finding applications. Previous work had also shown that it performed well when used on Titanium with an untreated surface finish (Jayaweera and Webb 2007).

Assembly end-effector

Although many robotic systems are available commercially, each project will usually require the design of a unique and customised end-effector to perform a particular task. The design of end-effectors is critical for the successful implementation of a system. For the assembly of the sector components (vanes, annulus with stand-up) a flexible end-effector was required to allow components with different geometries to be handled. In this case the end-effector was also developed to incorporate the metrology system. As the end-effector would also be required to hold the segment in position whilst tack welding is performed further design factors had to be taken into account, such as was their sufficient clearance for the welding operation? Could it withstand the heat?

The end-effector control system consisted of a digital input/output board, Relays, DC power supply unit, solenoid valves, and an industrial computer. Pneumatic cylinders were used to reconfigure the end-effector according to the component type. The complete end-effector is shown in Fig. 4.

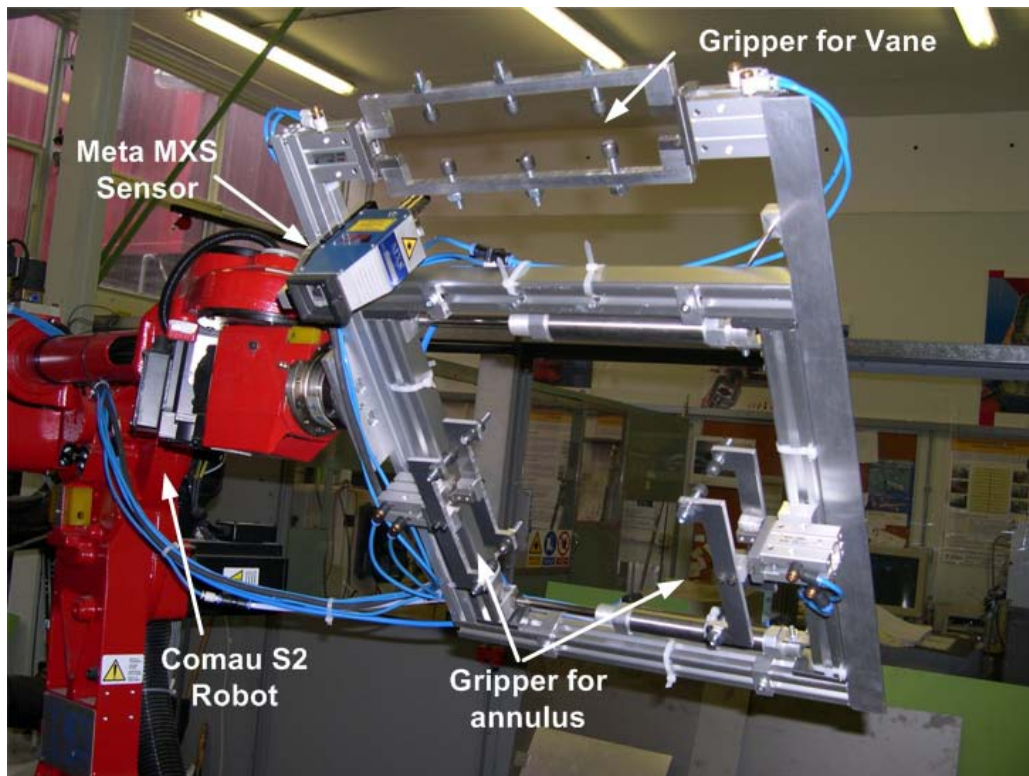


Fig. 4. Sector assembly end-effector mounted on Comau S2 robot

Development and implementation of mathematical algorithms

The methodology route map described in Fig. 2 required the development of mathematical algorithms for the optimal placement of sector components. The mathematical algorithms are used to calculate the part pickup and drop-off positions required for the robot and to locate the precise position of the parts. The MATLAB environment was used to implement

a mathematical algorithm which was designed to find the true edge positions around the assembly profile from the laser offset values and relevant robot positions. Initially component positions are calibrated globally within few millimetres. Matlab uses these one-off calibration positions point 1 and point 2 illustrated in Fig.7 to calculate twelve edge positions around the profile. These are then used as the base positions for the robot to move to during the scanning operation. The measured data for each point (laser offset values and relevant robot TCP positions) is automatically sent to MATLAB via the robot controller. A graphical representation of the measurement points around the vane profile is illustrated in Fig. 5.

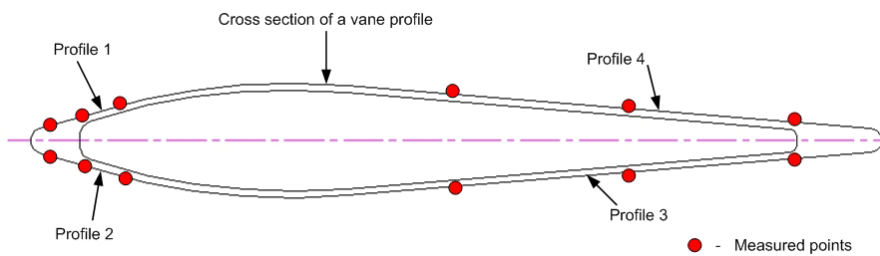


Fig. 5. Scanning points around the vane profile

For the edge measurements, the x, y and z offset values from the intersection of the laser beams with the edge are detected. Since the MXS sensor has two laser stripes it gives two measurements from a single position. The offset values are denoted as $x_1, y_1, z_1, x_2, y_2, z_2$. The acquired data is then processed to calculate actual geometry of the components to be processed. Based on this the algorithm performs a ‘best-fit’ operation to calculate optimal part pick-up and placement positions as illustrated in Fig. 6 and 7. In addition, these algorithms compensate for some of the error due to sensor uncertainty and inherent robot errors by incorporating additional measurement points in the programs to generate two best-fit lines for each feature and averaging all possible intersection points to give optimal part pick-up and drop-off positions.

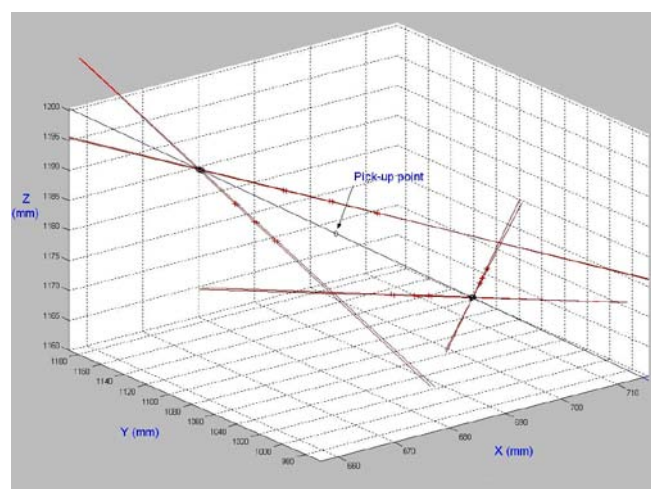


Fig. 6. Calculation of optimal pick-up point of vane using Matlab

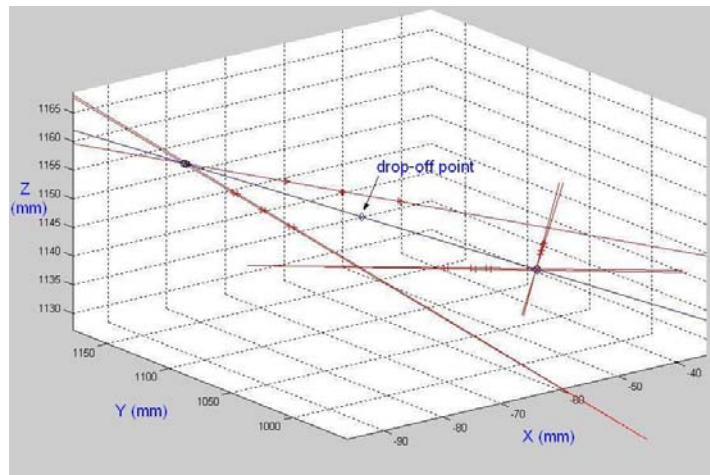


Fig. 7. Calculation of optimal drop-off point of vane using Matlab

Development and implementation of cell control system

A Graphical User Interface (GUI) has been implemented and allows an operator to control the complete assembly cycle and monitor all of the operation and data flows within the system Fig. 8.

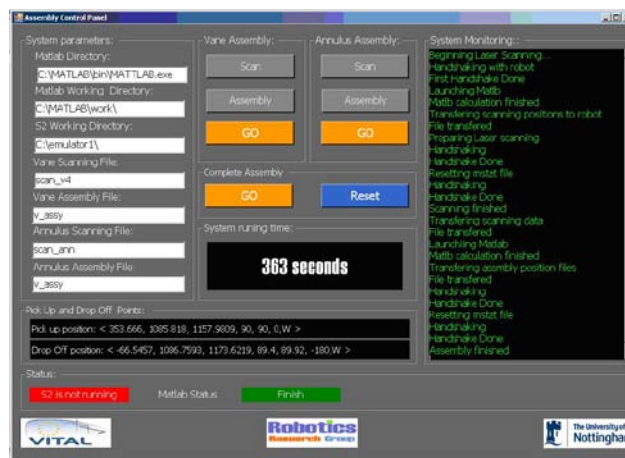


Fig. 8. Cell user interface

The basic principle of the approach used in the automated cell control system comprises of four tasks. In the first task the control PC activates the Matlab program to generate measurement points based on nominal component positions for the robot. The generated points are then transferred to the robot controller through FTP. In the second task, the control PC handshake with the robot controller and sends control signal to start the feature localisation program. Then laser offset values and relevant robot positions are sent back to the Matlab using FTP. In the third task the control PC activates the Matlab program

to generate the optimal part pick-up position and drop-off position and send these points to the robot controller. In the final stage, the control PC handshakes with the robot controller and sends a control signal to generate the final robot program for the assembly of the sector components.

Implementation of robotic assembly sequence

The developed core technologies were integrated by incorporating all the hardware and software modules together to pass data between all system elements through the developed control architecture. In this research a sector is considered to be made up of three segments namely inner annulus (with stand-up), vane and outer annulus (with stand-up) as illustrated in Fig. 1. A sector assembly consists of vane on inner annulus (with stand-up) and outer annulus (with stand-up) on vane. The robotic assembly sequence for segment components is illustrated in Fig. 9 as a flowchart.

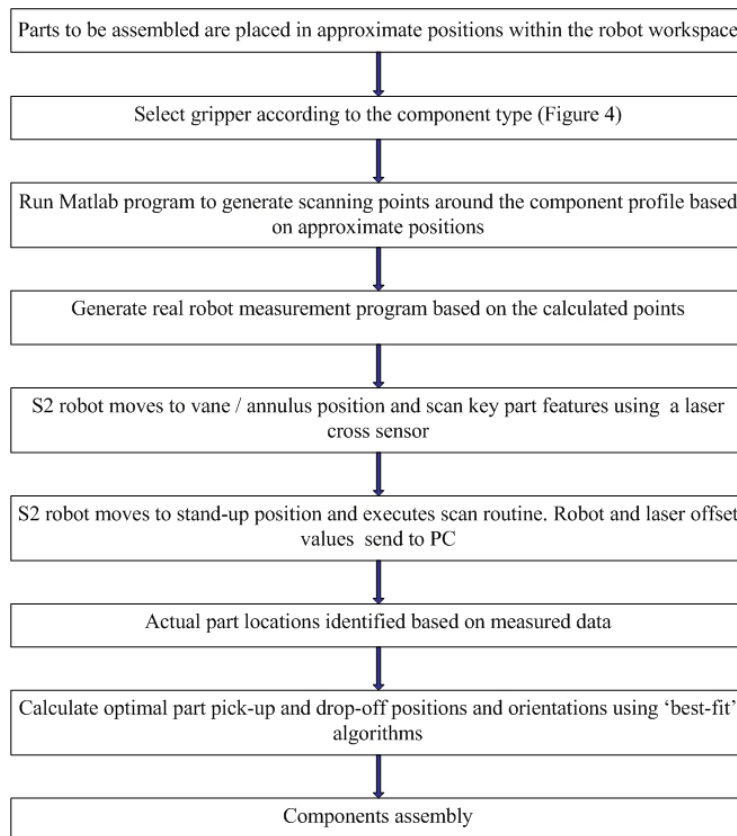


Fig. 9. Robotic assembly sequence

4. PRACTICAL WORK

To prove the assembly methodology two experiments were conducted. The assembly sequence of a vane on to annulus (with stand-up) is shown in Fig. 10. The experimental setup for outer annulus (with stand-up) on vane is shown in Fig. 11.

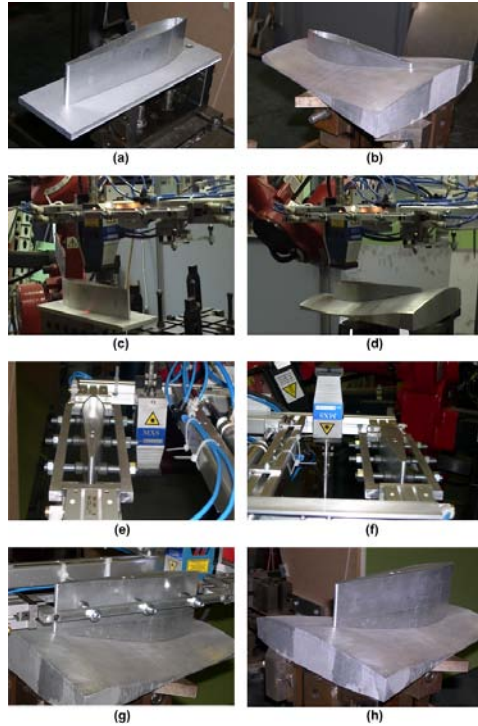


Fig. 10. Vane assembly sequence. (a) Vane kept on a fixture (b) stand-up kept on a fixture (c) vane localisation (d) stand-up localisation (e) vane picks up (f) rotate vane 1800 to mate scanned surfaces (g) assembly of parts (h) post assembly

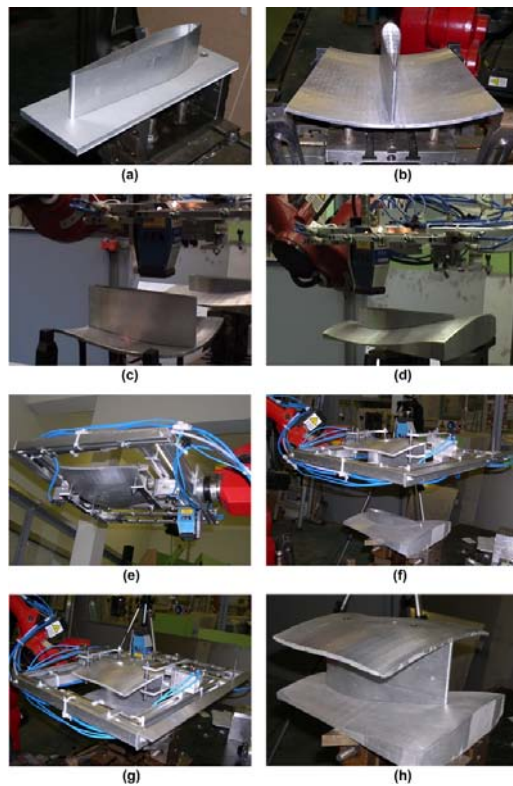
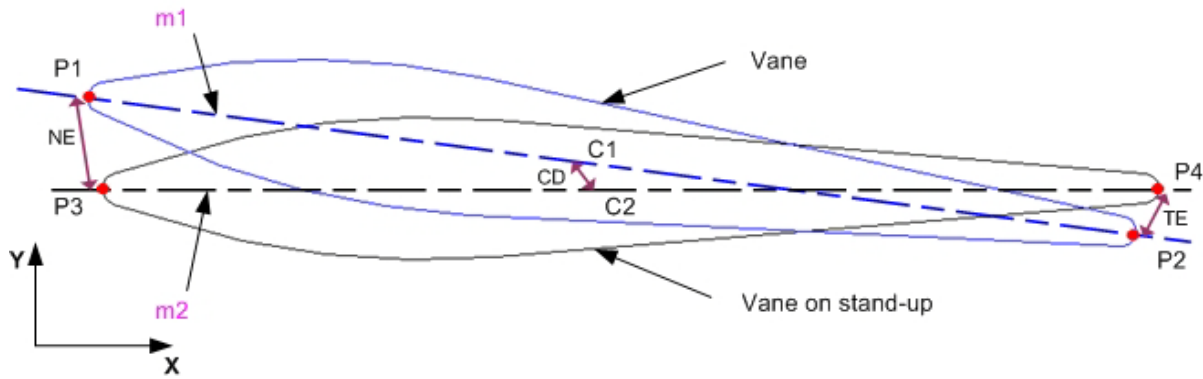


Fig. 11. Annulus assembly sequence. (a) Annulus kept on a fixture (b) stand-up kept on a fixture (c) annulus localisation (d) stand-up localisation (e) annulus picks up (f) rotate annulus 180⁰ to mate scanned surfaces (g) assembly of parts (h) post assembly

To determine the repeatability of the process ten experiments were performed each following the operational procedure described above. In each experimental trial, the parts were roughly placed on a table and the assembly process completed, LOCTITE 401 general purpose instant adhesive was used to temporarily hold the parts in place so that they could be measured with a Coordinate measurement machine. The measurement data was then used to calculate the part's misalignment as shown in Fig. 12. The results obtained are shown in Table 1. The notations used in the table are illustrated in Fig. 12.

Table 1. Assembly misalignment of vane on stand-up

Exp No.	d1 (mm)	d2 (mm)	CD	NE	TE	θ (deg)
1	206.55	206.37	0.37	0.44	0.31	0.01
2	206.54	206.37	0.39	0.37	0.44	-0.05
3	206.54	206.37	0.20	0.29	0.12	-0.03
4	206.50	206.36	0.46	0.55	0.48	-0.12
5	206.53	206.37	0.20	0.48	0.29	-0.19
6	206.53	206.37	0.19	0.43	0.32	-0.17
7	206.54	206.37	0.33	0.46	0.20	-0.06
8	206.55	206.37	0.23	0.32	0.14	0.01
9	206.56	206.37	0.20	0.31	0.13	0.05
10	206.54	206.37	0.21	0.35	0.11	-0.07



- P1, P2 : Calculated vane end points
- P3, P4 : Calculated stand-up end points
- C1,C2 : Calculated centre points of vane and stand-up
- m1,m2: gradient of P1,P2 and P3,P4
- NE : Distance between nose end points
- TE : Distance between tail end points
- CD : Centre offset distance after assembly
- d1 : Distance between P1 and P2 points
- d2 : Distance between P3 and P4 points

Fig. 12. Generic view of assembly misalignment

To optimize the end-effector performance, minor design and manufacturing defects need to be eliminated. These include reducing end-effector weight by introducing light-weight materials. When the robot moves from one position to another, the end-effector tends to vibrate depend on the trajectory. Therefore the assembly accuracy decreases with vibration. This vibration can be reduced by using higher payload robot for this application or changing the design of the end-effector. It was also necessary to set up the laser TCP and end-effector TCPs before start the experimental work. Setting up the TCP is not 100 % accurate and it may contribute to inaccuracy in the individual measurements. This can be overcome by using more precise measuring systems such a Laser tracker to calibrate the robot TCP.

5. CONCLUSIONS

The automated assembly of aero-engine components has been successfully demonstrated using a standard industrial robot, a non-contact metrology system, mathematical processing and a cell control system. The incorporation of an MXS sensor and mathematical algorithms allowed precision assemblies to be generated in spite of part tolerances, fixturing errors and robot positional accuracy. Reducing the reliance on part holding fixtures and the use of a laser-guided robot ensures that the integrated assembly system is highly flexible and re-configurable.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] ANDERSON J., *Advanced Robotic Applications in Aircraft Component Assembly*, Proceeding of Mechatronics, University of Twente, Netherlands. 2002.
- [2] EASTWOOD SJ, WEBB P, Mckeown C., *The use of the TI2 Manufacturing System on a Double-curvature Aerospace Panel*, Journal of Engineering Manufacture, Part B, Vol. 217, 2003, 849-855.
- [3] GROOVER M.P., WEISS M., NAGEL R.N, ODREV N.G., *Industrial Robotics - Technology, Programmin, and Applications*, McGraw-Hill, New York. ISBN: 0-07-024989-X, 1986.
- [4] JAYAWEERA N, Webb P., *Automated assembly of fuselage skin panels*, Assembly Automation, Vol. 27, No. 4, 2007, 343-355.
- [5] JAYAWEERA N.,WEBB P., *Adaptive robotic assembly of compliant aero-structure components*. Robotics and Computer Integrated Manufacturing, Vol. 23, No 2, 2007, 180-194.
- [6] KAYANI A., JAMSHIDI J., *Measurement assisted assembly for large volume aircraft wing structures*, 4th International Conference on Digital Enterprise Technology, University of Bath, UK, 2007, 426-434. ISBN 978-0-86-197-141-1.

- [7] PARK E., MILLS K., *Three Dimensional Localization of Thin Walled Sheet Metal parts for Robotic Assembly*, Journal of Robotic Systems, Vol. 19 No. 5, 2002, 207-217.
- [8] PARK E., XU W., MILLS K., *Calibration-based absolute localization of parts for multi-robot assembly*, Robotica, Vol. 20, 2002, 359-366.
- [9] ROCHE N.R., *Automatic Riveting Cell for Commercial Aircraft Floor Grid Assembly*, Aerospace Engineering, Vol. 15, No. 1, 1995, 7-10.
- [10] ROOKS B., *Automatic Wing Box Assembly Developments*, Industrial Robot, Vol. 28, No. 4, 2001, 297-302.
- [11] WEBB P, EASTWOOD S.J., *An Evaluation of the T12 Manufacturing System for the Machining of Airframe Subassemblies*, Journal of Engineering Manufacture, Part B, Vol. 218, 2004, 819-826.
- [12] WEBB P., EASTWOOD S., JAYAWEERA N., YE C., *Automated Aerostructure Assembly*, Industrial Robot, Vol. 32, No. 5, 2005, 383-387.