

Evolvable Assembly Systems: Mechatronic Architecture Implications and Future Research

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Abstract

The balance between assembly process optimality and their system's ability to adapt to new requirements is a key to success for assembly companies. To increase SME's survivability, an effective methodology is needed to handle the requirements of both agility and mass customization. Evolvable Assembly Systems (EAS) paradigm is a next generation assembly systems focused on these issues. Three key issues are here in focus: process-oriented approach, fine modular granularity, and module intelligence through lighter multi-agent technology at the shop floor level. These issues are the core of the European project IDEAS, where the key purpose is to improve system responsiveness.

Keywords:

Evolvable Assembly Systems; Modularity; Autonomous Systems

1 INTRODUCTION

Companies need to keep up with rapidly changing market conditions to stay competitive. The main issues are related to a company's market and competitors, e.g. it remains difficult for companies to predict the type and range of products that will have to be developed, the volume of production, and the lifespan of the products. Consequently, the uncertainty and dynamics of the internal and external environments are the grounds of difficulties in being responsive to market conditions. Being able to cope with rapid change is a necessity in order to survive, particularly for SMEs due to their limited buffer and position in the supply-chain.

To be competitive, assembly systems need to respond to changing environmental conditions and to perform the assembly tasks in an efficient way. The former can be measured in the time it takes for a system to be reconfigured for a new production scenario; the latter is measured as a function of an ideal assembly sequence. Assembly systems that are designed to function very close to optimum (maximum efficiency for certain criteria) for a specific production scenario need to be reconfigured and re-planned for the next in order to remain optimal. This configuration and the following ramp-up will unquestionably occupy a certain amount of time, during which the assembly system cannot produce anything and costly experts are involved to tune the system to the new requirements. Although optimality is possible to achieve, for most products it is rarely advantageous to delay the production for the sake of running a system in optimum, especially in the light of increasingly shorter time-to-market and frequent changes to customer requirements. For this reason there is a trade-off between system responsiveness and production optimality. Therefore, the balance between these two factors plays an essential role for companies to stay competitive. System responsiveness gained importance more than optimality in this balance with

shortening product life cycles and demanding process requirements. The desire for optimality and high resource utilisation has resulted in systems that are composed of specialised machines and equipments. The current trend towards adaptive and responsive systems, driven by increasingly dynamical market conditions, is incompatible with the specialised machines and equipments. Traditional systems are unable to achieve responsiveness with their current control and assembly solutions. Dedicated equipment and centralized control approaches are in themselves restricting adaption to new circumstances. To overcome these problems there is a need for new rapidly deployable and affordable (economically sustainable) assembly systems based on reconfigurable, modular concepts that would allow continuous system evolution and seamless reconfiguration [1].

The Evolvable Assembly Systems (EAS) approach [1] was first introduced in 2002. EAS targets highly adaptable mechanical and control solutions that can enhance reusability and interoperability of modules, enabling lifetime extension of the modules and short deployment times at shop floor level. Modularity of assembly components is the base of EAS which can subsequently be used interchangeably for the purpose of building specific assembly systems whenever a business opportunity arises [2]. EAS has an Agent Oriented Architecture (AoA) based on dedicated and task specific process-oriented modules that can form coalitions in order to accommodate complex tasks based on a detailed ontology. Autonomous process-oriented modules enable system reconfiguration regardless of the frequency and scale of the required assembly system change. Designing a modular system structure with a distributed control approach based on agent-oriented architecture both at the factory and device level is the aim of a recently initiated European project titled Instantly Deployable Evolvable Assembly Systems (IDEAS).

In the following sections requirements of the next generation assembly systems will be clarified; shortcomings of available paradigms in meeting these needs are addressed; the EAS concept is presented related to the requirements; and finally future research is addressed and paralleled with the planned efforts in the IDEAS project.

2 REQUIREMENTS OF NEXT GENERATION ASSEMBLY SYSTEMS

According to Shen W. et al. [3], strongly time oriented, highly responsive systems should satisfy a number of fundamental requirements: (1) full integration of heterogeneous software and hardware systems within an enterprise or across a supply chain; (2) open system architecture to accommodate new sub-systems, both hardware and software, or to decompose existing sub-systems; (3) efficient and effective communication and cooperation within an enterprise or across enterprises; (4) embodiment of human factors; (5) quick response to unexpected internal or external disturbances; and (6) fault tolerance both at the system and sub-system level to diagnose and recover system failures. To be able to meet the requirements above, the system must have modularity at different levels and it must have a distributed control structure, only then can high availability, robustness and responsiveness be achieved [4][5].

2.1 Modular architecture

Modules are exploited by companies as a means to divide a complex system into more manageable parts [6]. Their organisation and performance become dependent on both the modules themselves and the relationships between the modules. With the continuously developing information and communication technologies and standards, adoption of internet, instability of the market system boundaries are extended from a factory towards various types of network relationships [7].

A module can be described as the smallest building block of a system. Possibility of assigning varying functionalities to modules, their aggregation capabilities and contribution to control system grounds modular structure to have a wide application area in industry. Issues arising with modular systems include: accomplishing granularity at lower levels (fine granularity) where modular characteristics are shown; developing interface of the modules in order to communicate both to internal and external environment; defining skills and capabilities assigned to modules; and advancing abilities of cooperation and creation of coalitions in order to achieve a common target and their methodologies.

An assembly system can be decomposed physically as in figure 1. New system design requires reconfiguration and setting up of all lower levels. A modular structure need to be realized at the lowest level as possible, i.e. the device level, with high adaptability to be truly reconfigurable. Realizing the level of modularity at higher levels results in a costly integration, limited and slow reconfiguration as in the case of Flexible Assembly System (FAS).

EAS has already attained a modular structure at the shop floor level by process oriented reconfigurable modules. However, the main challenge is realizing the modularity at the lowest level in terms of control issues with embedding intelligence in modules.

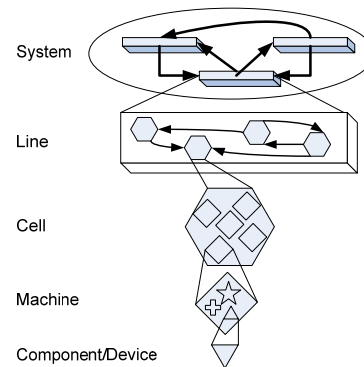


Figure 1: Levels of an assembly system.

2.2 Distributed heterarchical control system

In essence, control system refers to managing the physical and information processing activities of different entities on the shop floor, for example, products, equipments and material handling systems, for the purpose of accomplishing certain objectives [8]. Dispatching rules, heuristics, and mathematical modelling are some of the tools used for planning and control purposes. A control system should not limit the transformation of the assembly system, i.e. its adaption to new product and process requirements. The evolution of control architectures has been analyzed by Dilts et al. (1991) under four classes: centralized, proper hierarchical, modified hierarchical and heterarchical [9]. In centralized control all systems activities and control decisions are managed in a centre. Although centralized control has the advantage of obtaining global information in one place, enabling global optimization, it lacks the responsive ability to handle issues of expanding and shrinking assembly system due to complication of modification. As discussed earlier, responsiveness is more important compared to optimality in dynamic market situations; consequently, significant adaptation time in response to new system configuration needs has caused centralized control system to become inconvenient. A proper hierarchical control architecture is composed of several control levels with master/slave relationship. Achievements are adaptability up to a limit, higher robustness and responsiveness compared to centralized control. However, fast responding to disturbances and modifications remained an unsolved issue. To deal with this, interaction has been added between entities at the same control level, keeping all the characteristics of proper hierarchical system, which is called modified hierarchical control architecture. Loose master/slave relationship and cooperation ability in the same control level enabled local autonomy. Nevertheless adaptability remained a major problem due to the hierarchical structure. According to Wang L.C. et al. (2009) there are 3 main drawbacks of hierarchical control systems [10];

- Structural rigidity; difficulty in expanding and shrinking the system [11].
- Difficulty of designing a control system; complexity of managing interrelations between hierarchical levels when reconfiguring [9].
- Lack of flexibility; unpredictable disturbances invalidate current schedule because deterministic behaviour in

lower level controllers is assumed by higher level ones [11].

Heterarchical control system is characterized by autonomous components without different levels of authority to defeat the problems arising with hierarchical control. It is aimed to achieve full local autonomy, distributed decision making for activity coordination, no master/slave relationship and only local databases. Global decisions are made by cooperative approach of autonomous components. Improvements coming with distributed heterarchical control are [12];

- Diminishing long-term instability due to shorter reaction delays.
- Re-initialisation and reconfiguration issues which arise due to disturbances or system shutdown are becoming less complicated to manage.
- Enhance product traceability and enable more active products throughout the entire lifecycle.
- Eliminating different levels of control authorities prevents reorganization and reprogramming of higher level control elements every time a component is added or removed. This characteristic allows the control system to adapt more easily in response to unexpected disturbances occurring in internal and external environment.
- Facilitate supply chain collaboration mechanisms, as well as collaboration in virtual and networked enterprises or companies.

Distributed heterarchical control systems have found wide application areas based on multi-agent architecture which is building the ground of EAS control structure as well.

Although modularity and distributed heterarchical control systems have been modelled by varying paradigms such as flexible assembly systems, holonic and reconfigurable assembly systems, there has been limitations and lacking areas considering applicability, feasibility (in terms of cost and sustainability) and efficiency in responding to internal and external requirements.

3 CURRENT PARADIGMS

Flexible Assembly Systems (FAS) [13] aimed to encapsulate the required abilities and functions of one or a few similar product families in one unit. It is a costly solution, particularly for SMEs, since extra process capabilities have to be purchased even though they will not be needed. Configuring the system to product families whose process requirements go beyond the available capabilities of the assembly system resulted in costly and time consuming procedures. FAS were not appropriate to dynamic market conditions with its coarse modularity and product oriented structure, therefore could not extend its applicability in industry. Furthermore control structure is hierarchical which complicates system reconfiguration from the software point of view.

Reconfigurable assembly systems have an enhanced adaptability comparing to FAS taking into account its flexible capacity and functionality. Reconfigurability is defined as rapid adjustment of capacity and functionality in response to new circumstances by rearranging the system components [14]. The key characteristics are modularity, integrability, convertibility, diagnosability and customization. A typical feature of reconfigurability is that it does not handle the entire enterprise (which includes product design, organization,

management, marketing, operations etc.); however, it handles responsiveness of only production system [14]. It can be concluded that overall responsiveness with system approach and intelligent control strategies was lacking.

Holonic Manufacturing System (HMS) has been introduced with the concept of holon. Holon is identified as both a whole and a part the whole [15]. The requisite to be a holon is the ability of creating and controlling the execution of its own plans and strategies. Holons have to enclose an information processing part and optionally can contain a physical processing part. Any unit with information processing abilities can be represented as a holon such as a machine, a work piece, conveyor belt, scheduler and they are categorized into three main classes: resource holons, product holons and order holons [16][17]. There are 2 essential features of a holon: autonomy and cooperative behaviour. Autonomy is the capability of making their own decisions and controlling their activities whereas cooperative behaviour is the ability of communication and negotiate with other holons for the purpose of achieving a specific system target. A system of holons which are cooperating in order to achieve a common goal or objective is called a holarchy [18]. The control structure of holonic systems lies between fully hierarchical and heterarchical structures to compensate a weak point of fully heterarchical control systems, which is the inability to guarantee a certain global behaviour and performance [19].

In the above concepts there are three fundamental points that prevents achievement of full adaptability and responsiveness:

- Product oriented architectures: product requirements are imposed to assembly system by leaving freedom to product designers and assigning complexity to manufacturing and assembly systems.
- Coarse modularity: the system is abstracted by classifying the available system into manageable parts and relations are established between them with coarse modularity. Modularity with autonomous behaviour is achieved only at the machine level.
- Lack of intelligence at component/device level: although reconfigurability has been realized physically at component level, from the control point of view full autonomy could not be achieved at the lowest level.

4 EVOLVABLE ASSEMBLY SYSTEMS

The aim of EAS has not been to develop limited flexibility or barely physical reconfigurability with separate control mechanisms. Instead, the aim has been to achieve overall system adaptability by self-configuring, process oriented modules with short deployment time at the shop floor/component level based on agent oriented architecture. To be able to achieve system responsiveness (true agility/flexibility), the lowest building blocks of a system are required to exhibit highest rate of adaptability/evolvability [20]. In the EAS approach, process oriented modules are the basic building blocks that enclose computational power, thereby being autonomous with the capability of interconnecting with other modules to create coalitions for the purpose of accomplishing specific system objectives.

As discussed before, the product design process is in current approaches generally considered as an external part of the system from where product requirements are imposed to be met by the assembly system. Availability of skill-based EAS

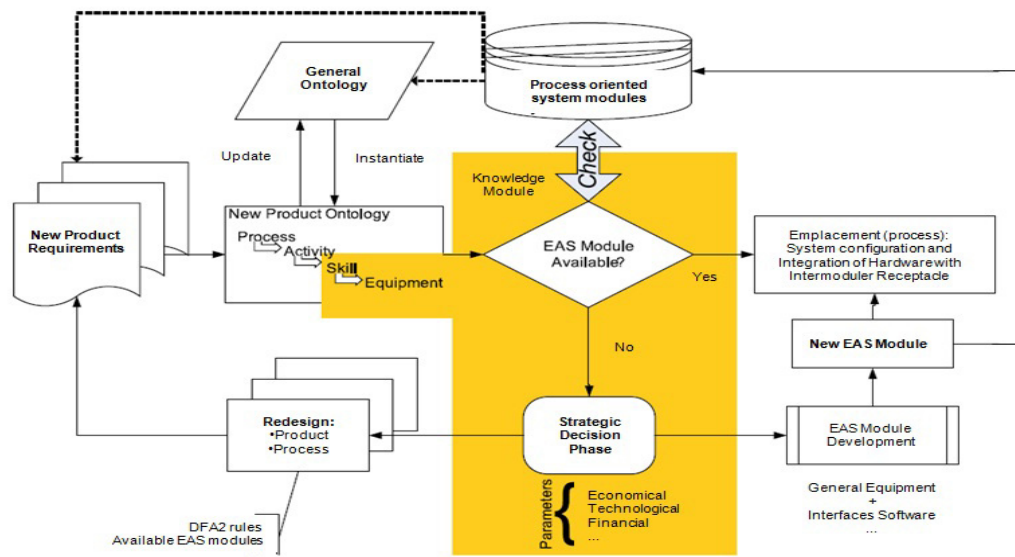


Figure 2 : The EAS approach (Onori et al., 2008).

modules is the foundation of a two way interaction between product design and assembly system, enabling designers to be aware of existing skills and capabilities of the current assembly system. A product can be described as a group of processes where each process has its equivalent skill or group of skills. Even complex processes can be described as a combination of basic skills [20]. With the available skill-based modules it is possible to know which processes are attainable in advance. As in the figure 2, every time new product requirements arise, processes are extracted to match the current skills and respective modules at the end. In the case of absence of a required module, a strategic decision is made either to develop a new EAS module or to redesign. The decision is based on several factors, e.g. company policy, technology, economical feasibility and so on. After the development of a new module, the module database is updated and the emplacement process takes place, which consists of system configuration, hardware integration, and set-up of assembly system. In EAS, emplacement of a module is the comprehensive description of the module functionality with its relation to all aspects such as product, process and interaction with other modules [21].

General ontology contains know-how of assembly processes of company. When new product requirements arise, product ontology needs to be developed by decomposing processes to activities, activities to skills and matching skills to equipments. EAS Methodology provides the reference architecture, enablers and modelling formalisms which are described in detail in [20].

4.1 Process oriented structure

Traditional approaches resulted in specialized assembly systems in response to the product types and their process requirements. A deeper look into relations between product, process and assembly system design allows to detect that although many processes are shared by different product families, product-specialized equipments are used with the intention of improving system efficiency and performance during the assembly of a specific product. However this prevents reuse of equipment for varying products. At the same time, dedicated systems lack quick reconfiguration abilities, adaptability and responsiveness. Process oriented

EAS modules are dedicated in terms of the requirements of the processes that enables the modules to be benefited again in different assembly system configurations. As far as sustainability is concerned, reusability of EAS modules brings about several advantages from economical, ecological and social points of view.

The necessity in process oriented structure is formalisation and classification of assembly processes which is accomplished by EUPASS in assembling process ontology specification.

4.2 Fine granularity

The EAS approach is distinctive on achieving fine granularity comparing to other paradigms. Granularity can be described as the level of complexity of the component which is building the system [22]. The higher the properties of modularity are exhibited in assembly system levels (figure 1), the coarser the granularity is. Extending or shrinking a system by reconfiguring cells is a case of granularity on cell level. The feasibility of device level granularity has been tested on an EAS during the EUPASS project [23], resulting in the development of a MASMEC cell, currently placed in KTH lab.



Figure 3: MASMEC cell.

Even though modularity at the device level enables physical adaptability; control system has to be even more adaptive in order to achieve full adaptability.

4.3 Intelligence at component/device level

A distributed heterarchical control structure avoids many of the drawbacks of hierarchical control; however, the control

systems are kept separate from the physical system in current approaches (for example, a scheduler holon in HMS). This fact led to the obligation of real time assembly system monitoring since unsynchronized control system from the real assembly environment can cause inconsistencies. To achieve full autonomy, modules must have computational ability together with standardised interfaces. Computational ability inside the modules allows them to self-configure and highly developed interfaces enable modules to communicate and negotiate effectively.

A key problem with completely decentralized systems is the lack of global information collected in a centre which leads to difficulties on optimization and decision making. This issue has been tried to be overcome by planning and scheduling agents or holons. Although some degree of control system decentralization has been reached by this approach, every time a reconfiguration happens the scheduling/planning mechanism is required to be updated, which shows that there are still vertical dependencies in the control structure. The purpose is to eliminate the dependence to a central control location when adding or removing any module, and thereby achieving true decentralized control structure. This requires intelligence to be embedded in the modules at the device level, which is an essential characteristic of assembly system evolvability. In essence, each module has three abilities: (1) being aware of its environment with the help of communication capability enabled by interfaces, (2) evaluating the information obtained by its embedded computational ability, and (3) acting appropriately. Self-* abilities become feasible with these features such as self-configuration of the modules, self-organization of coalitions, self-diagnosing of disturbances and self-healing mechanisms etc... Self-* properties are fundamental in evolvable systems to attain full autonomy in the sense they allow hiding system complexity and eliminating user dependence.

Self organizing coalitions are structured in response to process requirements that are so complex that any single module's skill is not sufficient to meet. Throughout coalition formation, skills that are beyond the combination of basic module skills may emerge. Emergent behaviour, which can be described as the properties that emerge from the coalition of modules, is playing essential role in evolvable assembly systems. This means that addition of a module to another module or to a coalition may contribute with more than its basic skill.

The EAS control structure is based on Multi Agent System (MAS) characteristics. There are two main reasons: MAS already holds the principle and structure of interaction within a society of individual agents, and emergence is best handled with multi-agent approach [24]. The decisions are made depending on several negotiations between the agents, which necessitate efficient communication protocols. Agent negotiations can result in difficulties with the response time when the size of the assembly system increases. Learning mechanisms can however construct a base to find out the patterns of system behaviour (e.g. cause-effect relations) in certain environment conditions, which can be exploited in decreasing the requirement of communication and negotiation between the agents. In a dynamic, stochastic assembly system environment an improved learning system can even lead reactive behaviour to be evolved into proactive behaviour.

5 FUTURE RESEARCH

Current paradigms are inadequate to satisfy next generation assembly system requirements. Problems arising from product-oriented architecture have been overcome by process-oriented modular approach that has already been validated by EAS (EC FP6 EUPASS project) and a demonstrator has been developed. The problems with coarse modularity and making modules intelligent are to be handled as the future development areas in EAS within the FP7 IDEAS project. The target is to achieve factory level responsiveness by full adaptability in module/device level. IDEAS proposes that production system adaptability goes beyond rapid physical configuration abilities. In order to attain responsiveness in the factory level, there has to be full adaptability in module/device level supported by decentralized multi-agent based control approaches. To achieve this, self-configuring, highly adaptive, process-oriented components have to be developed, and technological focus has to be shifted from complex, flexible, multi-purpose systems into simpler, dedicated machine modules maintained by a highly distributed control system approach. Some structural and control prerequisites need to be met which are;

- Process-oriented modules should construct the smallest building blocks, and coalitions which are gathered by different module combinations should meet overall assembly system requirements.
- The control system has to be even more adaptive, which obliges the use of distributed heterarchical control structure.
- Two points addressed above have to be structured based on adaptive control approach at three levels, factory, line/cell and module level.

At factory level high-end Agent Oriented Architecture (AoA) copes with the control. With the availability of light agents in the shop floor level, bidirectional communication becomes feasible between factory level and shop floor level. Each specific product is composed of a set of process requirements and process-oriented modules are dedicated to meet a basic process called skills. Hence, product orders, product introductions and processes are all linked to skill-based equipment, which is creating the opportunity for the agent oriented control architecture to minimize reconfiguration and deployment time.

Line/Cell level is the intermediate level where self-reconfigurability is aimed to be achieved. AoA enables autonomous reconfigurability in this level in response to factory level demands with the support of device level adaptability. Moderate level of adaptability will be attainable together with self-organisation, self-diagnosis and self-adaptation abilities, all based on the AoA approach.

Device level is the level where full adaptability and responsiveness capabilities exist. For the assembly system to exhibit evolvable behaviour full adaptability characteristic of this level plays vital role. Self-diagnosing ability within the modules, which is applicable with the forthcoming embedded intelligence will enable optimization of the modules to a selected process. This occurs by the update of knowledge base inside the modules by self-diagnosing ability according to the output of the system.

The modular structure allows coalition formation and stepwise improvement of the assembly system; therefore, the control structure has to be enhanced enough to meet the increasing demand of the system. To achieve full adaptability in the device level and to eliminate reprogramming efforts every time a module is added or removed, a central control structure must be avoided. Therefore, more than one single control system architecture is needed. There are two types of architectures to be considered; the individual architecture of each module and the architecture of the community of the modules that interactively create the assembly system. So self-* properties will be realizable for the modules.

IDEAS is not a pre-defined closed unit system with all the characteristics determined beforehand; however, it is a system composed of process oriented modules with evolutionary properties that can last several generations of product families. The development of a prototype industrial assembly system is one of the key goals of the IDEAS project.

6 CONCLUSION

EAS is a promising paradigm that can lead achieving system responsiveness with its device-level process-oriented modular structure supporting stepwise automation and with its embedded intelligence supporting true decentralized control systems based on multi-agent systems.

In order to establish communication to varying industry and research areas, as well as to circulate the updates of paradigm and its applications, a webspace has been created: <http://www.eas-env.org/>.

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