A Transformable Manufacturing Concept for Low-Volume Aerospace Assembly

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Abstract: This paper presents a vision for a transformable manufacturing system based on reconfigurable and adaptive intelligent technologies, anchored in the description of a real automation cell demonstrating the assembly of various aircraft structures. This production environment developed by the University of Nottingham is a new reconfigurable production environment for the complete manufacturing of high-accuracy high-complexity low-volume aerospace products. This agile reconfigurable cell can accommodate multiple product variants and families which ensures that the capital invested in fixturing is not tied to one application. By compressing the assembly of an aircraft wing structure into a single automated cell, the Future Automated Aircraft Assembly Demonstrator features a flexible, holistic, and context-aware solution that includes automated positioning, drilling, and fastening processes. The assembly cell is based on industrial robots for the handling of aircraft components while an intelligent metrology and control system monitors the cell and ensures that the operations carried out are safe and adhere to the tight tolerances required. These modules are integrated into a single, standardised interface requiring only one operator to control the cell. Performance analyses have shown that, using the reconfigurable production environment described hereafter, an assembly part location accuracy better than ±0.1 mm can be achieved.

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1. INTRODUCTION

The manufacturing industry is facing increased pressure to shorten the product lead-time, increase product diversity and efficiency, and produce more specialised products often with shorter lifecycles, all the while reducing production costs. In order to maintain profitability and efficiency in high labour-cost areas (Rhodes, 2015), there is a need to address a number of demands:

- Rapid ramp-up and -down of production systems.
- Elimination of non-recurring costs, such as those from jigs, fixtures, and line commissioning.
- Autonomous response to disruptions such as failures and demand fluctuations.
- The drive to Manufacturing as a Service (MaaS).

This is especially true for the increasingly crowded aerospace market. Considering the medium range jet market as an example; Airbus, Boeing, Bombardier, Comac, Embraer, and Mitsubishi are all vying for customer orders. As such, airframe manufacturers need to find new ways to obtain the competitive advantage. There are numerous ways a competitor can make its products attractive, the main ones are either a cheaper aircraft price, reduced operating costs, or a short product lead time. Accounting for around 80% of the overall product costs (Saravi et al., 2008), reducing production costs offers the most scope for cost reduction which can be passed on to the consumer or re-invested in advanced technologies.

Traditional aerospace assembly solutions see components manually located and constrained using large monolithic steel structures called assembly fixtures. Assembly fixtures are expensive dedicated structures offering little or no adjustment to accommodate design changes or product variants. They cannot be used elsewhere once a product is changed or discontinued, meaning the capital investment is not recovered. These fixtures are built to the required geometry, but offer no indication of their current condition between calibrations, which can be up to every two years. As a result there is no real-time update on the fixture condition. It is not uncommon for a traditional aerospace fixture to fall out of tolerance causing assembly errors which are passed downstream. It is not until the product inspection, often many processes later, that these issues are identified causing product and assembly re-work. This post-processing increases the cost and lead-time of the product.

In order to be cost-efficient and shorten the time-to-market, a production system must then be agile and flexible to adapt to design changes, volume fluctuations, and different product families. This paper presents the University of Nottingham (UoN) Evolvable Assembly Systems (EAS) model and its grounding in the Future Automated
Aircraft Assembly Demonstrator (FA³D) real-world aircraft structure assembly cell.

Section 2 of the paper reviews the concepts of Flexible, Reconfigurable, and Transformable Manufacturing Systems. Section 3 introduces the new architectural concept of Evolvable Assembly Systems. Section 4 outlines the features of the FA³D in more detail and describes how it is able to adapt itself to multiple product families and variants. Finally, conclusions and work remaining to be done are discussed in section 5.

2. FLEXIBLE, RECONFIGURABLE, AND TRANSFORMABLE MANUFACTURING SYSTEMS

In order to meet the new demands placed on manufacturing systems, new technologies that provide high levels of responsiveness, robustness and resilience are required. As a result, manufacturers from many sectors have investigated smart, flexible and adaptive assembly and manufacturing lines, contributing to the field known as the fourth industrial revolution (Kagermann et al., 2013). Manufacturers have been driven by customer demand for customised products to change their production processes more flexible and adaptive. The first example of this is the mass customisation seen in the automotive industry, but other industries such as pharmaceutical, aerospace, and general machine building are beginning to follow suit.

The first approach developed for this was Flexible Manufacturing Systems (FMS) (Brown et al., 1984; Sethi and Sethi, 1990), which increases the variety of parts manufactured by the system. This was followed by Reconfigurable Manufacturing Systems (RMS) (Koren et al., 1999; Mehrabi et al., 2000). As in agile manufacturing, RMS aims to reduce the response time to change of markets and customers.

Other approaches aim to increase the robustness (resilience against disturbances), autonomy and self-reliance of the manufacturing system. The concept of fractal factories considers factories that are composed of self-organising small components communicating and cooperating to form decentralised self-similar hierarchies and to execute tasks (Warnecke, 1993). Conversely, Bionic Manufacturing Systems are modelled on natural living organisms; as autonomous distributed systems where processing units are “living” components (Tharumarajah, 1996).

Holonic Manufacturing Systems (HMS) are based on the concept of a holon; an autonomous and co-operative building block. These holons form an agile manufacturing system holarchy (Van Brussel et al., 1998; Leitão and Restivo, 2006). Implementations of HMS often use autonomous cooperative intelligent agents (Wooldridge and Jennings, 1995), but agent-based control is used in other paradigms as well, e.g. Onori et al. (2012).

This research has led to the evolution of capital-intensive assembly lines into reactive smart assembly systems that can adapt to changes in product requirements and demand with short configuration and ramp-up times (Dashchenko, 2006). As shown in Figure 1, such transformable manufacturing systems should compress the capabilities of a traditional assembly line into a single transformable cell that is reconfigurable to accommodate a wide range of products and tasks, combined with a low cost of maintenance, system reconfiguration, and technology integration.

A transformable manufacturing system enables the production of high-cost, high-complexity, high-variability, low-volume products more effectively than has previously been possible. The ability to adapt the system configuration to accommodate multiple products addresses the batch size of one problem, wherein each item produced by the system must be unique. Adaptable and uncertainty-aware fixtures and production methods allows the time between each different product to be reduced, and the non-recurring costs inherent in the deployment of single-use fixtures and systems to be eliminated. The development of multi-purpose cells also allows the compression of a line of stations down to a single cell, resulting in a massive cost, space, and throughput improvement.

3. ARCHITECTURAL CONCEPT OF EAS

The development of a transformable manufacturing system requires a new architectural concept. The Evolvable Assembly Systems (EAS) project is a novel approach to a manufacturing environment that is able to respond rapidly to changes in product, process, or market (Chaplin et al., 2015).

The transformability of the system requires the system to be responsive to disruption at all times. In EAS this is achieved through a foundation of context-aware adaptation managed by distributed agent-based control.

3.1 EAS Adaptation Cycle

The context-aware adaptation in EAS is cyclic in nature, as shown in Figure 2. During operation, the system resources are performing business as usual. Concurrently to that, the system is monitoring all aspects of the operation. The progress of parts and products through the system is tracked, with each resource updating the system as a whole as to their status and the tasks being performed. Data concerning the environment in which the system is based is also recorded and correlated against the performance data. This can then be fed back into the production process to improve efficiency or identify potential sources of faults or quality failures.

Once the system has gathered data and identified a possible improvement that can be made, an internal adaptation may occur. Once the state and performance of the system that has been recorded reaches a predetermined threshold, the pressure on the operation of the system may require a configuration change to either mitigate or exploit the condition. Alternatively, the system operator...
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