Measurement Assisted Assembly for High Accuracy Aerospace Manufacturing ⋆

Adrien Drouot * **Ran Zhao** ** **Lucas Irving** **
David Sanderson ** **Svetan Ratchev** **

* *Institut FEMTO-ST, CNRS UMR 6174, UFC - ENSMM - UTBM, 25 000 Besançon, France (e-mail: adrien.drouot@femto-st.fr)*
** *Institute for Advanced Manufacturing, University of Nottingham, NG7 2TU Nottingham, UK (e-mail: ran.zhao, lucas.irving, david.sanderson, svetan.ratchev@nottingham.ac.uk)*

Abstract: Measurement Assisted Assembly is a key concept for the modernisation of aerospace assembly processes, i.e. improving their efficiency while reducing the manufacturing costs. This concept suggests a paradigm shift in the assembly of high-complexity products as it encompasses the development and the use of robotics solutions smartly integrated with innovative measurement technologies. Expected outcomes are, among others, a better positioning accuracy of the components and a significant reduction of the rectification and rework requirements that are usually common with traditional assembly processes, especially but not limited to aerospace manufacturing. To achieve these objectives, a high precision metrology system that automatically inspects and corrects the pose of the robotic manipulators during the assembly operations is of great importance. In this paper, a high-accuracy real-life application of the concept of Measurement Assisted Assembly is presented as a part of the Future Automated Aircraft Assembly Demonstrator developed by the University of Nottingham. Experimentations have shown that, using the production environment described hereafter, a positioning accuracy better than ± 0.1 mm can be achieved for large airframe components.

Keywords: Intelligent Manufacturing Systems, Flexible Manufacturing Systems, Agile Manufacturing, Industrial Robots, Assembly Robots, Positioning Systems, Accuracy

1. INTRODUCTION

Traditional aerospace assembly solutions see the aircraft components manually located and constrained using large monolithic steel structures called assembly fixtures or jigs. These structures are expensive to manufacture and offer little or no adjustment at all to accommodate design changes or product variants, meaning the capital investment may not be recovered. Additionally, there is no real-time indication of the structure condition and it is not uncommon for an aerospace assembly fixture to fall out of tolerance, causing assembly errors which are passed downstream. Unfortunately, it is not until the product inspection, often many processes later, that these issues are detected and identified, causing product and assembly post-processing and increasing both the cost and lead-time of the product.

As introduced by Maropoulos et al. (2014), Mei and Maropoulos (2014) and Muelaner et al. (2013), the concept of Measurement Assisted Assembly (MAA) offers an alternative solution as it enables part-to-part assembly, increases the use of flexible tooling, improves the levels of precision and ensures traceable quality and control (see Fig. 1). This approach hence paves the way for the shortening of the product lead-time and the increase the product diversity and efficiency, all the while reducing the production costs. It hence assumes its importance in what is now called the *Industry 4.0*, a new industrial age where the virtual and physical worlds are merged and where the separation between the technical and business processes fades away. This is achieved through the deployment of Cyber-Physical Systems (CPS), creating a networked world in which intelligent objects communicate and interact with each other, and making the *Industry 4.0* a potential hit as stated by the two ABB Corporate Research scientists Drath and Horch (2014). Such highly automated robotic systems guided by visual feedback will inevitably be required in the assembly stage of both military and commercial aircraft by any manufacturer who intends to remain competitive in the future.

Malamas et al. (2003) claimed that vision feedback systems are already widely used in industrial environment, mainly for the inspection processes and the quality control procedures. However, their use is now increasing in applications related to robot guidance such as obstacles avoidance, collaborative work with other robots or humans, tasks identification and positioning accuracy improvement, the latter being of keen interest to MAA. Different vision techniques have been developed, e.g. photogrammetry, stereo vision, structured light, time of flight and laser triangulation, and their performances in terms

⋆ The reported research has been funded by the EPSRC grant EP/K018205/1.

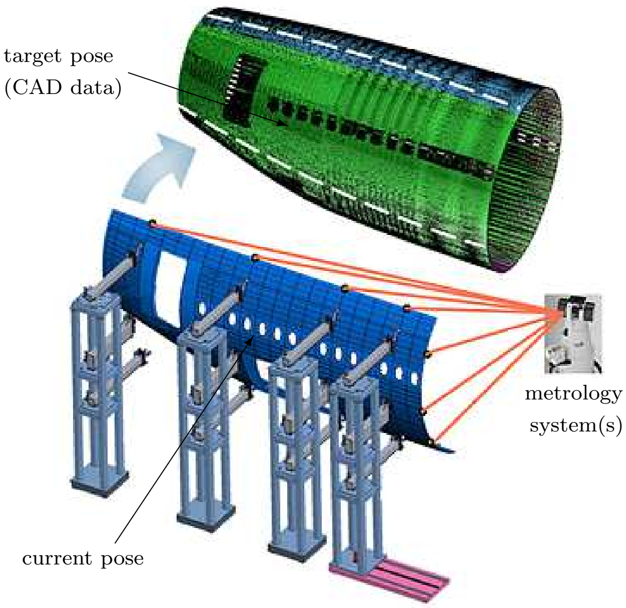


Fig. 1. Measurement Assisted Assembly conceptual model as introduced by Meffert et al. (2012) for the *EcoPositioner* developed by Dürr

of range, accuracy, processing time, safety, weight of the sensors and environmental influences have been compared by Pérez et al. (2016).

This paper presents the University of Nottingham Future Automated Aircraft Assembly Demonstrator (FA^{3}D), a real-world aircraft structure assembly cell. The demonstrator smartly combines the industrial robots' relatively low cost and high flexibility through programming and changeable end-effectors with a high precision metrology system to reach the narrow tolerances in terms of absolute accuracy repeatability in use in the aerospace assembly processes. This specific layout hence compresses the capabilities of a traditional assembly line into a single reconfigurable multi-purposes cell resulting in massive cost, space, and throughput improvements (see Fig. 2).

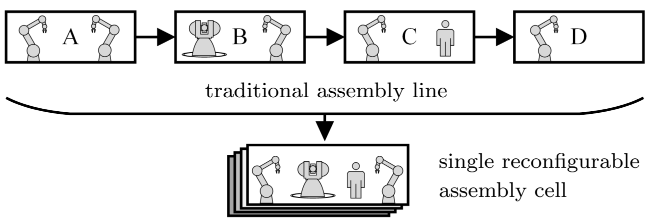


Fig. 2. Compression of an assembly line down to an assembly cell

Section 2 of the paper briefly introduces the concept of Evolvable Assembly Systems, to whom the FA^{3}D belongs. Section 3 outlines the features of the demonstrator and describes how the positioning accuracy of the robots can be greatly enhanced by the integrated photogrammetry and laser measurement systems. Section 4 focuses on the high-precision MAA procedure and how to deal with the dimensional uncertainties of the aircraft components. Finally, conclusions and work remaining to be done are discussed in section 5.

2. EVOLVABLE ASSEMBLY SYSTEMS

The concept of Evolvable Assembly Systems (EAS) introduced by Chaplin et al. (2015) is a novel approach to a transformable manufacturing environment enabling the production of high-complexity and high-variability products more effectively than it has previously been possible. The transformability property of EAS lies in their ability to respond to any change in product, process, or market and to any disruption at all times. This is achieved through a foundation of context-aware adaptation scheme managed by distributed agent-based control.

As shown in Fig. 3, the context-aware adaptation scheme of EAS is cyclic in nature. The phase *Operation* represents the normal execution of the processes within the manufacturing system. The configuration of the production line is settled and the resources complete their function, creating value for the business. At the same time, the phase *Monitor* is active and records information about the manufacturing system as it operates, e.g. current state and performance of the system, or operations performed on the components. Once the system has gathered enough data and identified a gap between the current and target performance or a possible improvement to be made, the *Internal adaptation* phase may be activated. A set of modifications to be done during the *Reconfiguration* phase will then be generated to mitigate or exploit the identified feature. Alternatively, the *Definition* of external pressures may be desired by the system operator, e.g. evolution of the product specifications, or changes to the capabilities of the available resources. As a response to the external stimuli, the *External adaptation* phase will produce a set of changes to be carried out during the *Reconfiguration* phase, e.g. a physical rearrangement of the resources, or an alteration to the parameters in the software. Depending on how the manufacturing system has been set up, the *Reconfiguration* phase may occur automatically or after the approval of the operator.

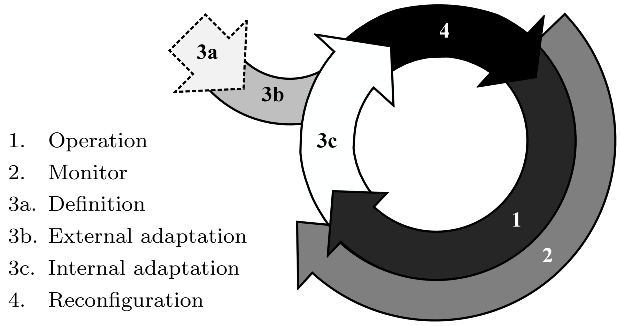


Fig. 3. The adaptation cycle of Evolvable Assembly Systems

The core of the EAS architecture is the intelligent agents environment. As defined by Wooldridge and Jennings (1995), intelligent agents are autonomous pieces of software that interact with their environment and proactively act upon defined goals. They also have the interesting ability to communicate with each other and control a resource, e.g. an operator with a smart device, or manufacturing equipment ruled by a Programmable Logic Controller. Therefore, by using distributed agents as part of the management unit, intelligence and communication capabilities are distributed throughout the manufacturing system, resulting in a reliable and resilient framework. Further details on this particular, innovative architecture can be found in the paper written by Chaplin et al. (2015).

3. EAS FOR AEROSPACE: THE FA^{3}D

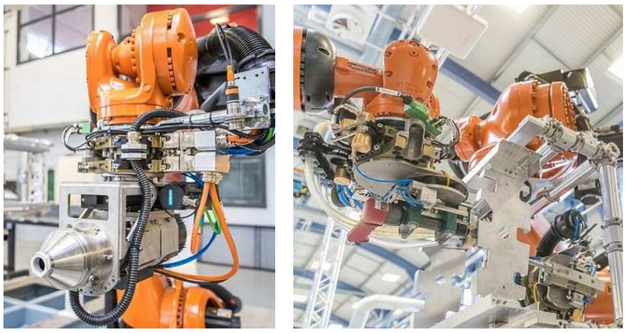
The Future Automated Aircraft Assembly Demonstrator (FA^{3}D) has been designed to allow a single cell production environment to automatically assemble a wide range of aerospace products. The objective being to replace the traditional large, dedicated, monolithic steel aerospace assembly fixtures that offer no feedback on the structure condition. To this end, it achieves the safe handling and the accurate positioning of the aircraft components and operating processes, such as drilling and fastening. Indeed, the reachable absolute accuracy and repeatability is respectively below ± 0.1 mm and ± 0.05 mm, which is suitable for the narrow tolerances imposed by aircraft manufacturers. In addition, the assembly cell is intended to be able to reconfigure from both the hardware and software perspectives, and evolve rapidly in time according to the market demand. Finally, the FA^{3}D has an independent metrology system that inspects the structure at each step of the building process, stopping it should anything fall out of tolerance. This environment, using a smart combination of standard industrial robots, high precision metrology system and control system, offers an attractive alternative to the classical outdated under-utilised assembly lines.

Fig. 4. Reconfigurable assembly cell of the Future Automated Aircraft Assembly Demonstrator developed by the University of Nottingham

3.1 Industrial Robots & Metrology Systems

As shown in Fig. 4, the FA^{3}D features three KUKA industrial robots, each of which can be used as adaptive fixtures. The additional functions of the two KR270 robots are to perform the drilling and riveting processes of the aircraft components in order to complete the whole assembly. Drouot et al. (2017) gave a detailed description of the drill end effector, presented in Fig. 5(a), and of the rivet end effector, shown in Fig. 5(b), and their features. The use of these standard robots, able to automatically swap end effectors to execute different applications, offers a level of flexibility that classical outdated assembly methods cannot. Yet, off-the-shelf industrial manipulators are affected by internal and external errors as explained by Sciavicco and Siciliano (2000) and Greenway (2000), and cannot achieve the required absolute accuracy nor repeatability unaided.

A first approach to damp down the influence of these errors is to theoretically and/or experimentally quantify them and compensate for them in the control algorithm. Consequently, some of the flaws, their effects, and how to neutralise them, were substantially investigated in literature, e.g. the manufacturing tolerances, the backlash, and the drivetrain nonlinearities by Ahmad (1988), the joints stiffness by Dumas et al. (2010), the elastodynamic properties by Rognant et al. (2010), the effects of temperature by Gong et al. (2000) ...



(a) Drill end effector (b) Rivet end effector

Fig. 5. Drill (on the left) and rivet (on the right) end effectors in the FA^{3}D

A second approach, requiring no calibration nor computation and dealing with all the aforementioned errors at once, is to use a high-precision photogrammetric system to automatically rectify the pose of the robots. The technology in use in the FA^{3}D is the Adaptive Robot Control (ARC) solution, provided by Nikon. This optical CMM is able to locate the positioning, drilling and riveting end effectors in a Cartesian coordinate system with a volumetric accuracy of 95 μm. The system relies on three CCD[1] cameras (see Fig. 6), each one scanning in a different plane, triangulating the position and the orientation of multiple infrared LEDs at the same time. Hence, by attaching a set of LEDs onto the objects of interest, the ARC solution gives the relative position of the end effectors in the workpiece coordinate system. Furthermore, if a specific target position is defined, the difference between the measured and target positions, i.e. the position error, is determined and compensated for by the robots if the required tolerance is exceeded. This tolerance, set by the system administrator, is contingent upon the assembly tolerance specification and can be lowered down to values below ± 0.1 mm.

Another, and independent, metrology system within the assembly cell is a Nikon laser radar MV331 (see Fig.

[1] Charge Coupled Device

Fig. 6. Nikon K-CMM camera in the FA^{3}D

7), providing automated and non-contact measurement capability for large-volume applications. This technology is well suited for the FA^{3}D operations as it can take accurate measurements from novel materials such as carbon fiber following inspection plans generated offline using CAD. While the ARC solution is used to measure and correct the positioning of the robotic manipulators, the purpose of the laser radar is to look over the assembly while it is being built. With this philosophy, it is possible to identify and fix any manufacturing anomalies at any step of the process, hence significantly reducing the number of irregularities in the final assembly and the amount of post-processing required. A report outlining the measurements and the deviation from nominal can also be generated upon requested. An excerpt of this report is shown in Fig. 8, where the CAD model of the assembly has been blurred for obvious confidentiality reasons.

Fig. 7. Nikon laser radar MV331 in the FA^{3}D

3.2 Additional features

Beside a reliable safety system and an efficient communication network both described by Drouot et al. (2017), the FA^{3}D is equipped with a radio-frequency identification (RFID) system which performs two functions. Firstly, because the end effectors and components are tagged, the system has the ability to detect and 3D track them within the cell. This way, the system is able to send an alert to the operator if an end effector or a component required for the build is missing, or in the wrong location. Secondly, the RFID tag on each of the aerospace component contains relevant information pertaining to its condition, e.g. part number, issue number, operations to be performed, or inspection data. Once a sub-assembly is finished, it is also RFID tagged with the addition of process data, i.e. constituent parts, non-conformities, and concessions. This then accompanies the sub-assembly throughout the whole assembly process, contributing to the entire product DNA. This also aids the inspection and verification procedures, as well as the airworthiness certification and maintenance course of actions. Furthermore, all the data stored within the RFID tags can be retrieved and shared among the resources of the manufacturing environment, contributing to the *Big Data* of the *Industry 4.0*.

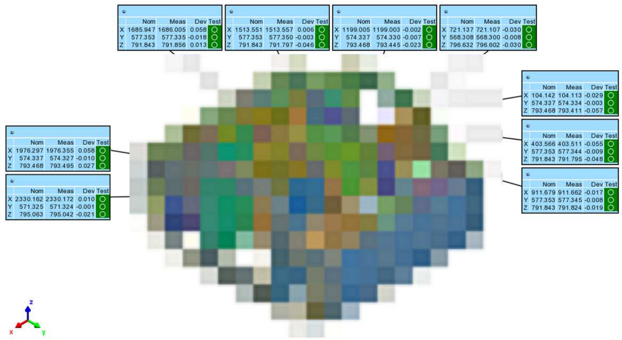


Fig. 8. A typical instance of the report generated by the laser radar in the FA^{3}D

4. THE MEASUREMENT ASSISTED ASSEMBLY PROCEDURE

The assembly process of an aircraft structure can be summarised to some extent as aligning the structural components with each other, checking they are correctly positioned, and fastening them together. The high-precision positioning of the components and end effectors, e.g. for drilling, riveting and sealant applying operations, hence represents the essential task during the whole assembly process. This section focuses on how the FA^{3}D metrology systems guarantee a positioning accuracy better than $\pm\,0.1$ mm despite the errors inherent to the 6-axis industrial manipulators.

4.1 Preliminary Work

Before the positioning process begins, a coordinate system must be defined in the production environment, as well as on each end effector to be used. This is achieved by manually probing specific geometric features such as holes, lines, and planes, selecting the correct orientation of the coordinate system's axes, and choosing the location of its origin. Great care should be given to the probing step as it determines the exactitude, and therefore the effectiveness of the positioning process. Having in mind the fact that the probing stage has to be performed only once (before the first use of each end effector), spending extra time and effort to achieve a better accuracy is always worthwhile. Furthermore, in order to simplify the programming of the robots, the origin of the environment and end effectors' coordinate systems should match the one of the CAD files. Indeed, with such approach, all the information in the CAD files can function as location targets for the robotic manipulators and the metrology systems.

The next step is to attach multiple infrared LEDs to the production environment and to the end effectors, and relate them to the coordinate systems. During the positioning process, all the LEDs will be tracked and triangulated by the K-CMM camera, hence providing an accurate relative position and orientation of the end effectors in the environment coordinate system. The main issue to be adressed in this stage is to make sure that occlusion of one or more LEDs never occur when the robots are moving and interacting with the environment. As it will be explained in the next section, the ARC technology is only used at the very end of the positioning process when the end effectors are close to their final position. Hence, the option that was used was to bring the robots in the exact same state as the one in which they would be just before the call to the Nikon metrology solution, and visually investigate the most appropriate locations for the LEDs. Appropriate locations are such that the LEDs are 3D spread all around the manufacturing environment and the end effectors, hence maximising the covered volume and therefore the positioning accuracy. Also, as distance decreases significantly the accuracy of the measurement, the position of the K-CMM camera must be as close as possible to the working area. But to be able to detect all the infrared LEDs at the same time, the K-CMM camera has to be placed further away from the working area as the field of view increases with distance. Therefore, a difficult trade-off between distance of the K-CMM camera and accuracy of its measurement has to be found. A different option, more time consuming but more effective, would be to model the production environment with a CAD software and determine the optimal LED placement by algorithm.

4.2 Positioning Process

Considering the assembly of aircraft components delivered to CAD nominal specifications, the positioning process, as sketched in Fig. 9, can be structured as follows:

1. Pick up the component at specific jigging holes located on it. In order to guarantee high holding, pull-in, and locking forces, the FA^{3}D uses the zero-point clamping system from AMF.
2. Drive the industrial robots from the current position to a well-chosen close neighbourhood of the target position defined by the CAD data (see $\langle\mathbf{1}\rangle$ in Fig. 9). Indeed, in case of overshoot from the robotic manipulators, aiming at the exact target position may damage the component. The generation of the motion path is out of scope of this paper but some examples are described by Biagiotti and Melchiorri (2008) and Kröger (2010).
3. Drive the industrial robots, now controlled by the ARC technology and the K-CMM camera, to the CAD target position and let the system operate until the desired tolerance is achieved (see $\langle\mathbf{2}\rangle$ in Fig. 9). As the neighbourhood of the target position is well-chosen in the previous step, there is absolutely no risk of collision when the robots automatically adjust their position during the iterative process.
4. Inspect the assembly with the MV331 laser radar to make sure the location reached by the component suits the CAD data and all key characteristics have been achieved (see $\langle\mathbf{3}\rangle$ in Fig. 9).

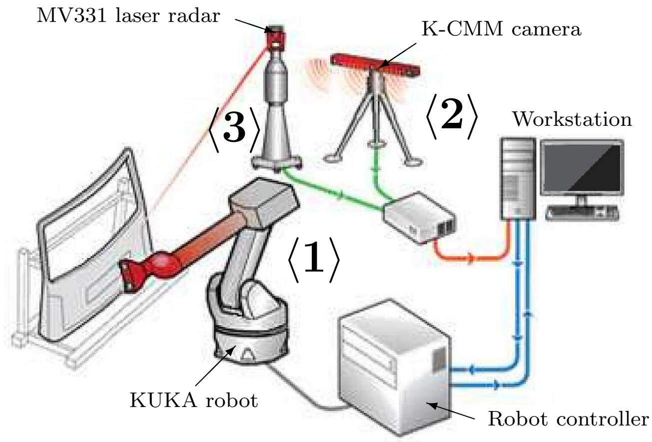


Fig. 9. Diagram of the FA^{3}D positioning system

4.3 Addressed Issues

In practise, aerospace components are manufactured according to their own tolerance and rarely have zero deviation from nominal, meaning that the CAD target position may not be the best position for the components. Indeed, these inherent manufacturing uncertainties may be the cause for the component to collide with the assembly, or for theoretically matching holes to end up misaligned. In that case, a measuring step, performed by the MV331 laser radar, is added before the final move to improve the robustness of the demonstrator. Some points specifically located on the components as well as their corresponding points on the assembly are recorded, and the application of the algorithm developped by Kabsch (1976) and enhanced by Kabsch (1978) provides the best fitting rigid transformation, i.e. the new target position, that best aligns the two sets of points. In any case, an absolute accuracy and repeatability below ± 0.1 mm can be achieved by the industrial robots in the FA^{3}D, as shown in Fig. 10. This figure displays the results of a repeatability test in which a robot, driven by the ARC technology, brings a 2400×800 mm aircraft component to a specific target position. It has to be noted that the initial position and orientation of the component are different at each time, proving that the positionning accuracy is independent from the direction of the move.

5. CONCLUSION

This paper briefly introduced the concept of Evolvable Assembly Systems (EAS), a novel approach to a manufacturing environment that is able to respond rapidly to changes in product, process, and market. A real world application of such a concept was presented through the Future Automated Aircraft Assembly Demonstrator, a single cell production environment able to automatically assemble a wide range of aerospace products. It has been shown that this system offers the adaptability and reconfigurability required to face the increasing pressure to manufacture more specialised and efficient products, often with shorter lifecycles, at a relatively reduced cost.

The research perspectives inherent to this system are multiple to improve its efficiency. For instance, it is well known

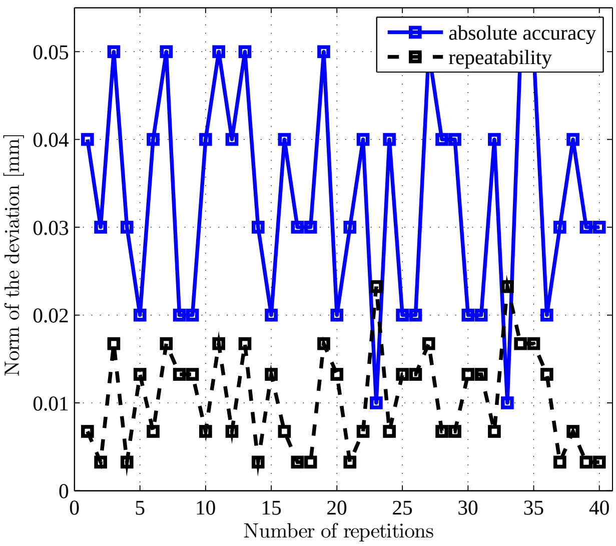


Fig. 10. Absolute accuracy and repeatability performance of the FA^{3}D positioning system for a 2400 $\times$ 800 mm aircraft component

in the aircraft industry that some of the most important functions associated with manufacturing, inspection and maintenance are conducted in confined spaces. Maintaining the same level of performance in such confined spaces represents a real challenge for the FA^{3}D as the TCP would not be visible to the camera. Also, currently run independently, the laser radar could be integrated into the cell control system for automated confirmation of assembly completion and automated permission or ban to proceed with the next step. In addition, by communicating information to each other, the industrial robots could also work in collaboration for specific operations such as rotation of assemblies for fuselage inspection, hence enhancing the capability of the FA^{3}D. Likewise, depending on past assemblies and their corresponding inspection reports, the system could generate by itself the operationnal planning in order to optimize the assembly process. Eventually, as the University of Nottingham is making strategic capability investments in the area of advanced informatics-enabled manufacturing, the demonstrator, currently fit for aerospace applications, will have the capability to address other manufacturing domains such as automotive, naval and energy.

REFERENCES

Ahmad, S. (1988). Analysis of Robot Drive Train Errors, their Static Effects, and their Compensations. *IEEE Journal of Robotics and Automation*, 4(2), 117–128.

Biagiotti, L. and Melchiorri, C. (2008). *Trajectory Planning for Automatic Machines and Robots*. Springer.

Chaplin, J.C., Bakker, O.J., de Silva, L., Sanderson, D., Kelly, E., Logan, B., and Ratchev, S.M. (2015). Evolvable Assembly Systems: A Distributed Architecture for Intelligent Manufacturing. *Proceedings of the 15th IFAC Symposium on Information Control in Manufacturing, Ottawa, Canada*, 48(3), 2065–2070.

Drath, R. and Horch, A. (2014). Industrie 4.0: Hit or Hype? *IEEE Industrial Electronics Magazine*, 8(2), 56–58.

Drouot, A., Irving, L., Sanderson, D., Smith, A., and Ratchev, S. (2017). A Transformable Manufacturing Concept for Low-Volume Aerospace Assembly. *Proceedings of the 20th IFAC World Congress, Toulouse, France*.

Dumas, C., Caro, S., Chérif, M., Garnier, S., and Furet, B. (2010). A Methodology for Joint Stiffness Identification of Serial Robots. *Proceedings of the IEEE-RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan*, 464–469.

Gong, C., Yuan, J., and Ni, J. (2000). Nongeometric Error Identification and Compensation for Robotic System by Inverse Calibration. *International Journal of Machine Tools & Manufacture*, 40(14), 2119–2137.

Greenway, B. (2000). Robot Accuracy. *Industrial Robot: An International Journal*, 27(4), 257–265.

Kabsch, W. (1976). A Solution for the Best Rotation to Relate Two Sets of Vectors. *Acta Crystallographica*, A32, 922–923.

Kabsch, W. (1978). A Discussion of the Solution for the Best Rotation to Relate Two Sets of Vectors. *Acta Crystallographica*, A34, 827–828.

Kröger, T. (2010). *On-Line Trajectory Generation in Robotic Systems*. Springer.

Malamas, E.N., Petrakis, E.G.M., Zervakis, M., Petit, L., and Legat, J.D. (2003). A Survey on Industrial Vision Systems, Applications and Tools. *Image and Vision Computing*, 21(2), 171–188.

Maropoulos, P.G., Muelaner, J.E., Summers, M.D., and Martin, O.C. (2014). A New Paradigm in Large Scale Assembly - Research Priorities in Measurement Assisted Assembly. *International Journal of Advanced Manufacturing Technology*, 70(1), 621–633.

Meffert, G., Mbarek, T., and Biyiklioglu, N. (2012). High Precision Positioning System for Aircraft Structural. *Proceedings of the 15th International Conference on Experimental Mechanics, Porto, Portugal*.

Mei, Z. and Maropoulos, P.G. (2014). Review of the Application of Flexible, Measurement-Assisted Assembly Technology in Aircraft Manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 228(10), 1185–1197.

Muelaner, J.E., Martin, O.C., and Maropoulos, P.G. (2013). Achieving Low Cost and High Quality Aero Structure Assembly through Integrated Digital Metrology Systems. *Proceedings of the 46th CIRP Conference on Manufacturing Systems, Sesimbra, Portugal*, 7, 688–693.

Pérez, L., Rodríguez, I., Rodríguez, N., Usamentiaga, R., and García, D.F. (2016). Robot Guidance Using Machine Vision Techniques in Industrial Environments: A Comparative Review. *Sensors*, 16(335).

Rognant, M., Courteille, E., and Maurine, P. (2010). A Systematic Procedure for the Elastodynamic Modeling and Identification of Robot Manipulators. *IEEE Transactions on Robotics*, 26(6), 1085–1093.

Sciavicco, L. and Siciliano, B. (2000). *Modelling and Control of Robot Manipulators*. Springer.

Wooldridge, M.J. and Jennings, N.R. (1995). Agent Theories, Architectures, and Languages: A Survey. *Proceedings of the 3rd workshop on Agent Theories, Architectures, and Languages, Amsterdam, The Netherlands*, 1–32.