Towards Industry 4.0: The Future Automated Aircraft Assembly Demonstrator

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Abstract. As part of the Future Automated Aircraft Assembly Demonstrator developed by the University of Nottingham, this paper presents a new flexible production environment for the complete manufacturing of high-accuracy high-complexity low-volume aerospace products. The aim is to design a product-independent manufacturing and assembly system that can react to fluctuating product specifications and demands through self-reconfiguration. This environment features a flexible, holistic, and context-aware solution that includes automated positioning, drilling and fastening processes, and is suitable for different aircraft structures with scope to address other manufacturing domains in the future (e.g. automotive, naval and energy). The assembly cell features industrial robots for the handling of aircraft components, while intelligent metrology and control systems monitor the cell to ensure that the assembly process is safe and the target tolerances are met. These three modules are integrated into a single standardised interface, requiring only one operator to control the cell. Performance analyses have shown that, using the reconfigurable production environment described hereafter, a positioning accuracy better than ± 0.1 mm can be achieved for large airframe components.

Keywords: intelligent and flexible manufacturing systems, positioning systems, high accuracy, industrial robots

1 Introduction

Over the last decade, the merging of the virtual and physical worlds and the fusion of the technical and business processes have led the way to a new industrial age known as *Industry 4.0* [5]. This has been achieved through the deployment of Cyber-Physical Systems (CPS), creating a networked world in which intelligent objects communicate and interact with each other. Therefore, CPS-based production systems, being optimized according to a global network of reconfigurable and self-organizing production units, greatly exceed classic production systems in terms of flexibility, adaptability, autonomy, efficiency, reliability, safety, and costs. Such flexible and reconfigurable production systems 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.

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.

Highly automated, flexible systems hence offer an alternative solution for aircraft manufacturers to shorten the product lead-time, increase the product diversity and efficiency, all the while reducing the production costs. Some ideas were suggested to materialise these smart assembly systems, e.g. Flexible Manufacturing Systems [3, 21], Reconfigurable Manufacturing Systems [16] or Holonic Manufacturing Systems [14, 23]. A relevant comparison of the latter with the concepts of bionic and fractal manufacturing systems has been performed in [22]. However, only few of these approaches were dedicated to the manufacturing of aerospace products, and they generally provided no reconfigurability properties, just as the *Lean Automation* strategy [12], or were dedicated to one main task only. Indeed, the *Automated Flexible Assembly System* [9] was a concept designed to allow a single machine cell to fasten and assemble exclusively geometrically similar aircraft parts. As for the *EcoPositioner* developed by Dürr [15], it was a modular and reconfigurable system limited to the high precision positioning process of aircraft components during the assembly.

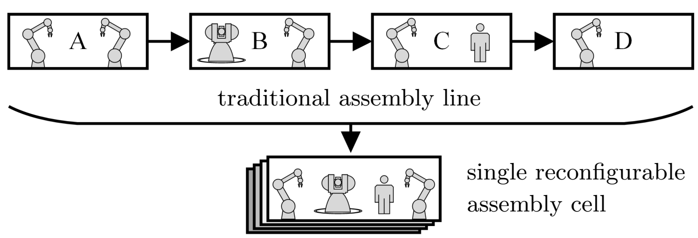


Fig. 1. Compression of an assembly line down to an assembly cell

This paper presents the University of Nottingham Evolvable Assembly Systems model and its grounding in the Future Automated Aircraft Assembly Demonstrator (FA^{3}D), a real-world aircraft structure assembly cell. The FA^{3}D 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. 1).

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 FA^{3}D in more detail and describes how it is able to adapt itself to multiple product families and variants. Section 4 focuses on the accurate positioning of the aircraft components and how to deal with their uncertainties. Finally, conclusions and work remaining to be done are discussed in section 5.

2 Evolvable Assembly Systems

The concept of Evolvable Assembly Systems (EAS) 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 [4]. 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.

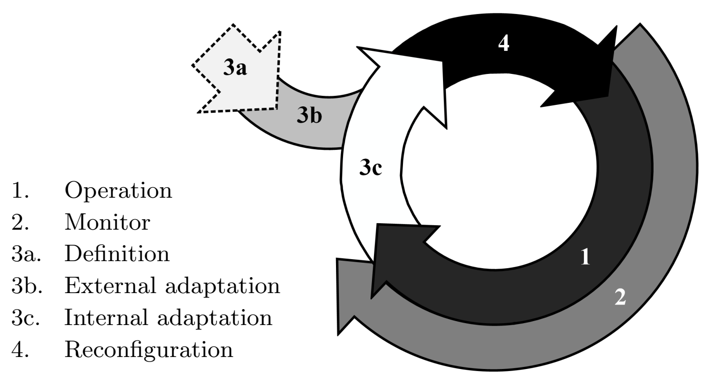


Fig. 2. The adaptation cycle of Evolvable Assembly Systems

As shown in Fig. 2, 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.

The core of the EAS architecture is the intelligent agents environment. Intelligent agents are autonomous pieces of software that interact with their environment and proactively act upon defined goals [24]. 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 [4].

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. The reconfigurable assembly cell of the FA^{3}D is shown in Fig. 3.

3.1 Industrial Robots & Operating End Effectors

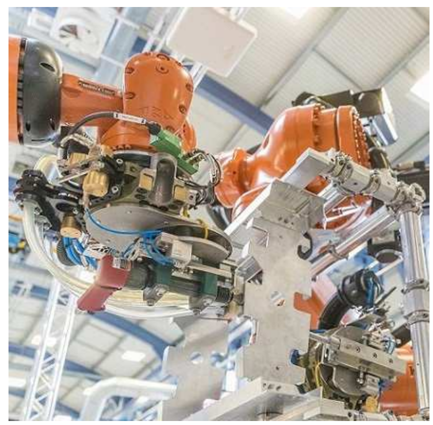
The FA^{3}D features three off the shelf industrial robots, each of which can be used as fixtures for the accurate positioning of aircraft components. The larger

Fig. 3. Reconfigurable assembly cell of the Future Automated Aircraft Assembly Demonstrator developed by the University of Nottingham

one is a KUKA KR1000 Titan, able to carry loads up to 1 000 kg, while the other two are the KUKA KR270 R2700 Ultra, controlled by a KR C4 unit. The function of the Titan is to convey the structures that can not be held by the two smaller robots and transfer the assembly out of the cell when completed. It can also be used to support the workpiece between the two operating robots while they work on it, thereby functioning as an adaptive fixture. The additional functions of the KR270 robots are to perform the drilling and riveting processes of the aircraft components in order to complete the whole assembly. The operation to be carried out dictates to the robots the appropriate end effector to retrieve, where to find it, and specifies its target position. The use of these robots, being able to automatically swap end effectors to execute different applications, offers a level of flexibility that classical assembly methods cannot. Furthermore, it has to be noted that the two KR270 robots are fastened onto pre-drilled plates allowing them to be moved forward or backward to adapt the work envelope to the required configuration. Indeed, while the metrology and control systems remain approximately the same for any task to be done, the set up of the production environment strongly relies on the task and may need reconfiguration. Additionally, in order for the FA^{3}D to handle a wide range of aerospace products, three sizes of bits, and therefore three sizes of rivets, are available within the assembly cell. Each end effector and each size of bits, having a different internal resistance, can be automatically identified by the robots, hence avoiding any process errors.

The drill end effector, presented in Fig. 4(a), has interchangeable countersunk drill bits depending on the size of the hole to be drilled. Those holes, ranging from 5 mm up to 8 mm, are made using a one shot process by sliding the spindle linearly towards the aircraft component. This mechanism ensures that the parallelism between the spindle axis of the drill and the normal axis of the component is preserved during the operation. Beforehand, the end effector, through its nosepiece, and its counterpart on the other KR270 robot will have come in contact with the workpiece to apply a suitable clamp load on it. Naturally, the clamp force, the spindle feeds and speeds, as well as the depth of the holes (up to 15 mm), are controlled during the process and depend on the required geometry and material properties. Swarf and dust collection and extraction is built in to the drill nosepiece end effector.

(a) Drill end effector



(b) Rivet end effector

Fig. 4. Drill and rivet end effectors of the FA^{3}D

The rivet end effector, shown in Fig. 4(b), is directly connected to three rivets feeders corresponding to the three sizes of drill bit available on the drill end effector. Once in position, the robot requests the delivery of a rivet from the appropriate feeder and blows it into the hole. In order to form the rivet and therefore fasten the components together, the two robots work in a synchronized way. While the first robot slides slightly over to align the air hammer with the head of the rivet, the second robot brings the rivet forming end effector against the back of the assembly. Controlled forming pressure is then applied by both end effectors using pneumatic cylinders and the first robot runs the air hammer for the required time, which is also controlled.

3.2 Metrology Systems

In order for the positioning, drilling, and fastening operations to be effective, the end effector must reach the process location accurately and repeatably. Yet, off the shelf industrial robots are affected by inherent errors [20] and cannot achieve the absolute accuracy nor repeatability required by aircraft manufacturers unaided. Internal sources of errors in robotic manipulators include the manufacturing tolerances of its linkages, the stiffness of its segments and joints, the presence of backlash in its gears, the inability of its controller to compute and achieve the correct joints value ... External sources of errors are usually changes to the working environment such as temperature and humidity fluctuations [8, 17].

A first solution to mitigate these errors is to characterise theoretically and/or experimentally some of these flaws and compensate for them in the control algorithm. Hence, the effects of the manufacturing tolerances of the robot arms, the backlash, and the drivetrain nonlinearities on the end effector position were investigated in [1]. A methodology to identify and compensate for the joints stiffness of serial robots, directly responsible for the displacements of the end effector, was suggested in [6], and later in [18]. A systematic procedure for the elastodynamic modeling of robotic manipulators in order to neutralise the nonlinearities that affect them has been developed in [19]. As for the effects of temperature variation, they were investigated in [7], which also proposed a method to cancel them out by inverse calibration.

Fig. 5. K-CMM camera of the FA^{3}D

A second solution, requiring no calibration nor calculation and coping with all the aforementioned errors at once, is to use a high precision metrology system to automatically correct the positioning of the robots in real-time. The metrology technology that is used in the assembly cell is the Adaptive Robot Control (ARC) solution, provided by Nikon. The main element of this measurement system is the K-CMM camera, an optical device made up of three CCD[3] cameras triangulating the position and the orientation of multiple LEDs at the same time (see Fig. 5). Hence, by attaching LEDs to the workpiece and to the end effectors, ARC provides an accurate relative position of the end effectors in the workpiece coordinate system. Furthermore, if a target position is specified, the

[3] Charge Coupled Device

difference between the measured and target positions, i.e. the position error, is determined and automatically corrected for by the robots if it exceeds a defined tolerance. This tolerance is chosen by the operator according to assembly tolerance specification and can be lowered down to values below ± 0.1 mm. This solution, relying on optical measurement, is therefore completely independent of the flawed kinematic chain of the robotic manipulators. Besides, the K-CMM camera can be moved around to overcome line of sight issues and still be able to accurately measure data providing that the LEDs are visible. This feature is of paramount importance for the reconfigurability and the adaptability of the production environment.

Fig. 6. Nikon laser radar MV331 in the FA^{3}D

A second, and independent, metrology system available within the FA^{3}D is a laser radar MV331, also provided by Nikon (see Fig. 6). This equipment offers automated and accurate non contact measurement capability for large-scale geometry 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 K-CMM camera are used to measure and correct the positioning of the industrial robots, the function of the laser radar is to inspect the aircraft assembly while it is being built. It is then possible to detect, and fix, any manufacturing irregularities at each step of the process, hence greatly reducing the number of defects in the final structure as well as the amount of rework required. As the MV331 does not require any target for its measurements, it can be moved around within the cell, locate itself, and still be able to provide reliable data about the assembly. 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. 7, where the CAD model of the assembly has been blurred for obvious confidentiality reasons.

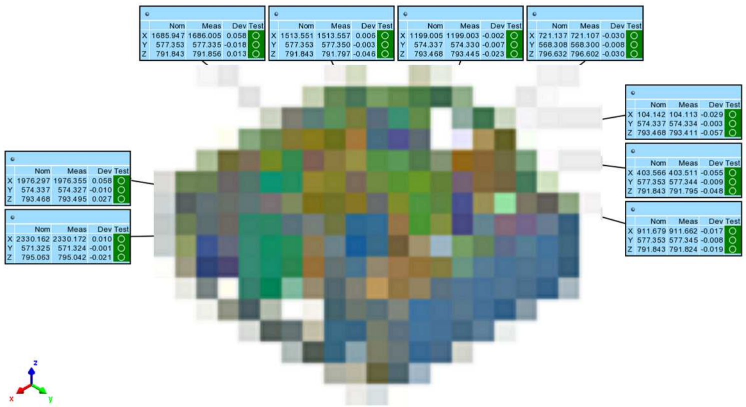


Fig. 7. A typical instance of the report generated by the laser radar in the FA^{3}D

3.3 Safety

As the safety of the personnel on the workshop floor is imperative, the industrial robots and the metrology systems are located inside a guarded area monitored by four S3000 laser scanners from Sick. These compact systems, by scanning their surroundings, are the assembly cell primary interlock, whose function is to stop all machinery within the guarded area if anyone steps inside. If the beam is interrupted, the laser scanners communicate the information to the PLC, which will send the signal to the robot controllers to safely stop and inhibit any motive power to the robots. The PLC will also isolate the pneumatic power to the cell so that the end effectors do not fall off the manipulators to harm any personnel or damage any equipment. Some specific zones explicitly marked as safe can however be configured into the Sick system for operator access to encourage human machine collaboration. In addition to the safety scanners, the fence of the FA^{3}D has two cable pull switches, each one having a steel wire rope connected to latching pull switches. Pulling on the rope in any direction and at any point along its length will trip the switch to cut off the machine power.

3.4 Communication

The communication between the laser scanners and the PLC is done over the PROFIsafe network, so is the communication among the PLC, the spindle slide servo drive and the spindle inverter drive. Indeed, the servo and inverter control units are each fitted with an Ethernet IP communication card, enabling the use of PROFIsafe. Each of these cards has two Ethernet ports and therefore can be connected in a ring topology using a standard Ethernet switch. In addition, as all the wiring for the PROFIsafe ring is inside the control panel, there is little chance of the cables getting damaged, therefore redundancy is not required. With that architecture, the management system, through the Ethernet communication, can control the spindle feeds and speeds, depending on the material to be drilled. Still using the Ethernet communication, the management system also controls each of the robots by sending specific commands, each with its own parameters structure, defining the operations to be carried out. Those commands, and all the associated data, is passed to the PLC which then forwards on the relevant commands to the robot controllers. Finally, the communication between the robots and the positioning metrology system is performed over Ethernet, the ARC metrology technology being called on by the robot program.

3.5 Radio-Frequency IDentification

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*.

4 Positioning Technology

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 ± 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. 8, 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^3D 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 ⟨**1**⟩ in Fig. 8). 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 in [2] and [13].
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 ⟨**2**⟩ in Fig. 8). 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 ⟨**3**⟩ in Fig. 8).

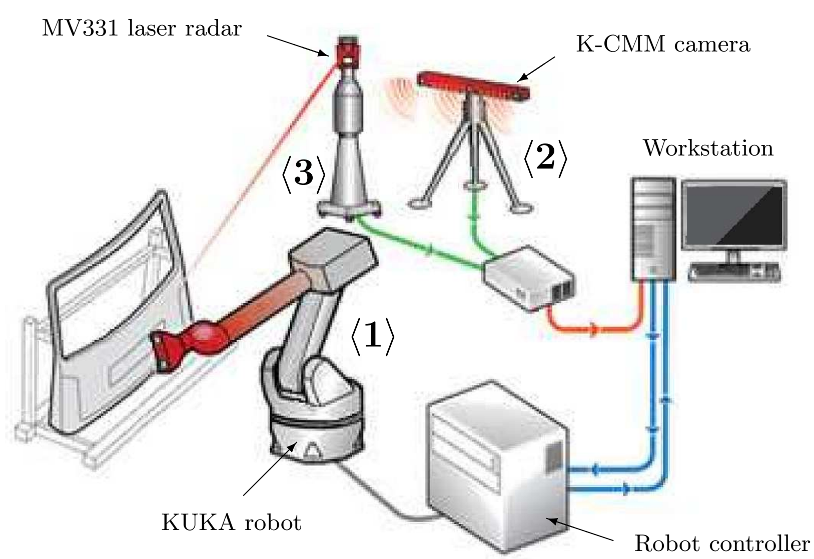


Fig. 8. Diagram of the FA^3D positioning system

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 [10] and enhanced by [11] 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. 9.

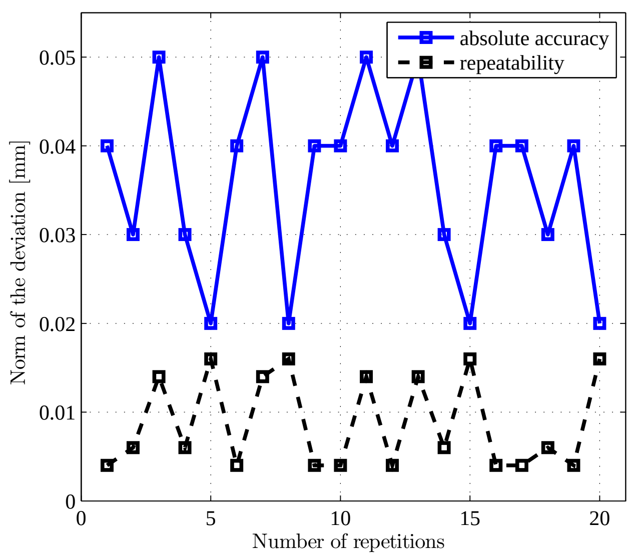


Fig. 9. Absolute accuracy and repeatability performance of the FA^{3}D positioning system for a 2400 $\times$ 800 mm aircraft component

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 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.

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