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Digital manufacturing and flexible assembly technologies for reconfigurable aerospace production systems

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Abstract

Reconfigurability is an important aspect of modern manufacturing systems as it facilitates the seamless introduction of new products to production and the adaptation to demand volatility. Advanced manufacturing technologies broadly used in automotive industry have limited application for typical UK aerospace manufacturing, as they require production volume and repetition of operations to deliver value. This paper discusses a framework of key technologies ranging from digital manufacturing concepts to flexible fixturing that enable reconfigurability in aerospace manufacturing systems. Initially, the overall architecture of the framework is presented illustrating the key components such as a cloud based data storage mechanism, an intelligent multi-product assembly station, kitting boxes embedded with sensors, a manufacturing network management portal and a decision support tool that combines data analytics and discrete event simulation. Afterwards, the main functionalities and technologies of the components are described and finally an industrial application scenario for the proposed framework is presented.

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Keywords: Aerospace; Manufacturing; Reconfiguration; Digital Manufacturing; M4.

1. Introduction

Today's manufacturing companies strive to improve their performance in a globalised, interconnected and volatile market environment [1]. Traditional approaches of dedicated production lines, although still in use/practice, cannot deal with changes related to the market such as; increases in product demand, product changes, such as the introduction of a new product in the line, and system failures, such as a machine breakdown, in a cost effective or timely manner.

In high volume manufacturing, such as automotive, the introduction of automation and information and communication technologies (ICT) on the shop floor, supported by digital manufacturing tools, has led to more flexible production systems which are capable of dealing with the volatile market demands and having a mixed product flow. In the aerospace sector, and in particular in manufacturing firms belonging first layer of the supply chain and below, the scale of product volume does not allow for the introduction of automation, such as robotics. In addition, the high complexity of aerospace products requires operations with high dexterity that make automation even more challenging and require operators of high skills and both technical and practical knowledge.

The concept of reconfigurable manufacturing systems has been introduced [2] as a new class of production system that lies between dedicated lines and flexible manufacturing systems, introduced in the mid-nineties [3]. The concepts of machine and system modifiability and the modularity of key operational functions and components are key elements of a reconfigurable manufacturing system and both of them are prerequisite for product and volume flexibility.

A modular and modifiable manufacturing system that is able to deal with an increased number of product varieties, high performance operations, flexible machines and reconfigurable systems structures is expected to be characterised with high complexity as well [4]. To handle this complexity, an integrated framework of data models, digital manufacturing tools and sensor network, is required to represent simulate, optimize, monitor and control a

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manufacturing system. The integration of such a framework with a manufacturing system would lead to Cyber Physical Production System (CPPS) [5], that following the definition of the Cyber Physical System (CPS), should be understood as "a system of collaborating computational entities which are in constant connection with the surrounding physical world with its on-going processes, providing and using (at the same time) data-accessing and data-processing services available on the internet."

There are three main technologies that could be considered as the main enablers of a CPPS: a) digital manufacturing tools, b) Internet of Things (IoT), and c) Cloud computing. According to the Verein Deutscher Ingenieure, "the digital factory includes models, methods, and tools for the sustainable support of factory planning and factory operations." [6] [7] and in a broader sense can be associated with the concept of the digital enterprise technology (DET) that is the collection of systems and methods for the digital modeling of the global product development and realisation process in the context of life-cycle management [8], [7]. "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" [9] [10]. IoT comprises network infrastructures such as sensor network, wireless and standard Internet in order to provide a wide range of services in many everyday life aspects. [11].

The application of Cyber Physical Systems approaches and technologies to manufacturing systems is driven by different international initiatives. In the USA it is the advanced manufacturing initiative that encompasses a number of research programmes and organisations covering CPPS amongst other research areas [12] [13]. In Germany, Industrie 4.0 is the research platform responsible for defining the research framework and the guidelines for the Factory of the Future vision [14] [15] and could be considered a continuation of the "smart factory" [16] concept. A number of research programmes and projects focusing on CPPS are funded by EU under Horizon 2020 and in particular Factories of the Future [17] [18]. Finally Innovate UK along with EPSRC and industrial initiatives are fostering research in the areas of high value manufacturing [19].

During the past years a number of different digital platforms and concepts have been proposed for reconfigurable manufacturing systems. PROMISE-PABADIS introduced an agent based architecture in order to overcome the limitations of typical centralized manufacturing execution systems [22]. Another architecture for service oriented process, monitor and control focusing on the next generation of industrial SCADA (Supervisory Control and Data Acquisition) and DCS (Distributed Control Systems) systems has been proposed by the IMC-AESOP project [23]. In the context of the R&D project VFF a digital framework that incorporates a series of digital tools, used during the entire lifecycle of a factory and provides both data and knowledge management functionalities [26]. ARUM project developed agent based planning and scheduling tools employing the service oriented paradigm in order to address disruptions taking place during the ramp up production of aerostructures [24]. In Sense&React a context aware information distribution systems has been developed that collects data from sensors located at the shop-floor in order to increase the visibility of shop floor processes by providing the right information, to the right people, at the right [25].

2. M4 Approach and Architecture

Meggitt PLC, an engineering group specialising in components and sub systems mainly for aerospace, defence and energy markets is exploring technologies under the umbrella of CPPS and introduces intelligent and digital manufacturing approaches to its production facilities around the globe starting from three UK factories.

Meggitt has a diversified product portfolio with numerous different products of high complexity and tends to use dedicated production lines of low flexibility. These products do not lend themselves to automation and in combination with their low volume, the underutilization of lines may often occur. On top of this, even the most sophisticated algorithms cannot unlock the full potential of a factory without considering a company's suppliers. The optimisation of a single factory requires an alignment with the supply network.

M4 "Meggitt Modular Modifiable Manufacturing" aims to address the aforementioned challenges investigating technologies such as digital manufacturing, cloud storage and services, and IoT. In particular M4 envisions the development of a flexible Cyber-Physical Production System interconnected with other factories within the company and with the companies suppliers. Advanced multi-product assembly stations, which will be operated by multi-skilled staff with the support of intuitive information distribution systems, and intelligent, potentially autonomous, product delivery systems will be capable of uploading product, process and operation data to the cloud using an array of embedded sensors. Additionally, expensive capital investment assets, such as state-of-the-art (SOTA) CNC or metal additive manufacturing machines will be connected via the cloud, allowing business units to share assets and facilities across an organisation. Harvested data will be analysed providing full historical traceability and real-time shop floor visibility in terms of KPIs, while predictive analytics algorithms will be applied for short and long term optimisation of shop floor operations, allowing the factory to improve itself over time.

A generic layered architecture has been proposed in order to fit into the manufacturing shop floor requirements that could be applied to different production systems. The architecture is composed of four layers and is illustrated in Figure 1. The first layer is regarding the physical components of the M4 platform and is related to the areas of kitting, internal logistics and assembly along with a plastic additive layer manufacturing machine. Key components on the shop floor are the intelligent workbench, which supports the build process of different types of products, fixturing and the loading/unloading mechanism that will almost eliminate setup time. Sensors of different types and technologies are deployed at the shop floor to ensure required data is captured for traceability and visibility purposes and belong to the second layer of the architecture. Data storage is the third layer and is where data coming from the shop floor sensors is stored either in a structured or an unstructured format. Finally, data coming from the digital manufacturing tools and analytics tools residing at the fourth layer are also stored in the repositories of the third layer.

The M4 assembly workstation improves the process flexibility of the manufacturing system, i.e. the capability of a system to produce a set of parts without major setups in two ways [21]. First the fixtures allow the assembly setup time minimization of three different products in the same workstation. Second the information provision system facilitates operators assemble three different products even if they are not experienced because they are guided by the digital instructions and a laser project system. The aforementioned functionalities of the assembly station in combination with the scheduling optimization algorithms increase also the routing flexibility of the system, i.e the ability to produce a part by alternate routes through the system [21]. Finally M4 will brings full KPIs visibility and product traceability that is of paramount importance in aerospace industry by capturing operational shop floor data that is stored using cloud based mechanisms and afterwards analysed by descriptive statistics algorithms.

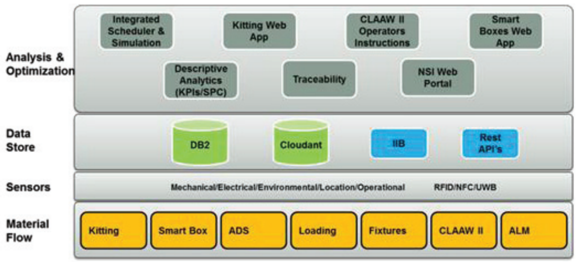

Figure 1 - M4 system architecture

3. M4 Major Components

In the M4 project the three manufacturing operations that being investigated are those of kitting, internal logistics and assembly, while additive layer manufacturing is also involved. In this chapter the main M4 components are described with the reference to the aforementioned overall architecture.

3.1. Kitting

The aim of the kitting technologies that will be deployed is to support operators in the selection of the parts, tools and consumables along with ensuring all necessary data is captured for traceability and visibility purposes. An operator equipped with a tablet with a web app (kitting web app) connected via the cloud data store will have access to the picking list. Technologies such as pick-by-light or sound will support the collection of the right parts that will be scanned and the cloud data store will be updated. As soon as the collected parts are placed in kitting boxes (smart boxes) a vision based inspection system will validate that the right parts have been kitted and will allow the transportation of the smart box to its next location.

3.2. Smart Boxes

All parts, tooling equipment, consumables, and fixtures required for the assembly of a product are placed in a smart box. A smart box is a kitting box equipped with environmental and mechanical sensors connected via the cloud data store. The smart box is accompanied by a web app (Smart box web app). An operator would be able to scan a QR code on the side of the box with the camera on a tablet and receive from the cloud data store a visual representation of the sensor measurements with the help of the web app GUI. A simple human display interface in the form of simple led lights is included on the smart box, in order to immediately inform the operator of any critical updates that could impact the parts in the box, such as a drop. This data is also uploaded to the cloud data store and accessed via the app.

3.3. Factory Delivery System

A delivery system will carry one or two smart boxes around the factory shop floor and could be in the form of an automated guided/intelligent vehicle (AGV/AIV) or, more simply, a trolley equipped with a tablet and a web app (DS web app) that provides the destination instructions to the operator. In both cases the delivery system will be connected via the cloud data store in order to receive the correct information regarding the route and will send back to the cloud data store all operational data of the process, for example; time taken for delivery.

3.4. Closed Looped Adaptive Assembly Workbench II - CLAAW II

CLAAW II is based on CLAAW I (**Figure 2**) that is currently under the phase of industrialization and its aim is to assist operators to build products of different types. A fixture (left side of **Figure 2**) includes targets to guide the calibration of an overhead laser. A shaft is encoded to enable precise rotation measurements. A power-on brake provides stability for torque operations. Product assemblies can be mounted and removed swiftly using a pneumatic easy-click clamp. On the right side of the figure there is a picture of CLAAW I with the three of its major components: fixture, screen for the digital instructions and laser projection system. CLAAW II will be equipped with flexible fixtures and loading/unloading mechanism that will minimise or even, eliminate the setup time during a product changeover. Assembly instructions will be provided to the operator through a digital display. Text based descriptions of the instructions can be accompanied by videos, CAD models and drawings or even more advanced techniques such as augmented reality (laser projection) and digital twins. CLAAW II will also be equipped with intelligent tools that are pre-programmed for each product. For example, an intelligent torque wrench can be wirelessly programmed to tighten a bolt to a specific torque for a specific operation. CLAAW II will have the ability to capture operational data such as the time spent on the assembly of each product and track the status of operations with the help of a camera. Additionally, operators will be supported by their supervisors or more experienced operators with a mechanism of remote assistance.

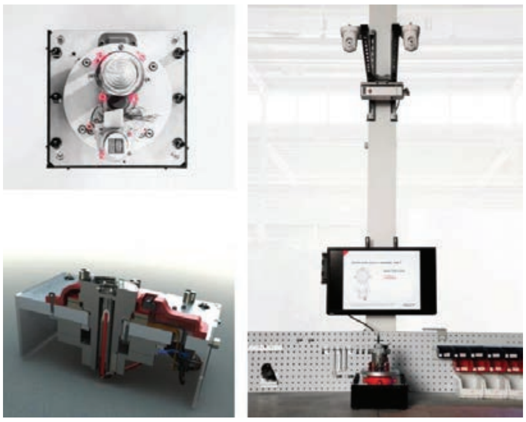

Figure 2 - CLAAW II [20]

3.5. Additive Layer Manufacturing (ALM) Machine & Network Services Interface - NSI

An ALM machine, most likely a plastic one based on fusion deposition modeling, is another M4 component. The ALM machine will be accessible by various company facilities via the cloud architecture and the NSI web portal. Facilities will be able to add jobs to the schedule of the ALM machine, which will reside in the cloud data store, and obtain a delivery date for the submitted parts. Another functionality of the NSI portal is the communication between the suppliers and the M4 factory. A supplier will use the NSI portal to provide an update of any change in the delivery of the order. Such a change will be stored in the cloud data store and the simulation/scheduler will be able to assess the impact on the factory delivery dates. The first functionality of NSI, the one that has to do with adding jobs, is related only with the ALM machine while the second affects not only the ALM machine but also CLAAW II and the other machines in the M4 system.

3.6. Cloud Data Store

The third layer of the M4 architecture is dedicated to the cloud based data storage, in both structured and unstructured formats. An IBM DB2 component will be used for storing structured data whilst Cloudant will be used for unstructured data. The logical data model (LDM) of DB2 includes four major macro areas; factory, events, key performance indicators and product. The “factory” macro area deals with the plant resources and follows a factory hierarchy of four levels. Plant stands for the highest level of the hierarchy and consists of a number of modules. A module is associated with a specific group of physical processes such as assembly or machining and belongs to the second level. Modules are made up of cells. A cell is a group of workstations (CNC machine or CLAAW II) that have the exact same skills and are the bottom level of the factory hierarchy. The macro area of “events” deals with the method of manufacture required for process planning and is described by the “reference event” entities. A reference event for a specific combination of resources for the production of a specific product is the base plan entity. The base plan entities are used for the storage of the schedule generated by the integrated simulation & scheduler mechanism. The actual plan entities are the same with the base plan entities only they are updated from the operation times coming from the shop floor. Another critical macro area is the one dealing with the Key Performance Indicators (KPIs). KPIs, which come as a result of the simulation or are generated by the descriptive analytics based on shop floor operational data, are also stored in the DB2. Cloudant is mainly responsible for storing data coming from the testing equipment in an unstructured way. Finally, the data store layer is supported by a file management system for storing video, cad files required by CLAAW II instructions. Product macro area includes tables, relationships and attributes related to product final assembly, parts subassemblies.

3.7. Simulation & Scheduling

Discrete event simulation is typically used in manufacturing for the evaluation of alternative configurations of production systems, or for different planning strategies and, in general, for the evaluation of what-if scenarios. A major challenge of using simulation is related to the frequent updating required of the simulation models. Process times, product routings and resource configuration changes should be updated accordingly in the simulation models in order to depict reality and support engineers to take informed decisions. The manual process of data collection is not adequate in terms of accuracy and frequency for updating the models. It is also quite an expensive method of data capture. In M4, a commercial discrete event simulation software solution will be integrated with the cloud data store allowing the automated update of simulation models with cleaned operational data coming from the shop floor.

In the context of M4, a scheduling algorithm will be integrated with the discrete event simulation providing a scheduling mechanism. The scheduling algorithm focuses on short term scheduling that allocates resources to jobs trying to optimise a multiple objective utility function, whose form is provided in **Equation 1**, and takes into account a set of criteria that are KPIs. A heuristic approach, in particular genetic algorithm is used in order to generate an optimised schedule that will be visualized in the form of a traditional Gantt chart. Stochastic phenomena taking place at the shop floor such as machines breakdowns, product reworks as well as the variability associated with operators and suppliers' potential delays will be also taken into consideration by the scheduling mechanism. Finally, the scheduling mechanism, similar to the simulation, will be integrated with the cloud data store and it will upload the optimised schedule to the DB2, so, afterwards, it can be executed by factory resources.

$$UF_j = \sum_{i=1}^{n} w_i \overline{C_{ij}}$$

$$\overline{C_{ij}}: normalized\ criterion, i, of\ alternative\ schedule, j;$$

$$\overline{C_{ij}} = \begin{cases} \dfrac{C_{ij} - minC_{ij}}{maxC_{ij} - minC_{ij}}, benefit\ criterion \\ \dfrac{maxC_{ij} - C_{ij}}{maxc_{ij} - minC_{ij}}, cost\ criterion \end{cases}$$

$$w_i: weighting\ factor\ of criterion\ i\ , \sum_{i=1}^{n} w_i = 1$$

Equation 1 - Utility function

3.8. Descriptive Analytics & Traceability

The M4 component entitled “Descriptive Analytics” deals with two different types of data. The first type is related with operational data whose analysis provides the factory KPIs while the second concerns testing data whose analysis is performed with statistical process control (SPC) methods. KPI analysis starts from the operational data that is captured by the sensors deployed in the shop floor and stored in the DB2. A set of queries will calculate the required performance indicators and various descriptive statistics methods will be applied for the calculation of the basic statistics measurements of the KPIs, such as average, standard deviation, median etc. Additionally, distribution fitting algorithms will be used for the identification of distributions that are followed by critical process variables such as process time. Following this, the information will be visualised in order to provide an overview of factory performance and also a detailed view to the manufacturing engineering managers and planners.

The goal of the SPC component in M4 analytics is to analyse testing data coming from an automated test rig, which stores its data in the cloud data store, and visualise the results through a web portal for all stakeholders to access and view. The functions that are to be captured in the SPC component are the following; performing a X-bar analysis for various testing product variables, calculating the standard deviation of test data, trend capturing, distribution fitting and full visualisation.

Traceability is the term used to describe “Product analytics” and “Product DNA”. The goal is for a fully digitised traceability system, which will include the unique identifiers for all components and sub-assemblies in a given product assembly as well as all of the manufacturing and supplier information captured at every stage in the manufacturing process. All this data will be connected via the data store and be available through an interactive dashboard.

4. Case Study – Demonstrator

The M4 demonstrator will combine all M4 components into a single system, all communicating via the cloud data store allowing the necessary information flow to occur.

The M4 demonstrator focuses on the final assembly of three exemplar products that are high technology, high value, and safety critical aerospace components. The first is a 5-pot solenoid valve whose main function is to control the bleed off of air from the engines compressors to regulate pressure. The second is a variable frequency starter generator heat exchanger which is mounted on a turbofan engine. This heat exchanger is in a shell and tube configuration and exchanges heat from the hot lubrication oil of the VFSG to the cold fuel. The final exemplar product is an e-brake that uses electromagnetic forces instead of conventional hydraulic systems.

The demonstrator will begin with the production of the optimised schedule for the given demand profile by the integrated scheduler and simulation tool. This optimised schedule will be based on reference manufacturing times stored in the cloud data store and executed through specific decision making criteria, KPIs, which will be weighted according to their importance by using a simple additive weighting method.

The base plan will be stored in the cloud based data store, allowing the shop floor components; CLAAW II, delivery systems and kitting operators, to retrieve the schedule for each specific resource and execute accordingly.

Operators will kit parts using digital work instructions displayed on a tablet or fixed screen via the kitting web app, which will visualise data in the cloud data store. Smart boxes will be filled with all the required components and tools for the specific job ahead, and its contents will be validated by a vision system in the kitting area and, then, will be ready for transport via the delivery system.

The delivery system will be loaded with the smart box and will retrieve its route from the cloud data store. Following transport, the delivery system will arrive at a CLAAW II workstation, and its arrival is confirmed to the cloud data store.

CLAAW II accepts the smart box from the delivery system, verifies it is correct, and then the smart box is unloaded, ready for the operation ahead. An operator has already used an NFC card to log in and the correct work instructions for the specific product will have been downloaded from the cloud data store and displayed on a digital display.

As the assembly procedure commences, the instructions will update and the operator will have the flexibility to choose the method of delivery, from video to simple text, whilst operational times are being tracked continuously.

Once the assembly has finished and the finished product is placed back into the smart box, ready to go to the next operation or back to stores. The delivery system is instructed to collect the part and return to the kitting area.

Throughout the demonstrator process, operational data will be captured by sensors from the kitting phase to the final step, and all data will be stored in the cloud data store as actual events.

The descriptive analytics component will then automatically analyse the data, updating the reference events accordingly and displaying a digital dashboard of the factory performance.

5. Conclusions & Future Work

This paper discussed the approach, the overall architecture and the major components of the M4 while a brief description of an industrial case study showing the information flow between the various M4 components has been provided. Key concepts of the M4 approach are those of modularity and modifiability that are expected to boost product and routing flexibility. Digital manufacturing tools, cloud computing and internet of things are considered as they key enabling technologies and are exploited in the context of the M4 architecture. The industrial case study provides a simple example that gives a flavour of the future deployment of the M4 technologies at the shop floor. The application of the M4 is expected to bring cost reduction by exploiting scheduling optimization, full KPI visibility and traceability by utilizing a network of shop floor sensors and descriptive analytics. M4 is reaching the end of its first year, whose main results have been the identification of the most promising technologies and approaches, the development of a logical data model and the cloud data storage mechanism, the implementation of discrete event simulation models and the formalization of the scheduling problem. The finalization of the technical specifications and the detailed design will be achieved within the next months while the definition of a real lab demonstrator where all the M4 technologies are going to be integrated and tested will drive the integration of the M4 system. Finally, at the later stages of the M4 a migration analysis will identify the M4 components that are expected to bring the greatest benefit in Meggitt's factory and will define their introduction to existing company production lines.

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