

# Implementing Large-Scale Aerospace Assembly 4.0 Demonstration Systems<sup>\*</sup>

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**Abstract:** The Future Automated Aerospace Assembly phase 1 technology Demonstrator (FA3D) was commissioned at the University of Nottingham and used to demonstrate concepts from the EPSRC Evolvable Assembly Systems project in specific industrial use cases. A number of lessons were learned from the specification, procurement, commissioning, and use of the cell. These lessons have been applied to the specification of Phase 2 of the Future Automated Aerospace Assembly Demonstrator (FA3D2) — currently in development — that will translate the Evolvable Assembly Systems research to a higher technology readiness level and address the challenges of scalable and transformable manufacturing systems. The FA3D2 will act as a showcase national experimental testbed and technology demonstrator in digital- and informatics-enabled aerospace manufacturing technologies, and the project itself will generate knowledge, skills, and experience in the delivery of such systems for academia and industry. After summarising the Evolvable Assembly Systems project, this paper presents details of the technologies demonstrated through the FA3D, and how this experience has been used to develop a novel approach to specifying the FA3D2.

*Keywords:* Aerospace, Assembly, Implementation, Industrial Robots, Integration, Intelligent Manufacturing Systems, Systems Concepts

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## 1. INTRODUCTION

Many manufacturing industries, for example automotive, aerospace, pharmaceutical, food, and others, rely on the assembly of final products in high-labour-cost areas such as the UK. There is a need for manufacturers to transform current capital-intensive assembly lines into smart systems that can react to external and internal changes and can self-heal, self-adapt and reconfigure.

In order to address this need, the EPSRC Evolvable Assembly Systems (EAS) project was proposed in order to develop a new approach towards the development of future assembly systems that are able to continuously evolve in response to changes in product requirements and demand (Ratchev, 2012). Any such system should be able to take advantage of new technologies in order to enable extremely short set-up or changeover times, as well as supporting low-cost maintenance, reconfiguration, and expansion. To support the research into these systems, a number of smaller demonstrator cells were developed as part of the EAS project. These led to the Future Automated Aerospace Assembly Demonstrator (FA3D), a pair of large industrially representative production cells focussed on robotic assembly and inspection of aerospace

components and products. Building on the FA3D, and with the support of UK Research and Innovation's Innovate UK and the UK Industrial Strategy Challenge Fund (Innovate UK, 2018b), we are currently in the process of delivering the FA3D Phase 2 (FA3D2), a showcase national experimental testbed and technology demonstrator in digital- and informatics-enabled aerospace manufacturing technologies.

As part of the delivery process for the FA3D2, a number of lessons learned were identified from the EAS and FA3D projects; these were used to inform and improve the definition and procurement processes. The FA3D2 project is being run in collaboration with an industrial advisory board (IAB) made up of representatives from a number of aerospace original equipment manufacturers (OEMs) and tier one suppliers. As well as the physical equipment, the FA3D2 project aims to generate knowledge around the specification, delivery, integration, and operation of large-scale aerospace assembly systems. With this in mind, this paper aims to record the useful knowledge and experience generated thus far. After a brief review of the advanced manufacturing research area and the EAS project, the whole delivery process for the FA3D is discussed in Section 3 before Sections 4 and 5 go into more detail on the lessons learned from the FA3D and how they have informed the FA3D2 process.

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<sup>\*</sup> The authors gratefully acknowledge the support provided by the UK Engineering and Physical Skills Research Council (EPSRC) under Evolvable Assembly Systems (EP/K018205/1) and by Innovate UK under FA3D2 (reference 113163).

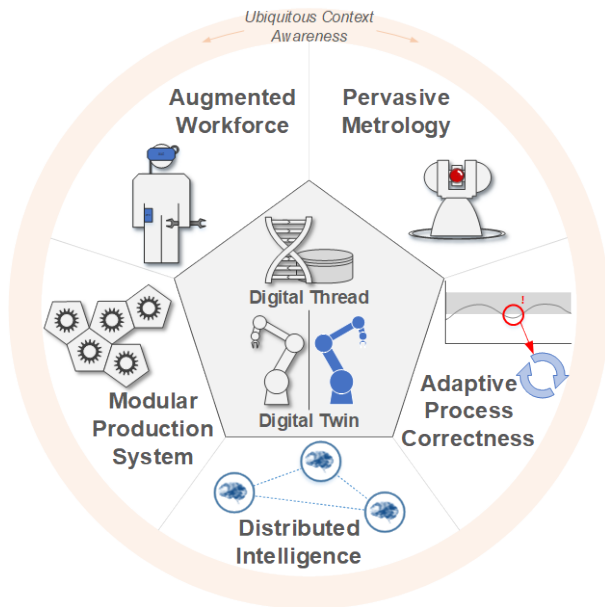


Fig. 1. Ubiquitous context-awareness in CPPS.

## 2. EVOLVABLE ASSEMBLY SYSTEMS (EAS)

The manufacturing industry as a whole has been undergoing a process of change from the traditional electro-mechanical and computer-controlled approaches to a cyber-physical systems and cyber-physical production systems (CPS and CPPS, respectively; see Monostori (2014)) approach typified by national programmes and broad paradigms described as “Made Smarter”, “Industrie 4.0”, “Digital Manufacturing”, or similar<sup>1</sup>.

Against the background of these developments, the EAS project built on research in the area of manufacturing systems that can adapt their behaviour over time (Neves and Barata, 2009; Onori et al., 2011) and investigate the concept of co-evolution of products, processes, and production systems in response to external disruption (Tolio et al., 2010). The aforementioned paradigms and national programmes have identified a number of properties investigated by EAS that are key to future responsive and flexible production systems: these include adaptability, changeability, self-resilience, self-improvement, and co-creation (Rosen et al., 2015; Monostori, 2014; Zuehlke, 2010).

One of the main overarching concepts delivered by EAS, a conceptual framework for ubiquitous context-awareness in CPPS (Sanderson et al., 2018), is a useful tool for summarising the project concepts. The framework, shown in Fig. 1, presents a vision for complex CPPS anchored in ubiquitous context-awareness and based around a number of key technologies that have enabled the advancement of production systems in recent years. The framework builds on the concepts of digital twins and digital threads (Rosen et al., 2015; West and Blackburn, 2017; Kritzinger et al.,

<sup>1</sup> See the following for a selection: Made Smarter Commission (2017); Widell and Lundberg (2016); Digital Manufacturing and Design Innovation Institute (2015); Industrial Value Chain Initiative (2014); Kagermann et al. (2013); Bundesministerium für Bildung und Forschung (2014); Manufuture (2004); European Chamber of Commerce in China (2017)

2018; Kinard, 2018), to deliver results in five main concept areas linked through context-awareness:

**Pervasive Metrology** The replacement of large and expensive coordinate-measuring machine inspection processes with more application-specific and cost-effective metrology spread throughout the system, which generates data that can be fed into the digital thread and update the digital twins.

**Adaptive Process Correctness** With pervasive metrology acting as the sensors for the CPPS, the system can use that information to monitor and analyse its performance to self-adapt, self-improve, and self-optimize, both at the level of a single specific process operation, and in terms of the whole system performance.

**Distributed Intelligence** While the digital twin and digital thread provide the information, models, and simulation capacity for the CPPS, the addition of intelligence can enable the system to know what its current capabilities are, to make decisions about whether and how a given product can be produced with those capabilities<sup>2</sup>, and to flexibly respond to disruptions by adapting those capabilities.

**Modular Production System** This modularity should not just be in terms of physical connectivity, but also in terms of parameterised control and capabilities. This is in contrast to the traditional production system that repeatedly executes a single list of instructions.

**Augmented Workforce** In highly complex production scenarios in high-labour-cost economies, it will be vital to optimise any human operations and to fully consider how the human and the system will interact.

Although many of these issues were addressed during the EAS project through a variety of small demonstrators (Sanderson et al., 2019), none of those were able to address the challenges inherent in large-scale aerospace assembly.

## 3. FUTURE AUTOMATED AEROSPACE ASSEMBLY DEMONSTRATOR (FA3D)

### 3.1 Aims and Industrial Challenges

In 2014–16, the University of Nottingham self-funded the development of the FA3D to support its advanced manufacturing research. The intention was to support the EAS project and its application to the assembly of aerostructures through the provision of industrially relevant demonstration equipment. The FA3D was also used to support other aerospace assembly projects, including the University of Nottingham’s contribution to the VIEWS project (Aerospace Technology Institute, 2014) and research programmes funded directly by industry. To this end, the FA3D was required to enable research activities ranging from very low Technology Readiness Level (TRL) “academic research” through to higher TRL “industrial development”.

In order to provide a clear business case for industrial engagement with the project, the FA3D was designed primarily around the desire to reduce cost in aerospace structural assembly solutions. Traditional approaches to

<sup>2</sup> This addresses the “batch-size-of-one” problem, where anything being produced by the system may be unique in some way.

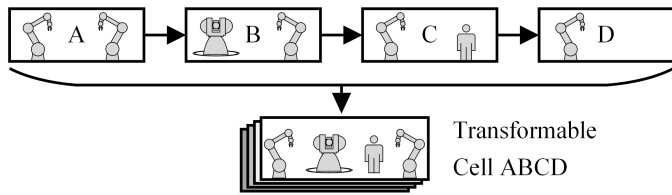


Fig. 2. Transformable manufacturing concept.

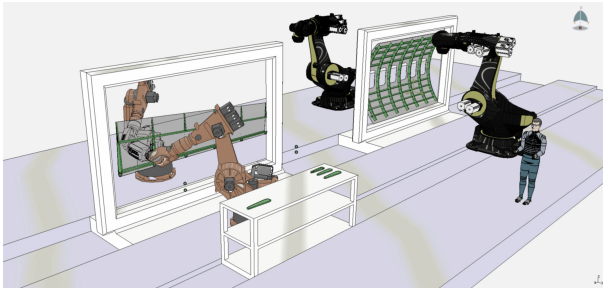


Fig. 3. Original two-cell concept for FA3D.

aerostructure assembly use large monolithic steel assembly fixtures to locate and constrain part positions. These structures are extremely expensive to manufacture and generally provide for very little, if any, adjustment in response to design change or product variants. There is often little to no real-time information on the condition of the fixture structure.

A shift to flexible automated systems provides the opportunity to shorten product lead-time as well as ramp-up and changeover times, increase product diversity, and as a result reduce production costs. Many of the approaches discussed in Section 2 aim to accomplish this, with some specific aerostructure assembly examples including Kihlman et al. (2004) and Inman et al. (1996). The FA3D was an attempt to target these challenges specifically by combining the relatively low cost and high flexibility of industrial robots with a high-precision metrology system to achieve the tight positional tolerances required by aerospace assembly in terms of both repeatability and absolute accuracy. By replacing jig/fixture-based workcells (or workstations, or assembly line stages) with flexible robotic automation cells, the capabilities of a traditional assembly line can be compressed into a single reconfigurable and multi-purpose cell. This “transformable manufacturing” concept shown in Fig. 2 should therefore result in large improvements in cost, floorspace, and throughput when assembling low or variable volume product batches. At the same time, the cell can be used to show that a diverse range of product geometries can be assembled within a single automated system, with it adapting or reconfiguring to manipulate the various components and perform process operations on them.

### 3.2 Development, Specification, and Commissioning

The initial concept design for the FA3D was for two cells, each with two industrial robots, connected with a track or rail that carries a “picture frame” fixture between them. This concept is shown in Fig. 3. Two “intellectual-property-free” products were specified for the system to assemble an aluminium fuselage panel section,

approximately 3m x 2m, and a hybrid (aluminium / composite) wing flap, approximately 3m x 1m.

The intention was for the product parts to be loaded into a kitting rack and then robotically assembled. The following typical aerostructures assembly processes were specified in detail as requirements, with a general requirement for a positional accuracy of  $\pm 0.250\text{mm}$ : one-shot drilling and countersinking, temporary fastener installation and removal, hole measurement, and final fastener installation. The process end effectors were all required to be interchangeable through the use of automatic tool changers that integrated all systems, wiring, and pipework.

In addition to the robotic and process end effector equipment, a set of metrology equipment was specified, as was the supporting informatics infrastructure. The metrology requirements were for non-contact inspection systems for automated and manual inspection of large-scale objects (the products defined above), and of part gaps, features, and surfaces over the entire system area. The metrology systems were required to be integrated with automated production tools in order to provide a metrology-assisted assembly (MAA) positional correction process (Maropoulos et al., 2014) and to allow access to all measurement data for export and evaluation.

The informatics infrastructure was comprised of an RFID part tracking system, a data acquisition interface (to connect to a number of sensors and data loggers) and archive, and an overall control system to replicate the “modular production system” discussed in Section 2.

The tendering process followed EU procurement rules. Prospective suppliers could bid for any number of the work packages (WPs) that the project requirements were divided into. When the demonstrator was complete, a demo day was held to present the system to a number of industrial stakeholders and show how it was capable of carrying out the specific processes on demonstration parts.

### 3.3 Results and Technologies

The system as delivered is shown in Figs. 4&5. The finished system was split into two cells each named for the brand of robots used in them: the FA3D-ABB consisting of two ABB IRB6700 industrial robots; and the FA3D-KUKA, consisting of a KUKA KR1000 Titan and two KUKA KR270 industrial robots. The FA3D-ABB acted as a component preparation and inspection cell and the FA3D-KUKA acted as a product assembly and inspection cell. A number of technologies were demonstrated with the completed cells, as discussed in the remainder of this section. The division of the two cells allowed both industrial and academic approaches to be demonstrated in parallel, rather than the entire system being constrained to a single solution. Some of these technologies are discussed in the remainder of this section.

*Modular and Recipe-oriented Production* The two cells take different approaches to modular production, but both enabled the specification of the system capabilities as modular and parameterised subroutines in the programmable logic controllers (PLCs). The FA3D-ABB presented these subroutines through variables in the PLC code that could





Fig. 4. FA3D-ABB cell.

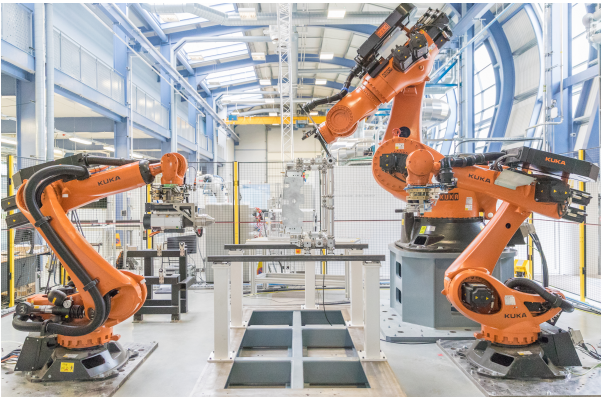


Fig. 5. FA3D-KUKA cell.

be modified by an agent control layer directly implementing the EAS project approach (Chaplin and Ratchev, 2019). The FA3D-KUKA on the other hand, used an industrial databus-driven manufacturing operations management (MOM) system to set up the process using a B2MML operations schedule (MESA International, 2013) implementation of the ISA-95 integration standard (International Society of Automation, 2013). In both cases this allowed the system to have a previously-unseen assembly process specified and carried out in an automated manner.

#### *Large Volume Metrology (LVM) and Accurate Positioning*

Matching its role as being aimed at component-level assembly tasks, the FA3D-ABB used a Leica laser line scanner and T-Mac to scan aerospace ribs and skins for identification and quality of supply, and to inspect sealant beads. The FA3D-KUKA used a MV331 laser radar for non-contact feature and surface measurement, and a Nikon K-CMM adaptive robot control system for online positional correction to overcome the inherent inaccuracies of robot kinematics. This allowed an absolute accuracy and repeatability of better than  $\pm 0.1\text{mm}$  to be achieved in the FA3D-KUKA with off the shelf industrial robots (Drouot et al., 2018). Both cells could be used with the Leica laser tracker, T-Scan, and T-Probe.

*Part and Equipment Tracking* Item tracking was implemented in the FA3D in two ways. The FA3D-ABB pallet conveyor and parts rack incorporated short-range tag readers, and in the FA3D-KUKA a large volume RFID tracking system was used to locate RFID tags on parts

and equipment in 3D space. In the FA3D-KUKA this was connected to the MOM so that an operation schedule was only initiated if all required parts and equipment were present in the cell. This functionality feeds into the modular production approach discussed above.

*Part Manipulation and Low-Cost Fixturing* In the FA3D-ABB cell, the ribs and skins were manipulated with two complex general-purpose grippers: a single pneumatic mechanical gripper capable of accommodating a variety of rib geometries, and a vacuum gripper for a number of composite skin panels. Conversely, the FA3D-KUKA used an MAA approach in combination with low-cost and lightweight bespoke tooling made from aluminium extrusion<sup>3</sup> and AMF Zero-Point clamping modules<sup>4</sup>.

### 3.4 Outcomes

In addition to being used for the EAS and VIEWS projects, the FA3D cells enabled other research programmes during their initial lifecycle, including the EPSRC Cloud Manufacturing project (EPSRC, 2013) and an industry-funded investigation into the hybrid automated/manual precision assembly of an aerospace product. Following production trials with other equipment, the EU CleanSky 2 ASTRAL project (CleanSky 2, 2015) is now utilising the FA3D-KUKA equipment to assemble the wings for the Airbus Helicopters RACER flying demonstrator, and Innovate UK AutoRamp (Innovate UK, 2018a) is utilising the FA3D-ABB equipment to investigate precision automated positioning of wing ribs.

By providing the opportunity to investigate the state of the art in both “academic” and “industrial” advanced manufacturing research in the same environment, and by acting as a showcase for the research group’s activities during events and visits to the University, the FA3D created a network of partners. This network has resulted in further activities: Innovate UK Flexcelle (Innovate UK, 2019) began through contacts that were developed based on an FA3D demonstration day, and other activities that were directly funded by industry were also begun through contacts that were developed through this network.

In general, the success of the FA3D has allowed the University to leverage its existing investment to launch, support, or extend research programmes beyond the initial FA3D lifecycle. Based on the experience gained through the FA3D, the University was successful in securing funding from the UK government Industrial Strategy Challenge Fund (administered by Innovate UK) to begin the FA3D2 project (Innovate UK, 2018b).

## 4. LESSONS LEARNED

A lessons learned process was carried out involving as many of the original project stakeholders from FA3D as possible. This was in order to reflect on the project outcomes and capture learning to be applied in FA3D2. The lessons can be divided into five main areas: vision, project management, procurement, technical specification, and people and skills. It is expected that these will benefit

<sup>3</sup> Compatible with Rexroth Aluminum Structural Framing.

<sup>4</sup> <https://www.amf.de/en/products/clamping-technology/>



both the FA3D2 project and any other organisations aiming to develop their own large advanced manufacturing demonstration system, particularly those in the areas of aerospace assembly and “Assembly 4.0” (Cohen et al., 2017; Bortolini et al., 2017). The lessons themselves are summarised in this section, while the steps taken in the FA3D2 project to address them are discussed in Section 5.

#### 4.1 Vision

A key point highlighted in the lessons learned process was to ensure that there is a clear shared vision for the system. Although a vision existed for the FA3D and was linked to the research strategy, the challenge was ensuring that this vision was explicitly shared with all stakeholders and suppliers. By expanding the vision into detailed aims and objectives for the project, they can then be used to create the detailed requirements specifications. In this way, the vision can be used to inform a set of measurable success criteria and ensure that the project outputs match the high-level project goals.

#### 4.2 Project Management

It is widely acknowledged that effective project management is key to the success of any large and high-capital programme. Project management schemes such as PRINCE2 focus on ensuring clarity of roles, responsibilities, and processes around system integration and risk management, as well as keeping all stakeholders informed according to a clear communication plan throughout the whole project. Unlike the majority of universities, the group responsible for the procurement of the FA3D works to PRINCE2 project management processes. This is generally applied to research project delivery, rather than capital infrastructure projects. Perhaps because of this and the complexity of the multi-vendor supply arrangement, there were gaps in the project management approach. Indeed, an Association for Project Management report on the conditions for successful projects () confirms that around 80% of projects fail to meet their planned objectives, often due to poor project planning and review.

#### 4.3 Procurement

Large organisations often have complex procurement processes in place in order to comply with regulatory frameworks. These processes may not be designed with research equipment procurement in mind, and it is unlikely that any of the research team involved in the specification and use of the equipment are intimately familiar with the procurement processes. The interactions between organisations are also areas where problems may occur, particularly where there are multiple functions involved across multiple organisations (e.g. research, sales, procurement, etc). Engaging these functions as early as possible in the process and ensuring that the procurement strategy and sign-off criteria are clear and robust is key to a successful procurement process. Working with such a complex system will also require robust change management and contract management procedures to be in place in order to deal with any issues that do arise. For FA3D, this became particularly challenging when the contractor responsible for

integrating the final solution had limited direct influence over the other suppliers. This led to miscommunications and delays in implementing a final solution that was fully integrated. This also had the negative side effect that the University did not capture all of the integration knowledge, so was unable to pass that on to its other research partners or leverage it in other projects.

#### 4.4 Technical Specification

Once the supporting processes have been defined, the system itself must be specified and procured within them. These processes are primarily designed to support the procurement of equipment that either already exists (buying off-the-shelf) or can be easily specified as a modification of something off the shelf. As a research demonstration testbed, the specification of the FA3D had to cover something that was cutting edge and in many cases was not (widely) available. This was coupled with the requirement for the system to be highly flexible and reconfigurable, rather than being a turnkey system in common with the usual business for industrial suppliers. These two aspects led to great difficulty in specifying the system in such a way as to: deliver on the vision; support existing and future (i.e. unknown) research; be something that suppliers could tender against; and incorporate specific and measurable acceptance criteria. This was the primary challenge faced by the FA3D project, and was the main focus of the lessons taken forward to the FA3D2.

#### 4.5 People and Skills

As a research organisation, the members of the team who aimed to use the finished system did not have the time or the skills to be involved in every step of the delivery process. Two potential hurdles are assigning tasks to people without the required skills, and over-committing people. This can be mitigated through effective delegation and by giving ownership and accountability to the correct people within the team, as well as by using specialist experts (potentially outside the team) to input on the definition of the specification and acceptance tests. This will help to ensure that the system delivers in line with the vision, and that it is aligned with the current state of the art and practice in both industry and academic research.

## 5. FUTURE AUTOMATED AEROSPACE ASSEMBLY DEMONSTRATOR PHASE 2 (FA3D2)

### 5.1 Project Aims and Approach

Building on the FA3D, the FA3D2 will deliver a national experimental testbed and technology demonstrator in digital- and informatics-enabled aerospace manufacturing technologies. In addition to supporting a number of University of Nottingham research projects, it will also provide an opportunity for UK-based aerospace manufacturing businesses — with a particular focus on SMEs — to test, demonstrate, and accelerate the implementation of new technologies thereby allowing them to compete with rival offshore businesses on productivity, quality, and cost. Beyond delivering a physical testbed for flexible, reconfigurable, transformable, and intelligent manufacturing in

the same vein as EAS and FA3D, the project also aims to develop expertise, skills, and knowledge that can be leveraged by both academia and industry for the specification and delivery of similar large-scale production systems.

The project is guided by an IAB made up of representatives from a number of aerospace OEMs and tier one suppliers. These representatives contributed to a roadmapping exercise to identify the main areas of interest in the aerospace manufacturing industry, and have continued to provide feedback on the process as the project has progressed. One major change that has been implemented on IAB advice is to develop the integration of the system in-house at the University, rather than relying on an integrator partner. As well as addressing some of the challenges faced during the FA3D integration process, the University will be able to draw knowledge from the network of delivery partners, develop an integration process, and provide information back to the IAB and the wider community by developing a set of best practices. This paper is the beginning of that knowledge exchange.

Based on the project aims and the lessons learned from the FA3D, the following decisions were made during the specification of the system:

- Involve the IAB and the prospective delivery partners in the process as soon as possible, within a clear procurement process administered by the University functions. Ensure that the system vision and concept support long-term industry requirements and medium-term industry development targets. Technical and research staff should be placed at the heart of the specification process to support this, with the appropriate procurement functions being delegated elsewhere.
- Contextualise the system around generic product families rather than specific geometries. These product families should be chosen based on the projects initially identified for the system, in line with the industry roadmap.
- Structure the project in stages: the first stage should deliver the underlying platform infrastructure and implement the system concept as a flexible research baseline; later stages should deliver specific process capabilities required for the identified product families and specific projects, potentially through “turn-key” functionality.
- Structure the requirements specification around generic use cases. These use cases should inform how the research team would like to be able to use the system. This should be in contrast to specifying what the system should be from the beginning (“solutionising” the specification), or specifically what it should do.
- The use cases should be balanced against specific technical sign-off criteria that are informed wherever possible by existing industrial standards.
- Bring in external specialists to review and develop the specification for technical requirements in collaboration with the research team.

## 5.2 Use Cases

In line with the lessons learned from the FA3D and the approach set out in the previous section, the require-

ments specification for the FA3D2 was based around a set of use cases for how the research team plans to use the system, rather than a more traditional specification process focussed on acceptance criteria. This process was developed in order to ensure that the delivered system is able to fulfil all stakeholder requirements and address as much of the vision as possible, rather than focussing on the assembly of project-specific products. The FA3D team recognised the difficulty in specifying acceptance criteria for smart manufacturing systems and the enabling digital infrastructure. A particular challenge exists in determining the responsibility for intelligent adaptive control in the system, and whether it forms part of the simulation, digital twin, control infrastructure, equipment supply, or elsewhere. The set of use cases was developed to describe how the FA3D2 system will be used in an attempt to ensure that all partners in the project are aware of the overarching aims of the system and enable the suppliers to develop a solution in collaboration with the University. The use cases are meant to be used in conjunction with the technical requirements and form part of the selection criteria for the tenders submitted by potential suppliers.

The project is therefore defined in terms of an overall virtual and physical commissioning concept and five generic use cases:

- (1) Integration of a new process end effector
- (2) Integration of new automation equipment
- (3) Reconfiguration of a cell
- (4) “Business as usual” — process control, data input/output, and real-time dashboard
- (5) “Open data” — data collection and accessibility, and provision of a digital twin

The overall concept for the FA3D2 to support flexible, reconfigurable, and transformable production is to use a virtual and physical commissioning process. This is planned to happen at two levels:

*Project-level reconfiguration* at a higher level, whereby the initially delivered system is a research baseline that can be built upon. This baseline can provide the base functionality and supports the reconfiguration process (jointly defined through the use cases). The system can then be re-commissioned to support specific projects through the delivery of process end effectors and additional functionality that may be “turn-key” in nature. This is reflected by the two stages of procurement: stage 1 of procurement involves a design process that will deliver a system that is virtually commissioned as part of the acceptance process, and then physically commissioned at the end of the commissioning process; in stage 2 this system can then go through a number of rounds of virtual and physical commissioning to implement specific projects.

*System-level reconfiguration* at a lower level, where the use case processes allow for the system to be reconfigured on a day-to-day basis in order to support the required activities. This is reflected in how the use cases relate to each other in terms of the reconfiguration process described in use case 3. Use cases 1 and 2 provide for the integration of “plug and produce” equipment that can be integrated into physical and virtual commissioning activities without any loss of fidelity in either type of activity. This equipment is then used in use case 4’s “business as usual” activities

to deliver flexible production processes that generate data. This data is available for access and can be used to build up a digital thread and update digital twins in use case 5.

Although we hope that the use case approach will address some of the challenges faced during the FA3D specification process, particularly around technical specification, we run the risk of overcorrection. The challenges that remain are:

- Enabling innovation whilst being specific and tangible enough for firm requirements and sign-off criteria that potential suppliers can tender against. The use case approach aims to strike a balance by making suppliers aware of the vision and by writing sign-off criteria that specify how we want to use the system.
- Future-proofing the system by finding the balance between the industrial state of the art and techniques that are more experimental and lower TRL. The use case approach should enable suppliers to propose less mature solutions that are in the context of the industrial landscape.
- Creating a platform for research requires a higher level of flexibility than an industrial platform; most suppliers (and the IAB) have experience of more rigid requirements. By specifying a combination of use cases and sign-off criteria, the suppliers should have a greater understanding of the project goals.
- Work packages are highly interdependent; this requires clear decisions on where responsibility lies for each task and what aspects fall into which work packages, particularly around integration requirements. This is also a challenge for creating sign-off criteria that aren't heavily reliant on other work packages that may be provided by a different supplier.
- Ensuring that the concepts presented by the specification are accessible from more than one perspective — a single stakeholder should not be solely responsible for the whole thing, as this risks the finished product not addressing all stakeholder requirements.

## 6. PROGRESS, NEXT STEPS, AND CONCLUSIONS

The FA3D2 project is currently in the process of reviewing the tender responses submitted by potential suppliers. An overview of the concept vision for the project is shown in Fig. 6. Broadly speaking, the initial stage of the project will deliver equipment similar to the image: a reconfigurable floor, some robotic automation platforms, the digital technologies underpinning the control system (shown in the left-hand box), and the precision metrology systems required to enable automated accurate robotic positioning. This will create a research baseline that can be built upon to deliver the industrial use cases in the future stages of the project.

The use cases and requirements specification was well received by the IAB and other stakeholders, both at the University and externally (for example, other funding agencies and industrial partners not directly involved in the project). Although it is too early to say with complete confidence, the tender returns from prospective suppliers appear to have been well-received and seem to have been engaged with in such a way as to validate the use-case-based approach over a more traditional quantitative test-based approach.

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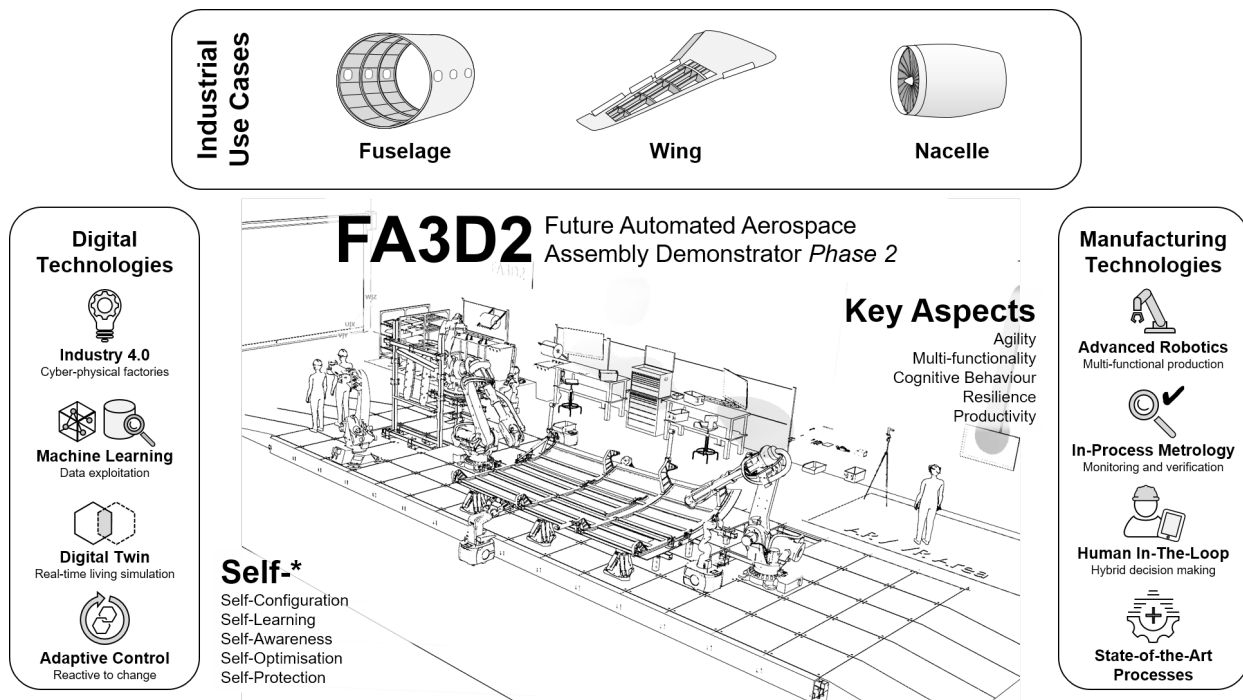


Fig. 6. Overview of the FA3D2 concept.

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