Computers in Industry 66 (2015) 99–111

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution

José Barbosa [a,c,d,*], Paulo Leitão [a,b], Emmanuel Adam [c,e], Damien Trentesaux [c,d]

[a] Polytechnic Institute of Bragança, Campus Sta Apolónia, Apartado 1134, 5301-857 Bragança, Portugal
[b] LIACC – Artificial Intelligence and Computer Science Laboratory, R. Campo Alegre 102, 4169-007 Porto, Portugal
[c] Univ. Lille Nord de France, F-59000 Lille, France
[d] UVHC, TEMPO Research Center, F-59313 Valenciennes, France
[e] UVHC, LAMIH, F-59313 Valenciennes, France

ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 29 October 2014
Accepted 29 October 2014
Available online 20 November 2014

Keywords:
Holonic manufacturing systems
Multi-agent systems
Evolutionary systems
Self-organization

ABSTRACT

Nowadays, systems are becoming increasingly complex, mainly due to an exponential increase in the number of entities and their interconnections. Examples of these complex systems can be found in manufacturing, smart-grids, traffic control, logistics, economics and biology, among others. Due to this complexity, particularly in manufacturing, a lack of responsiveness in coping with demand for higher quality products, the drastic reduction in product lifecycles and the increasing need for product customization are being observed. Traditional solutions, based on central monolithic control structures, are becoming obsolete as they are not suitable for reacting and adapting to these perturbations. The decentralization of the complexity problem through simple, intelligent and autonomous entities, such as those found in multi-agent systems, is seen as a suitable methodology for tackling this challenge in industrial scenarios. Additionally, the use of biologically inspired self-organization concepts has proved to be suitable for being embedded in these approaches enabling better performances to be achieved. According to these principals, several approaches have been proposed but none can be truly embedded and extract all the potential of self-organization mechanisms. This paper proposes an evolution to the ADACOR holonic control architecture inspired by biological and evolutionary theories. In particular, a two-dimensional self-organization mechanism was designed taking the behavioural and structural vectors into consideration, thus allowing truly evolutionary and reconfigurable systems to be achieved that can cope with emergent requirements. The approach proposed is validated with two simulation use cases.

1. Introduction

Nowadays, manufacturing systems face unprecedented challenges imposed by highly demanding constraints ranging from high product customization to the demand for lower prices as well as increasing product quality to significant fluctuations in market demands [1]. Current manufacturing systems, based on traditional hierarchical and rigid control structures, can no longer cope with these demanding constraints [2,3], and require the use of new manufacturing paradigms that meet these constraints better. In this sense, to respond more quickly and efficiently, manufacturing systems are shifting to novel paradigms composed of features such as modularity, scalability, reconfigurability, robustness and flexibility, to name a few. Despite the benefits that these features bring, new control structures also need to be developed in parallel and all the potential extracted from the manufacturing paradigms.

Traditionally, manufacturing control systems use hierarchical control structures which concentrate the processing power of a shop-floor control under one central node. They improve performance and optimization, but respond inadequately to changes in conditions, scalability and unpredictability. These monolithic, rigid control structures are insufficient to meet the current requirements imposed by manufacturing environments which demand flexibility, robustness, reconfigurability and responsiveness. New manufacturing paradigms have thus emerged of which the common denominator is the decentralization and distribution of processing power over several entities, but with a decrease in

* Corresponding author at: Polytechnic Institute of Bragança, Campus Sta Apolónia, Apartado 1134, 5301-857 Bragança, Portugal. Tel.: +351 918985512.
E-mail addresses: jbarbosa@ipb.pt (J. Barbosa), pleitao@ipb.pt (P. Leitão), emmanuel.adam@univ-valenciennes.fr (E. Adam), damien.trentesaux@univ-valenciennes.fr (D. Trentesaux).

http://dx.doi.org/10.1016/j.compind.2014.10.011

system performance regarding process optimization. Examples of such paradigms are Reconfigurable Manufacturing Systems (RMS) [4], Multi-agent Systems (MAS) [5], Bionic Manufacturing Systems (BMS), Holonic Manufacturing Systems (HMS) [6], and more recently, Evolvable Production Systems (EPS) [7].

RMS is a concept that suggests the rapid change in the factory's structure using changes in hardware and/or software to adjust the production capacity and functionality quickly [8]. A RMS system should exhibit the following characteristics [4]: modularity, integrability, customization, convertibility and diagnosability. A MAS [5,9] is both a paradigm and technology that advocates the design of systems based on societies of decentralized, distributed, autonomous and intelligent entities, called agents. In such systems, each agent has a partial view of the surrounding world and must therefore cooperate with others in order to achieve the global objectives; the behaviour of the global system emerges from the cooperation between individual agents. An HMS [6] is a paradigm that translates the concepts of living organisms and social organizations developed by Koestler [10] to the manufacturing world. A holon, as Koestler coined the term, is an identifiable part of a system that has a unique identity, yet is made up of subordinate parts and is in turn part of a larger whole. Koestler also defines the term holarchy as a hierarchically organized system populated with self-regulating holons, and the system goals are achieved by the cooperation between holons. An HMS is the encapsulation of the entire manufacturing system in a holarchy. The holons can represent physical resources and logic entities.

MAS technology and/or HMS concepts have been successfully developed and applied to different domains (see for example the reviews (Leitao et al., 2013; [11])). MetaMorph [12] and its successor MetaMorph II [13] were projects that firstly aimed to provide an agent-based approach for the creation and management of agent communities in distributed manufacturing environments, and secondly to integrate cross-enterprise activities such as design, planning and scheduling. AARIA (Autonomous Agents at Rock Island Arsenal) was developed in the early years of agent-based architectures for military production, with the particularity of using internet as a means of communication between agents [14]. One of the best-known practical implementations using multi-agent systems is probably on one of the Daimler Chrysler production lines ([15]; [16]). This architecture aimed at using agent technology for both dynamic and flexible transportation systems and control systems.

One of the most remarkable HMS architectures is the PROSA (Product-Resource-Order-Staff Architecture) reference architecture that defines the main guidelines for developing a generic manufacturing control layer [17]. A real application of PROSA was conducted at Cambridge University using a packaging cell [18], where a collaboration was formed between order and resource holons to accommodate clients' demands. Order holons use negotiation techniques to ensure fast and reliable production and are also responsible for tracking production progress. On the other hand, the main aim of resource holons is to maximize the return on the execution of their services, and finally, product holon deal with the buying and selling of goods.

The ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) [19] is a holonic architecture that proposes an adaptive production control approach balances from a stationary state to a transient state, in normal and unexpected conditions, respectively, combining the benefits of hierarchical and heterarchical control structures using an adaptive mechanism. Complementarily, a deeper and up-to-date description of the current holonic and multi-agent systems solutions can be found in the surveys of [20–22,23], where a more detailed description of the aforementioned and other not mentioned solutions is made.

To sum up, the existence of one central node controlling the low-level entities in the hierarchical approaches constitutes a drawback in the sense that if it fails the whole system may fail. On the other hand, decentralized systems, such as those elaborated using MAS and HMS concepts, respond better to perturbations where the failure of an isolated entity only affects part of the system, and the other parts can continue operating with no major impact. Despite the benefits shown, decentralized systems do not attain optimization levels as high as those depicted by hierarchical solutions. As illustrated in Fig. 1, under normal conditions, system performance of hierarchical architectures is better than heterarchical architectures. However, in unexpected situations, e.g. due to a resource malfunction or a rush order, the heterarchical architectures behave better as they are able to respond promptly to perturbations.

Essentially, the challenge is to combine the best of both worlds, where a system displays the optimization levels of hierarchical systems under normal conditions and behaves like heterarchical approaches in unexpected situations. An approach like this brings hierarchical features to distributed entities whilst retaining their autonomy. For this purpose, some hybrid solutions have been developed exhibiting *ha(t)* behaviour illustrated in Fig. 1. ADACOR [19] is a well-known example of such an approach as it considers an adaptive production control mechanism that balances between two states: a hierarchical stationary state and a heterarchical transient state. In spite of the important progress made in this field, further developments must be made to achieve a truly dynamic and evolvable system that is able to cope with system constraints, without significantly affecting its functioning.

Biology and nature, as well as chaos and evolutionary theories are suitable sources of inspiration to design and develop solutions for solving complex, large-scale problems aimed at increasing their potential by embedding emergent concepts such as self-organization [24]. One example is the use of self-organization principles, which can be described as the ability of a system to arrange itself autonomously and spontaneously, mainly due to internal interactions, and without the need to use a central authority [25]. Among the most known biological sources of inspiration, one can find food foraging of ants [26] or food foraging of bees [27] as well as fish schooling or birds' flying pattern [28].

Some approaches have already tried to use self-organization concepts as a way to cope with the complexity and unpredictability associated with disturbances that may appear in the system. Some examples: the PROSA architecture was extended using food foraging behaviour of ants as a forecasting methodology [29]; the P2000+ [15] used a virtual buffer mechanism in machines that act as the self-organization regulator; ADACOR where the perturbation propagation uses a pheromone spreading technique as a warning signal among entities, which can assess the impact of the perturbation on themselves [19].

However, these biologically inspired mechanisms are only considered very lightly, lacking truly evolutionary concepts as a way to handle complex systems properly, e.g. minimizing the impact of disturbances. In this way, this paper proposes an

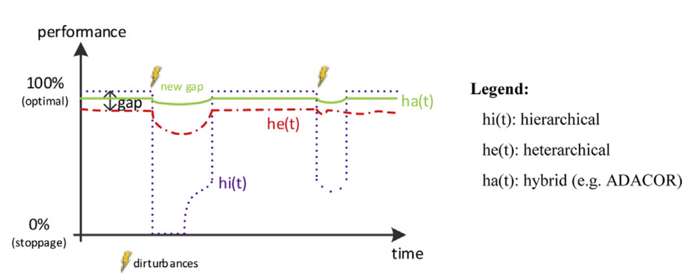

Fig. 1. Performance behaviour of different classical control structures.