Conceptual Framework for Ubiquitous Cyber-Physical Assembly Systems in Airframe Assembly ⋆

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Abstract: Current sectoral drivers for the manufacturing of complex products — such as airframe assembly — require new manufacturing system paradigms to meet them. In this paper, we propose a conceptual framework for cyber-physical systems driven by ubiquitous context-awareness by drawing together a unique and coherent vision that merges several extant concepts. This framework leverages recent progress in agent-based systems, flexible manufacturing, ubiquitous computing, and metrology-driven robotic assembly in the Evolvable Assembly Systems project. As such, although it is adapted for and grounded in manufacturing facilities for airframe assembly, it is not specifically tailored to that application and is a much more general framework. As well as outlining our conceptual framework, we also provide a vision for assembly grounded in a review of existing research in the area.

Keywords: Adaptive Systems, Agents, Agile Manufacturing, Context-Awareness, Flexible Manufacturing Systems, Intelligent Manufacturing Systems, Ubiquitous Computing

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1. MOTIVATION

The manufacturing sector in the EU and beyond must respond to demands for low and variable volumes of high quality, heavily-regulated products, in a high-labour cost area, at low cost (in terms of time, energy, space, and price). This is of particular relevance to the aerospace sector and the final assembly of airframe products. Such production systems must therefore deal with the challenge of increasing demand and regulation whilst also increasing autonomy, adaptability, and resilience (Kagermann et al., 2013). The key challenge is then the transformation of manufacturing systems into dynamic facilities that can self-learn, self-adapt, and self-reconfigure whilst maintaining verifiable performance characteristics within acceptable boundaries.

There is a significant volume of research in reconfigurable manufacturing, adaptive control, modular system design and modelling. Growing from the field of multi-agent systems (Wooldridge and Jennings, 1995), autonomous systems have long been acknowledged as a potential method for solving problems of scale and dynamics. One catalyst for its adoption has been the Autonomic Computing vision of IBM (Kephart and Chess, 2003). Autonomous systems research is extremely cross-disciplinary embracing learning, robotics, collective intelligence (Bonabeau et al., 1999), complex adaptive and self-organisation systems (Hillston et al., 2015), pervasive computing (Zambonelli et al., 2015), modelling and verification (Fisher et al., 2013), rule-based or norm-governed systems (Boella et al., 2006), human-computer interaction (Klein et al., 2004), decision support (Rodríguez-Aguilar et al., 2015), and sensor networks (Akyildiz et al., 2002). Cognitive Computing (Hussain, 2009; Modha et al., 2011) is another emerging disruptive technology with potentially significant impact on developing systems' abilities to understand regulatory requirements and rules. This includes how to adapt behaviour and structure to remain compliant whilst capturing the evidence justifying the changes or recommendations to the human operator. Several recent research projects have been reported that address some of the core research challenges in this area: decentralised self-aware and adaptive services and nature-inspired pervasive computing (EU FP7 SAPERE — see Zambonelli et al. (2015)); self-adaptive autonomic components and goal-oriented context-aware e-vehicles (EU FP7 ASCENS — see Wirsing et al. (2015)); rational agent architecture for autonomous decision-making (EPSRC Reconfigurable Autonomy — see Fisher et al. (2013)); formal verification of autonomy (EPSRC Formal Methods for Reliability Control of AUVs — see Veres (2007)) and decision environment for complex designs (EPSRC DECODE — see Scanlan (2009)). There has also been a considerable amount of work in artificial intelligence on 'fully autonomous' systems. The remote agent architecture used on NASA's Deep Space 1 mission allowed autonomous operations over long periods of time with tight deadlines, resource constraints, and concurrent activity among tightly coupled subsystems (Muscettola et al., 1998). There has furthermore been a significant amount of work on 'flexible' or 'adjustable' au-

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tonomy, where a human operator determines the appropriate degree of autonomy in a system (Bradshaw et al., 2004) and the use of 'social norms' to coordinate autonomous agents (Boella et al., 2006).

New fundamental research is required into methods for future production systems that can use self-* properties — self-adaptation, self-organisation, self-learning, self-healing, self-configuring, and so on (Seebach et al., 2007; Onori et al., 2011) — to autonomously function and adapt to accommodate any potential product with little to no human intervention. To achieve such functionality, production systems require new levels of context-awareness based on the concepts of ubiquitous computing. To that end, we propose a conceptual framework for ubiquitous context-awareness in cyber-physical production systems (CPPS), grounded in existing research and building on the programme of work begun in the UK EPSRC Evolvable Assembly Systems project (Ratchev, 2013).

2. UBIQUITOUS CONTEXT-AWARE DECISION-MAKING AND ADAPTATION IN MANUFACTURING

2.1 Ubiquitous Computing

Mark Weiser's vision of "The Computer for the 21st Century" (Weiser, 1991) coined the phrase "Ubiquitous Computing", and kick-started our understanding of ubiquitous context-aware technologies. This work envisioned a new way of thinking about computers, taking into account how humans interact with them, by making them 'invisible'. These first experiments showed that the power of the concept came from interactions, rather than from the individual devices. Following Weiser's work, various paradigms related to ubiquitous computing have appeared, all stressing the need to develop technologies that share a number of characteristics: they are distributed, co-operative, autonomous, heterogeneous, flexible, responsive, robust, (usually) human-centred, and possess many self-* properties.

2.2 Context-Awareness

Pervasive systems (Zambonelli et al., 2015) and ambient intelligence (Frei et al., 2010) are continuations of the vision of ubiquitous computing, which furthermore link the problem of designing such systems with coordination of distributed components. This link between context-awareness and coordination or co-operation is a recurring and vital concept and challenge for applications of context-aware systems, and can further be generalised to the concept of 'teamwork' and decision-making. Their approaches take advantage of RFID tags, ubiquitous sensors, and autonomous agent-based control to improve product design and production.

Reconfigurable autonomous systems (Dennis et al., 2014) are proposed to be useful in a number of scenarios where direct human control is inappropriate. The adaptability of the system is therefore key, and requires accurate context-awareness information on which to base its reconfigurations.

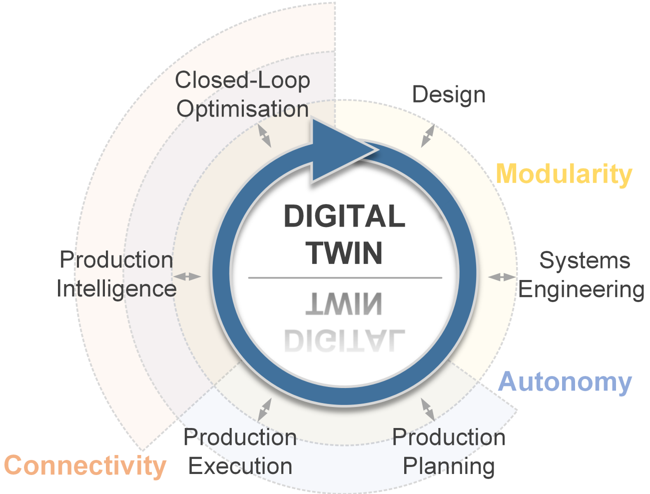

Fig. 1. The digital twin as part of the production lifecycle, adapted from Rosen et al. (2015).

Autonomic systems are a class of context-aware systems that have their origin at IBM and are described as follows: "The system collects information from a variety of sources including traditional network sensors and reporting streams, but also including higher-level devices and user context. These are analysed to construct a model of the evolving situation faced by the [system] with this model used as a basis for adaptation decisions" (Kephart and Chess, 2003). They have also been extended to specifically deal with autonomic communications networks (Dobson et al., 2006).

Collaborative innovation (Serrano and Fischer, 2007) has been proposed as the basis for a future product lifecycle management (PLM) system that collects all the digital data that was generated throughout the entire lifecycle of the product; from design, through prototyping and manufacture, into use by the customer. Similar in concept to ubiquitous context-awareness, this enables the quality of information used in planning, integration, operations, and problem solving to be greatly increased.

CPPS possess a number of properties that are common to ubiquitous context-aware systems, and recognise that the human-machine-process-logistics connectivity across all levels of production can lead to a variety of key applications (Zuehlke, 2010; Rosen et al., 2015). In some cases these CPPS are supported by a digital twin, designed to be a digital replica of the real system. Such a digital twin should incorporate the key enablers of modularity, autonomy, and connectivity; by building these into the production lifecycle at appropriate times, the information created in each stage becomes available to all following stages (see Fig. 1).

2.3 CPPS: Context-Awareness in Manufacturing

These ubiquitous context-aware systems have found use in the manufacturing domain; their properties provide a potential solution to a number of challenges facing modern industry. While traditional manufacturing control systems are centralised and hierarchical in order to optimise production, this also leads to their rigidity and inability to rapidly respond to changes (Colombo et al., 2006). A variety of approaches have applied the principles of lean manufacturing, leading to a shift to networks instead of hierarchies, dynamic self-coordination instead of assembly lines, and localisation of decision-making — in the areas of both human organisation and the automation itself. Examples of these paradigms are the development of multi-agent systems (Wooldridge and Jennings, 1995); intelligent manufacturing systems (Monostori and Prohaszka, 1993); bionic, fractal, and holonic manufacturing systems (Tharumarajah, 1996); reconfigurable manufacturing systems (Koren et al., 1999); digital and virtual factories (Kádár et al., 2013); and the co-evolution of products, processes, and production systems (Tolio et al., 2010). Other self-adaptive systems paradigms such as organic computing (Müller-Schloer et al., 2011), are concerned with complex systems more generally, but manufacturing is rapidly becoming a common application domain.

Current trends in intelligent and context-aware manufacturing are partially driven by the German concept of Industrie 4.0 (Kagermann et al., 2013). This 'fourth industrial revolution' is often characterised as being based on Cyber-Physical Systems (CPS). CPPS are the result of combining the CPS concept with some of the aforementioned manufacturing paradigms, and provide a number of advantages to industry that are vital to this new intelligent manufacturing domain, with autonomy being of particular importance (Monostori, 2014). However, it has long been recognised that the decisions required of the automation will occur too fast, too frequently, and will be too complex for humans to provide direct supervision; this was a main driver for the development of autonomic computing (Kephart and Chess, 2003).

3. CONCEPTUAL FRAMEWORK

We now present our conceptual framework for ubiquitous context-awareness in CPPS, shown in Fig. 2, and based around a number of key enabling technologies.

3.1 Edge Intelligence and Pervasive Metrology

The context-awareness required by our vision can be enabled through the use of *pervasive and ubiquitous metrology* throughout the wider manufacturing system, a process that has already begun to be investigated (Drouot et al., 2017). This will be leveraged by the kinds of distributed *multi-agent control systems* already being used in the Evolvable Assembly Systems project to provide batch-size-of-one production (de Silva et al., 2016). Progress in *edge computing and ambient intelligence* (Akyildiz et al., 2002; Aarts and Wichert, 2009; Dobson et al., 2010) will allow the use of small, low power, low cost, bolt-on sensors that act as both metrology sources and also data aggregators. This approach will also encompass real-time asset tracking for all resources, tools, materials, and parts. Processing at the edge will help to minimise the costs of data transmission and storage, with the remainder being addressed through the use of smart *autonomic wireless communication networks* (Dobson et al., 2006).

3.2 Simulation, Optimisation, and Traceability in a Fully Autonomous Factory

The use of a *digital twin* backed by context-awareness allows all items in the factory to be fully traceable. This live virtual replicant of the production environment enables full-3D simulation for testing new methods, machines, parts, etc. The physical system can thereby be optimised virtually, leading to reduced cost, risk, and decision time along with increased production. The information gathered by the pervasive metrology systems can be used to generate a real-time 'ProductDNA' for all parts that pass through the production system, tracking all operations that have been performed.

A *modular production system* (Drouot et al., 2017; Lohse et al., 2005) will push the concept of plug and produce (Antzoulatos et al., 2014) to new levels of flexibility, allowing new technology to be introduced to the system in mid-production cycle. The digital twin allows the validation and verification of autonomous systems, taking adaptive composition (Sanderson et al., 2013) into account. Such a system continually provides evidence of compliance and manages itself into a compliant state (i.e. '*adaptive process correctness*', or proven continuous dynamic compliance (Nafz et al., 2010, 2011)).

The dynamic process control and optimisation required to take advantage of such an autonomous factory can only be provided by *self-adaptive and self-organising machine intelligence* (Sanderson et al., 2015; Pitt, 2014). In addition to the process control, this system will use the context-awareness data and digital twin simulations to perform real-time condition monitoring with autonomous planning of maintenance and logistics operations, connecting to future MES, MRP, PLM, etc.

This *enterprise integration* is also required for the provision of holistic decision-making on the impact of any disruptions which may occur that the system is not empowered to address automatically (Golightly et al., 2016). It should also present flexible and dynamic real-time reporting information with role-based dashboards that target the specific issue and corrective action. This integration furthermore lets the system keep records of all processes during the production for both internal and external auditing, linked to the ProductDNA.

3.3 Augmented Workforce

These autonomous production systems will provide a wide array of methods by which the operator or manager can be augmented in their tasks. Previous work has highlighted context-awareness as a key input for new methods of *hybrid decision-making* in production systems that are acknowledged to be joint cognitive systems (Hollnagel and Woods, 2005; Golightly et al., 2016). Ubiquitous context-awareness improves not only safety (Zachary et al., 2015), but also automatic capture of operator processes at each step in the project. This saves on manual reporting and can also provide *contextual work instruction or support.* Real-time autonomic communications will also allow operators to provide *real-time remote assistance* to any resource in the factory, be that human or robotic.

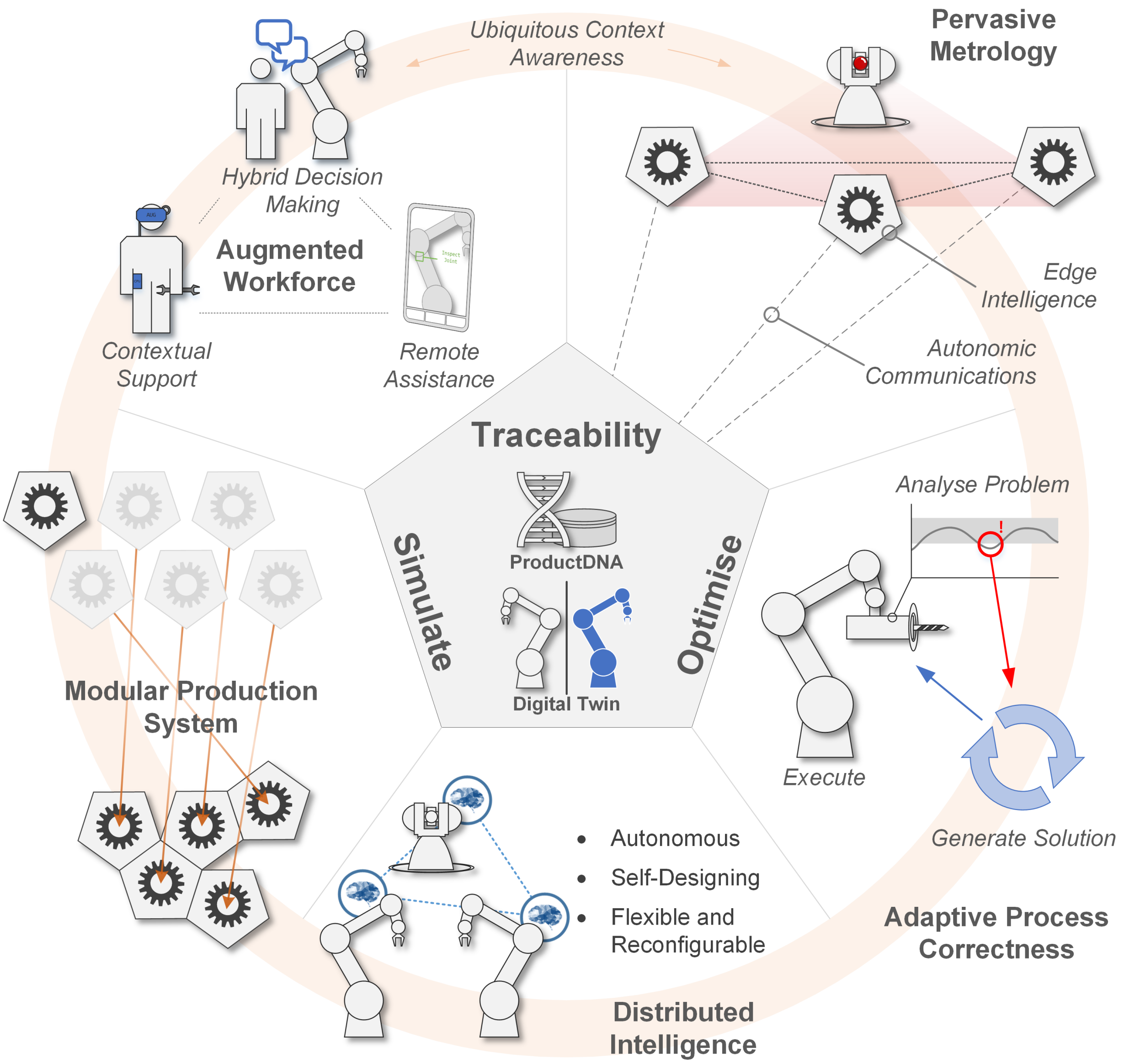

Fig. 2. Conceptual Framework for Ubiquitous Context-Awareness in CPPS.

An immediate benefit of this would be the introduction of a *smart work bench* containing smart tools that automatically assists the operator with part recognition, positioning and orientation, build instructions, inspection, and recording of all process parameters (Niedersteiner et al., 2015).

3.4 Context-Aware Robotic Automation

The use of robotics powered by ubiquitous context-awareness of the factory situation will enable a fully-autonomous factory that is accurate, repeatable, safe, and right first time, with zero waste and total in-process measurement for traceability.

As well as 'traditional' robotic platforms, we propose to leverage innovative robotic solutions for challenging situations. 'Tentacle-like' *continuum arms* have been suggested as a potential solution to multi-purpose robotic arms due to their flexibility and ability to work in extremely restricted spaces and for inspection behind obstructions. Some challenges to their adoption include (Walker, 2013) working length and thickness (most current examples are quite short) and stiffness (their tentacle-like shape makes whole-length stiffness an issue). These arms can be deployed in self-organised clusters with distributed decision-making that autonomously determines the best methods to manipulate parts. "*Dreaming robots*" have been proposed as a solution to capturing experience and propagating learned optimisations. During down time, the robots in a system 'dream together' by exchanging simulations based on individual experiences that can then benefit robots that did not directly encounter those situations (Braun, 2015). *Soft robotics* has contributed to a new field of novel grippers in addition to its human-safe applications. These include those based on granular jamming (Brown et al., 2010), variable stiffness (Li et al., 2017), and controllable adhesion (Song et al., 2014). *Self-designing reconfigurable fixtures and tooling* allow for a massive reduction in associated non-recurring costs and further contribute to the transformability of a production system. An extension of previous work on uncertainty-aware fixturing (Bakker et al., 2009, 2017), this can be accomplished through a combination of automatic actuation and use of continuum surfaces matched to part morphology (Merino et al., 2012).

4. CONCLUSIONS

In this paper we have used a review of existing cross-disciplinary research to develop a vision for complex cyber-physical assembly systems anchored in ubiquitous context-awareness. This vision forms the basis of a conceptual framework that extends our previous work on the EPSRC Evolvable Assembly Systems project. Such systems leverage self-* properties to autonomously function and adapt to accommodate any potential product with little to no human intervention.

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