Production-Related Testing and Optimisation Environment for Hardware and Software in Aircraft Production of Today and Tomorrow

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***Abstract* – In response to the predicted growth trends in the aerospace industry, a gradual implementation of future industrial production systems with a strong focus on robotics and automation is inevitable. These technologies enhance production performance by automating repetitive tasks, allowing workers to concentrate on more complex activities. This paper introduces a new automation concept and validation system for aircraft structural assembly, set up at the Center for Applied Aviation Research in Hamburg. This system enables the validation of the research topics in the dtec.bw-funded project iMOD and includes recent key innovations developed by Airbus like the Multi-Function End Effector, which can perform multiple processes.**

Keywords – Aircraft production, structural assembly production optimisation, robotics, automation

I. INTRODUCTION

The aircraft industry deals with the challenge of achieving high accuracy in the assembly of extremely large products. Efforts to address this challenge using robotics designed for the automotive industry have proven unsuccessful due to fundamental differences in the requirements and nature of the components involved. Specifically, the components in the Major Component Assembly (MCA) and Final Assembly Line (FAL) are unique due to their size and exhibit production-related geometric deviations. Despite these challenges, the assembly process requires a high level of precision and quality [1].

The importance of precision in the aircraft industry cannot be overstated. Even minor errors can lead to significant safety risks and increased production costs, necessitating the development of specialized automation systems tailored to the unique challenges of aircraft assembly.

One of the primary issues for the specialized automation system are the geometry deviations that occur during the production of large aircraft components. These deviations can significantly impact the assembly process, making it difficult for standard robotic systems to achieve the required precision. Therefore, there is a need for adaptive, modular, and flexible automation solutions that can accommodate these deviations and ensure accurate assembly.

In the dtec.bw-funded project "Intelligent modular robotics and integrated production design in aircraft construction" (iMOD) research is being conducted on how to optimise the automated structural assembly in aircraft manufacturing through the use of advanced digital engineering methodologies, including Model-based System Engineering (MBSE), AI Planning, and simulation models.

A robotic system developed by Airbus is used as a validation platform for the research results of iMOD. This platform is capable of performing both longitudinal and orbital joining processes of the aircraft fuselage within a single station. Currently, this validation platform, including the new robotic system and a fuselage, is being set up as a research demonstrator at the Center for Applied Aviation Research (ZAL).

The remainder of the paper is organized as follows: Section II provides a state-of-the-art overview of production systems for structural assembly at Airbus. Section III presents detailed insights into the iMOD validation platform. Section IV outlines the research topics that are being investigated as part of the project and evaluated on the validation platform. Section V summarizes the results and outlines future research directions.

II. STATE OF THE ART AT AIRBUS

In the area of part and sub-assembly production, automation is already state of the art. For example, shells for the aircraft fuselage with stiffening elements are already assembled fully automated. These automatic drilling and riveting machines are very large and usually the workpiece, in this case the shell, is moved to the tool, which is the drilling and riveting end effector.

For the future of production, automation solely at the component level is not sufficient. A consistent portfolio of automation along the whole value chain is required. This contribution deals with the automation for connecting the longitudinal and orbital joints in the MCA and/or the FAL. The target is to perform most operations in one station with one single system, where today several automation solutions and manual work are required. The main advantage of this station is that it combines different automated drilling and riveting processes to minimize human-robot interaction and achieve efficient system utilization.

One of the systems used at Airbus is the Flextrack (see Figure 1), which is primarily employed for longitudinal or orbital joints on A320 family fuselage pre-assembly lines. Flextrack robotic systems consist of flexible rails that can be easily disassembled and reassembled around the aircraft, allowing lightweight and modular drilling robots to move alongside the fuselage, without the need for separate holding devices [2].

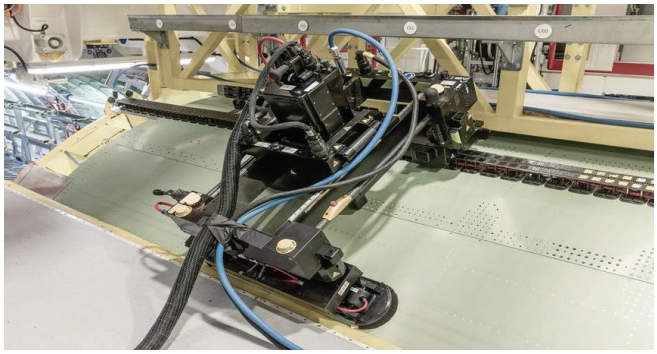

FIGURE 1: FLEXTRACK SYSTEM ON LONGITUDINAL JOINT

Other systems mainly used for orbital joints are 6-axis-robots based on floor-mounted linear axis (see Figure 2). Due to the combination of reach and load capacity, the working area is limited. Furthermore, the size of the components requires several systems to carry out the work in a coordinated manner.

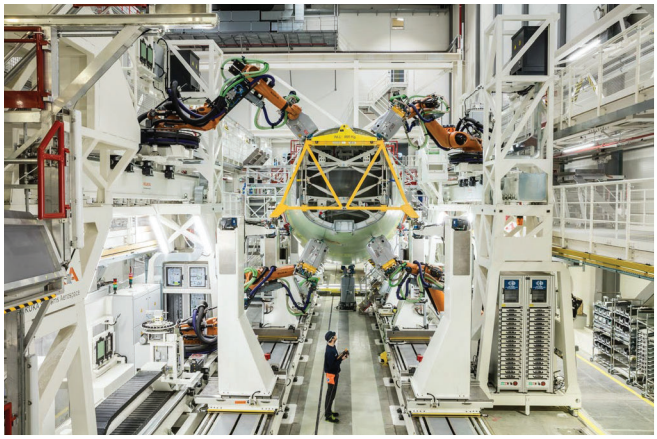

FIGURE 2: NEW AIRBUS STRUCTURE LINE A320 FOR ORBITAL JOINT [2]

End effectors that can reference, drill, and rivet are required to carry out the work efficiently. Given the weight of these multi-functional end effectors (MFEE), a strong support structure and handling technology is needed to enable the required accuracies and forces. Due to the weight of the end effector, the majority of services or repairs are performed directly on the robot in the event of malfunctions. This leads to reduced equipment effectiveness due to planned stops and delays in lead time in case of breakdowns.

Against the background of the production ramp-up, it is imperative to establish an efficient automation system. For example, the end effector should be easily replaceable with a spare part, allowing maintenance, repair, and overhaul (MRO) to be carried out outside the station, thus minimizing any impact on ongoing production.

III. IMOD VALIDATION PLATFORM

The dtec.bw-funded research project iMOD addresses the need to increase efficiency against the backdrop of an increasing number of variants. The focus here is on the use of advanced Industry 4.0 technologies and the digitalization and automation of manufacturing processes and production workflows.

The project has the following objectives:

- to digitally map resources, products, and processes via the MBSE approach which can be used in future early engineering phases,
- to support the optimisation of assembly and inspection activities and
- to develop corresponding algorithms for collaborative order execution and validation.

These objectives are to be achieved through a collaboration between the Helmut Schmidt University/University of the Federal Armed Forces (HSU/UniBw H) and Airbus. To facilitate this, a validation platform is currently being set up in Hall A of the ZAL. This platform will serve as a research demonstrator to validate the research results for achieving the project objectives. A virtual model of the validation platform is presented in Figure 3.

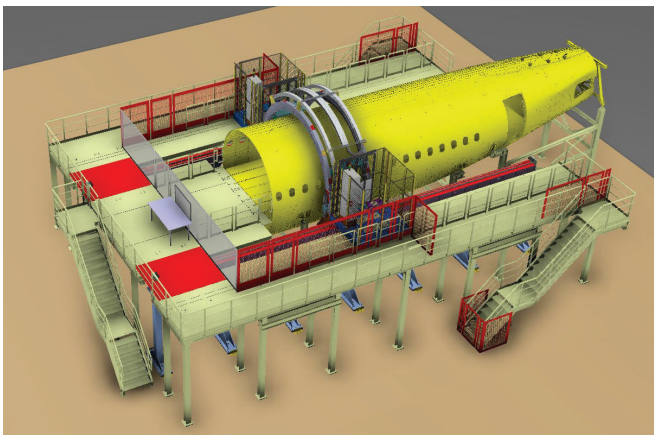

FIGURE 3: 3D MODEL OF THE IMOD VALIDATION PLATFORM

The iMOD validation platform includes a jig to provide access and carry the fuselage section 17-19 of an A320 and the robotic system. The complete robotic system, incl. actuators, MFEEs (co-developed with Setitec), and controls have been developed by Airbus and will be provided to the iMOD project.

The robotic system consists of an orbital gantry that moves on an auxiliary axis. The two MFEEs are installed on the gantry to enable process parallelization. Auxiliary devices required for the process, along with the control system, move with the gantry.

The scope of the automated tasks consists of performing drilling and fastening of the joints and will be split into sequences based on the provided NC-part program. The flow of each sequence, regardless of whether it involves a longitudinal or orbital joint, is fundamentally based on the repetition of the following tasks:

1. Load process parameter for sequence
2. Local referencing
3. Move to drilling point, read process parameters for current hole, and rotate carousel for correct cutter
4. Clamping on fuselage
5. Measure normality
6. Drilling and countersinking, including monitoring the process and collecting process data
7. Insert the fastener with applied sealant while receiving the fastener for the next hole
8. Rotate carousel and control squeeze sealant ring with camera of MFEE
9. Unclamping
10. Repeat beginning from Point 3 until sequence is finished

This process flow will be repeated until all sequences are done and the joint is finished. Each sequence will be performed by one MFEE.

A. Virtual Commissioning

Over the last decade, advancements in digitalization technology have enabled comprehensive testing, also known as validation and verification (V&V), of individual devices to entire plants within a virtual environment before actual implementation. Virtual Commissioning (VC) is one such technological advancement, designed to validate production system control programs through virtual simulation models. It is particularly useful for simulating complete automated manufacturing processes in aircraft production [1], [4]. Manufacturing systems in the aerospace domain are highly complex due to component size, tight tolerance requirements, process variation, and multi-tier manufacturing processes. Accurate simulations of robots and other programmable assets are needed to lower the risk of collisions and manufacturing downtimes [5]. Moreover, the VC environment allows re-evaluation of the control logic in case of design change, software updates, or new feature deployment without disrupting the actual production schedule. By testing and validating production systems virtually before physical construction, VC aims to reduce commissioning time and costs while improving system accuracy and reliability [6].

As mentioned earlier in the section, the iMOD robotic system carries two MFEEs on a gantry system. Robots are controlled by a custom controller chip with a specialized real-time Linux-based operating system. This controller is selected for its small, flexible, embedded computer for industrial applications that require high performance and reliability. It combines an ARM processor, an FPGA, and a high-density connector to interface with application-specific I/O. The gantry systems are operated by software PLCs and drive control systems with safety encoders. The overall manufacturing process and coordination are enabled through process orchestration and the control software. Since there are multiple robot controller systems and the co-simulation between control software and robotic simulations, a modular architecture using modelling and communication standards is proposed [7]. The VC system for this automation system is created as part of the project to support product development, commissioning, and operational scenarios. The VC testbed is the core of the validation platform allowing the utilization of Test-Driven Development (TDD) methodology for the project. It allows the implementation of a V-cycle for development and better testing of the concept. Furthermore, criteria such as modularity, ease of use, accuracy of simulation, as well as the cost of the simulation system are considered for the selection of the architecture.

Due to the lack of availability of accurate simulation models, a Hardware-in-the-loop (HiL) approach is used for the robot controller and the safety-relevant components due to their criticality (see Fig. 4). On the other hand, software-in-the-loop solutions are utilized for PLC control logic, motor simulation, as well as process orchestration software. The iMOD VC solution co-simulates these models to simulate accurate behaviour of the automation and robotic systems. Several standard interface and modelling technologies such as FMI/FMU, OPC UA, and Docker are utilized for successful co-simulation.

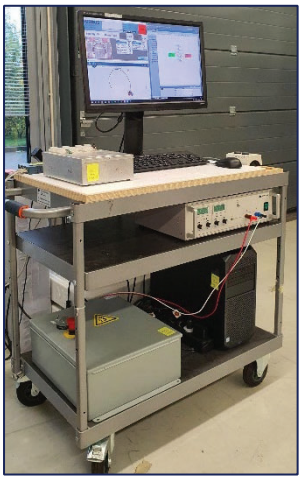

FIGURE 4: IMOD - VIRTUAL COMMISSIONING WORKBENCH

Standalone simulation models and software are run on the same simulation PC with standard containerization technology to reduce reliance on HiL. For both PLC and robotic system simulation, it is crucial to work closely with the solution supplier and the controller supplier to make overall solutions and individual components compatible with the simulation workbench. Due to the robotic systems, moving components, and the danger of collision, the simulation workbench is connected with a visualization platform to visualize robot motions and check for possible collisions with the environment. Here as well, a standard communication protocol such as OPC UA is used for simplicity of the solution.

A derivative of TDD is used for the validation of the system. The VC solution will first be used to validate elementary models such as motors, robot controllers, gantry drives, etc. Afterwards, integrated testing of one robotic system will be performed. Once the tests are successful and suggested changes are implemented, both robotic systems will be co-simulated for behavioural tests with NC programs before the system is made operational.

IV. RELATED RESEARCH WORK

The iMOD validation platform supports extensive academic research, including five Ph.D. theses and various bachelor and master theses, advancing future automation and digitalization in aircraft production. This section introduces the current research efforts within the iMOD project.

A. MBSE Modeling

In the initial phases of engineering, the application of MBSE methods proves to be highly advantageous. These methods facilitate the analysis of various production system configurations to evaluate their effectiveness in accommodating the significant variability stemming from individual customer requirements.

Typically, system engineers encounter difficulties in responding to changes within the system. Moreover, they often face challenges in identifying and assessing implementation alternatives, a process that can be time-intensive and requires considerable manual effort [8]. Consequently, the modelling and management of production resources have gained increasing importance in recent years [9]. This is particularly relevant in the aircraft manufacturing sector, where the future use of reconfigurable resources is anticipated to rise [10].

To address these challenges, a modelling workflow was developed to enable consistent modelling of production systems during the early engineering stages of aircraft manufacturing. This workflow aims to offer a comprehensive solution to the difficulties associated with modelling complex production systems, thereby supporting effective decision-making throughout the design process. This solution includes detailed modelling of individual resource components, their interfaces, and capabilities to identify suitable components [11].

To support and guide the modelling process, Domain Specific Modelling Languages (DSML) have been designed based on established standards. These languages address the existing need for standardization and the lack of terminology and reusability in the practical application of MBSE methods [12]. Two notable examples are the SysML profile, which facilitates process modelling in accordance with the VDI3682 standard [13], and the standardized description of robotic resources [14].

The iMOD validation platform model aids not only in system development but also in simulation purposes. Based on these simulation results, it becomes possible to determine the optimal tool configuration for the MFEE to minimize the need for reconfiguration. The tools required for executing the processes are derived from the product model, particularly from rivet information such as rivet type, diameter, and the number and position of the rivets [15].

B. AI-based Process Planning

In early engineering phases, it is crucial to compare different feasible system configurations to identify the most effective solutions [16]. For instance, while adding an additional MFEE to the gantry of the iMOD validation platform may reduce the lead time, it could also lead to increased idle times for other MFEEs. To make informed decisions and enable such comparisons, a preliminary process plan is needed to consider specific values for cycle times and resource utilization. This plan must define a sequence of processes necessary to manufacture the given product and allocate an appropriate resource to each individual process.

The description and algorithmic solution of such problems underlies the research area of AI Planning [17]. Within this area, the Planning Domain Definition Language (PDDL) has become the de facto standard for describing planning problems [18]. PDDL is a formal language used to represent the tasks, actions, and resources involved in a planning problem. However, modelling PDDL descriptions is often particularly challenging, time-consuming, error-prone [19], and can lead to data inconsistency issues [20].

To address these challenges, the iMOD research project focuses on developing methods to automate the generation of PDDL descriptions by leveraging existing engineering artifacts such as system models and product models. A workflow was developed in [21] that specifies the necessary steps to process existing knowledge and transform it into PDDL descriptions. System and product models are systematically enriched through a SysML profile for PDDL [22], enabling algorithms to accurately retrieve the required information. Consequently, PDDL descriptions for various system configurations can be created during the engineering phase of the robotic system. These descriptions are used to generate process plans, allowing for performance assessments of the system.

C. Continuous Virtual Commissioning in Operation

VC is traditionally used in the early development phases up to the commissioning phase of automated systems, enabling thorough analysis and testing of control programs and resource behaviour using 3D models and control emulations [6]. In the iMOD validation platform, VC will be used to virtually simulate and validate control program updates for the robotic system and its lightweight MFEE. This process ensures that the system's drilling and fastening operations on both orbital and longitudinal joints are thoroughly tested in a virtual environment. By doing so, potential issues can be identified and resolved before implementation, minimizing disruption and ensuring seamless integration during the manufacturing process of aircraft fuselage sections.

Since VC is traditionally used only during the development and commissioning phases, disruptions that occur during the operational phase remain a significant source of downtime for automation systems, such as in the iMOD validation platform. Therefore, VC is employed to optimise the testing and validation procedures of the changes in the control program in the operation of automated manufacturing processes. These changes in the control program are an attempt to mitigate disruptions like delays or collisions, which occur in the automation system during operation. Hence, the aim is to develop a method that focuses on testing and validating only the changes in the updated control programs, thus enabling the continuous operation of the automation system with minimal interruption [23].

This approach extends the traditional use of VC by integrating it into both the preparation and operational phases through Continuous Virtual Commissioning in Operation (CVCO) [23]. This method builds upon the concept of Integrated Virtual Preparation and Commissioning (IVPC) [24], a holistic approach that utilizes the same virtual models of the automation system throughout the preparation, control system implementation, and commissioning phases. By incorporating VC into the operational phase, CVCO ensures that any changes in the control programs are identified and validated in real-time, allowing for immediate adjustments and minimizing downtime.

D. *Logistics-oriented analysis of highly automated production systems*

The first study within iMOD's logistics division looked at hybridizing different production structures to increase throughput time potential while increasing variant complexity in aircraft manufacturing. In previous articles, the main potentials, challenges, and basic approaches to realizing hybrid production principles were presented. Based on this, a concept was developed for the ideal combination of automated and manual processes in a hybrid production structure. [25, 26]

Based on the structural analysis, research was conducted to derive the best possible supply strategy for highly automated production systems. Inventory management in the production planning and control (PPC) process was identified as a key lever for a reliable order fulfilment process. The goal was to extend a logic for inventory dimensioning in order to supply the relevant production areas with the right quantity at the right time. Low standardization and lack of supplier diversity posed a particular challenge. Therefore, an approach for predictive inventory management based on product portfolio characteristics was developed. In addition, a new mathematical model for dimensioning safety stocks under the increasing influence of volatility is developed [27].

In order to analyse the reliability of an automated system and the associated impact on downstream processes in the early engineering phase, it is not enough to focus solely on material availability and warehouse management. The integration of resilience analyses into risk management for the systematic identification of vulnerabilities in systems and their linkage with upstream or downstream systems was identified as a key factor for logistics-oriented risk assessment. This is necessary to provide support to engineers in the early development phases with regard to the cost-benefit dilemma and to assist in the identification and evaluation of risk strategies through static or dynamic resilience. A framework is presented that shows how risk assessment and resilience analysis can be combined to support decision makers in the above-mentioned dilemma. Furthermore, a concept for utilizing different information from different MBSE models has been developed [28].

V. SUMMARY & OUTLOOK

This paper presents optimisation approaches for automation concepts in aircraft production. To thoroughly test these concepts, a validation platform is being set up at ZAL in Hamburg, in which the various research approaches are being validated as part of the dtec.bw-funded iMOD research project. This will lay the foundation for the automated aircraft production of the future.

Furthermore, this validation platform will pave the way for future research activities, including cooperative task execution of multiple robotic systems, algorithm development for production-specific applications, data-driven process optimisation, automated inline monitoring of assembly processes, and the integration of AI technologies under consideration of compliance and certification guidelines like EASA or ISO.

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