ADACOR: A holonic architecture for agile and adaptive manufacturing control

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Abstract

In the last decades significant changes in the manufacturing environment have been noticed: moving from a local economy towards a global economy, with markets asking for products with higher quality at lower costs, highly customised and with short life cycle. In these circumstances, the challenge is to develop manufacturing control systems with intelligence capabilities, fast adaptation to the environment changes and more robustness against the occurrence of disturbances. This paper presents an agile and adaptive manufacturing control architecture that addresses the need for the fast reaction to disturbances at the shop floor level, increasing the agility and flexibility of the enterprise, when it works in volatile environments. The proposed architecture introduces an adaptive control that balances dynamically between a more centralised structure and a more decentralised one, allowing combining the global production optimisation with agile reaction to unexpected disturbances.

1. Introduction

In the last decades world has moved towards a global economy, with markets demanding for products with high quality at low cost, highly customised and with short life cycle, the so called mass customisation. Companies, to remain competitive, need to respond more closely to customer demands, by improving their flexibility and agility while maintaining their productivity and quality, thus imposing significant changes in the manufacturing environment.

Charles Darwin, in his book *The Origin of Species*, explained that species change over a long period of time, evolving to suit their environment, and that the species that will survive are not the strongest or the most intelligent, but those that are more responsive to change. Translating to the manufacturing world, the companies better prepared to survive would be those better responding to unpredictable and volatile environments, by adapting dynamically their behaviour.

The traditional manufacturing control systems are not designed to exhibit this capability of adaptation and evolution. In fact, their centralised and hierarchical control approaches present good production optimisation, but the rigidity and centralisation of the control structure implies a weak response to change. On the other hand, heterarchical-like manufacturing control approaches present a good response to change and unpredictable disturbances, but as decisions are based in partial knowledge of the system, the global production optimisation is not guaranteed.

In these circumstances, the challenge is to develop manufacturing control systems with autonomy and intelligence capabilities, agile and fast adaptation to the environment changes, prepared to handle efficiently the occurrence of disturbances, and allowing the easy integration of manufacturing resources and legacy systems.

Holonic manufacturing systems (HMS) is a paradigm that translates to the manufacturing world the concepts developed by Arthur Koestler for living organisms and social organisations [1]. Holonic manufacturing is characterised by holarchies of autonomous and cooperative entities, called holons, which represent the entire range of manufacturing entities. A holon, as devised by Koestler, is an identifiable part of a (manufacturing)

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system that has a unique identity, yet is made up of sub-ordinate parts and in turn is part of a larger whole. The introduction of the holonic paradigm allows a new approach to the manufacturing problem, bringing the advantages of modularity, decentralisation, autonomy and scalability.

In spite of the promising perspective and the research developed by the holonic community, such as referred in [2–7], and others, compiled in [8,9], the holonic manufacturing achievements leave some important questions open, as described in [10], namely how to achieve global optimisation in decentralised systems, how should the production control structure evolve to adapt to change, how to specify formally the dynamic behaviour of holonic systems, how to introduce learning and self-organisation capabilities, how to integrate automation resources and how to develop holonic-based control applications.

The proposed control architecture, designated by ADAptive holonic COntrol aRchitecture (ADACOR for distributed manufacturing systems), intends to contribute to the improvement of the manufacturing control systems performance in terms of the agile reaction to emergence and change, by increasing the agility and flexibility of the enterprise when it works in volatile environments, characterised by the frequent occurrence of disturbances. The focus of ADACOR architecture is the shop floor level and especially flexible manufacturing systems organised in job shop production, characterised by concurrent and asynchronous processes with non-pre-emptive operations and alternative routings. The proposed adaptive architecture intends to be as decentralised as possible and as centralised as necessary, i.e. using a centralised approach when the objective is the optimisation, and a more heterarchical approach in presence of unexpected events and modifications.

ADACOR architecture is based on the holonic manufacturing systems paradigm, and in the following main foundations: decentralised systems, supervisor entities and self-organisation. The manufacturing control functions are in charge of a community of autonomous and cooperative holons, bringing the advantage of modularity, decentralisation, agility, flexibility, robustness and scalability. The introduction of supervisor entities allows the establishment of hierarchies in decentralised systems, to achieve global production optimisation. The introduction of self-organisation capabilities allows the dynamic evolution and re-configuration of the organisational control structure, combining the global production optimisation with the agile reaction to unexpected disturbances.

This paper focuses in the description of the ADACOR control architecture, by indicating the system components, their functions and their interactions, and the adaptive production control model. The formal modelling of the dynamic behaviour of each ADACOR holon class and the synchronisation between the individual models, using high-level Petri nets, is out of scope of this paper, being described in [11].

This paper is organised as follows. Section 2 describes the components of the proposed architecture, referring the holon classes, the supervisor role and the main characteristics associated to each holon. Section 3 describes the interactions among the ADACOR holon classes and Section 4 describes the driving forces of the self-organisation concept, namely the autonomy factor and the propagation mechanisms. Section 5 discusses the adaptive production control approach and Section 6 refers the validation of the ADACOR concepts through their implementation and test in a prototype. At last, Section 7 presents the conclusions.

2. Components of the ADACOR architecture

ADACOR architecture is build upon a set of autonomous and cooperative holons, to support the distribution of skills and knowledge, and to improve the capability of adaptation to environment changes. Each holon is a representation of a manufacturing component that can be either a physical resource (numerical control machines, robots, programmable controllers, pallets, etc.) or a logic entity (products, orders, etc.).

2.1. ADACOR holon classes

An ADACOR holon is autonomous, since it can operate on its own, without the direct assistance of external entities, and has full control over its behaviour. Having its own objectives, knowledge and skills, each holon has the capability to reason in order to take decisions about its activities. Each ADACOR holon possesses only a partial view of the system, needing to cooperate with the other holons in order to achieve its goals or to get additional information about the system, sharing knowledge to transform local knowledge into global knowledge.

ADACOR holons perceive their environment and response quickly to changes, reacting to the stimulus provided by the environment. In spite of their predominant reactive behaviour, ADACOR holons do not simply act in response to their environment, but they are also able to take the initiative, for example elaborating product plans or predicting the occurrence of future disturbances. ADACOR holons are of the plug and produce type, being possible to add a new element without the need to re-initialise and re-programme the system, thus allowing high flexibility in system adaptation and re-configuration.

ADACOR architecture defines four manufacturing holon classes, product (PH), task (TH), operational (OH) and supervisor holon (SH) classes, according to their functions and objectives. The product, task and operational holons are quite similar to the product, order and resource holons defined in PROSA reference architecture [3], while the supervisor holon presents characteristics not found in the PROSA staff holon. The supervisor holon introduces coordination and global optimisation in decentralised control and is responsible for the formation and coordination of groups of holons.

Each product available to be produced in the factory plant is represented by a product holon, containing all information related to the product and being responsible for the short-term process planning. The product holon acts as the bridge between the shop floor and planning levels, contributing to the integration of all the manufacturing control functions, i.e. planning, scheduling and plan execution.

Each production order launched to the shop floor (to execute a product or sub-product) is represented by a task holon, containing the dynamic information about the production order, and being responsible to manage its execution.

Operational holons represent the physical resources available in the shop floor, such as operators, robots and numerical control machines, managing their behaviours according to the resource goals and skills. The operational holons manage the agenda of the resources, i.e. the planned list of work orders that the manufacturing resources have to execute over the time.

2.2. Supervisor role

The organisation of holons in stable hierarchies is frequently associated to the global performance optimisation in normal operation. The existence of different hierarchy levels requires the presence of coordinating entities, to combine synergies, to aggregate the skills of the members of each group and to offer the combined services to other entities in the manufacturing system.

In ADACOR architecture, this role is executed by supervisor holons, which major function is the elaboration of optimised production plans for the operational holons under their coordination domains. The elaboration of optimised schedules is performed periodically, triggered by the internal clock of the supervisor holon, or by the occurrence of a disturbance.

The supervisor holons are also responsible for the coordination of groups and their dynamic evolution according to the environment context. The decision to create a group can result from the need to combine synergies to optimise the production or from the existence of geographical constraints. Once a new member is added to the group, the supervisor holon aggregates the information related to the new member, namely the list of skills that the holon contributes to the group. A group can be formed to represent a machine equipped with a set of tools, a manufacturing cell, or a complete shop floor, with the supervisor holon assuming the role of group coordinator.

2.3. Internal architecture of a generic ADACOR holon

The conceptual model of a generic ADACOR holon shows a logical control device (LCD) and a physical resource capable to perform the manufacturing tasks, if it exists, Fig. 1. The LCD device is organised in three main components: communication (ComC), decision (DeC) and physical interface (PIC) components.

The *communication component* is responsible for the inter-holon interaction, supporting the sharing of local knowledge by the distributed holons. Interoperability requires that a common vocabulary, or an appropriate manufacturing ontology, has been previously agreed.

The *decision component* regulates the holon behaviour, namely performing the manufacturing control functions, such as process planning, scheduling, and plan execution (which includes the dispatching, monitoring and reaction to disturbances), and adaptation to emergence (such as group formation or dynamic re-organisation). The decision-making model comprises basically the loop around the following phases: sensing, deciding, acting and learning.

The holon is continuously available to make a decision, according to the available knowledge and to the implemented decision-making technique. Knowledge is acquired by sensing the environment and through the arrival of messages from other holons. After a decision is taken, the selected actions, in the form of commands for actuators, messages for other holons, or execution of procedures, are dispatched and executed. The results from the executed actions are evaluated and new knowledge is generated.

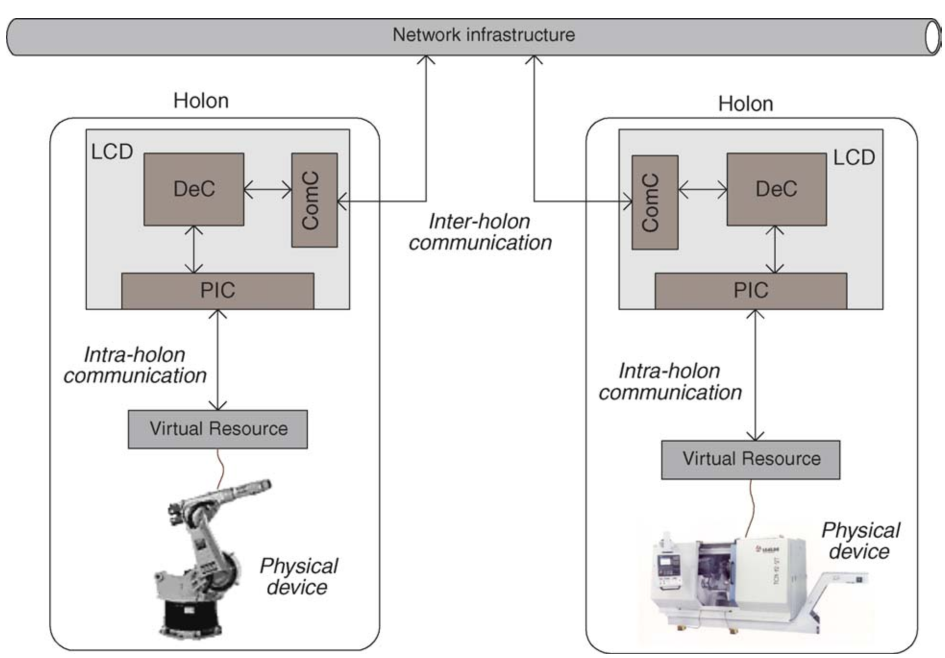

Fig. 1. Conceptual model for an ADACOR holon.

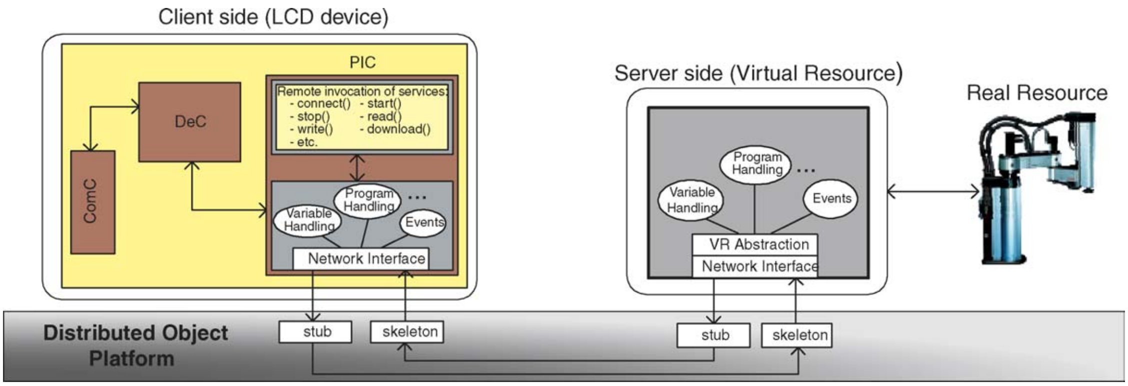

Fig. 2. ADACOR resource integration scheme.

As local resource controllers usually have closed architectures it is necessary to develop wrappers to hide the details of each resource controller and to implement primitives that represent the functionality of the physical manufacturing resource. The physical interface component fulfils this objective, by providing mechanisms to support resource integration based on the virtual resource concept and the client-server model [13], Fig. 2.

The server part in the proposed mechanism is the virtual resource, inspired by the virtual machine device (VMD) concept of the manufacturing message specification (MMS) protocol [14]. It acts as an abstract machine that represents the functionalities of the real manufacturing device and supplies primitives to be invoked remotely by the client part. A virtual resource must be developed for each physical device according to its specifications, but it can be re-used in new applications, since the manufacturing resources are independent from the control application.

The PIC component acts as the client part, accessing to the real manufacturing resource by invoking remotely the primitives supplied by the virtual resource that represent the services in the physical resource. The industrial manufacturing environments are characterised by its heterogeneity, with the distributed resources running in distinct platforms. This heterogeneity requires the use of distributed object platforms, such as CORBA and .Net, to support the interoperability between the clients and virtual resource components.

In ADACOR, an operational holon can be made of a set of several operational and/or supervisor holons, with the top supervisor holon acting as the logic component, and the several operational holons acting as the physical part of the holon [12]. This feature allows the structured development of manufacturing control applications through the encapsulation of functions or manufacturing components.

As an example, illustrated in Fig. 3, a manufacturing cell can be represented by an operational holon that is constituted by several other operational holons, each one representing a manufacturing resource, and one supervisor holon representing the manufacturing cell controller. Additionally, each one of these operational holons could be constituted by other operational holons, representing the numerical control machine itself and the several tools stored in its tool magazine.

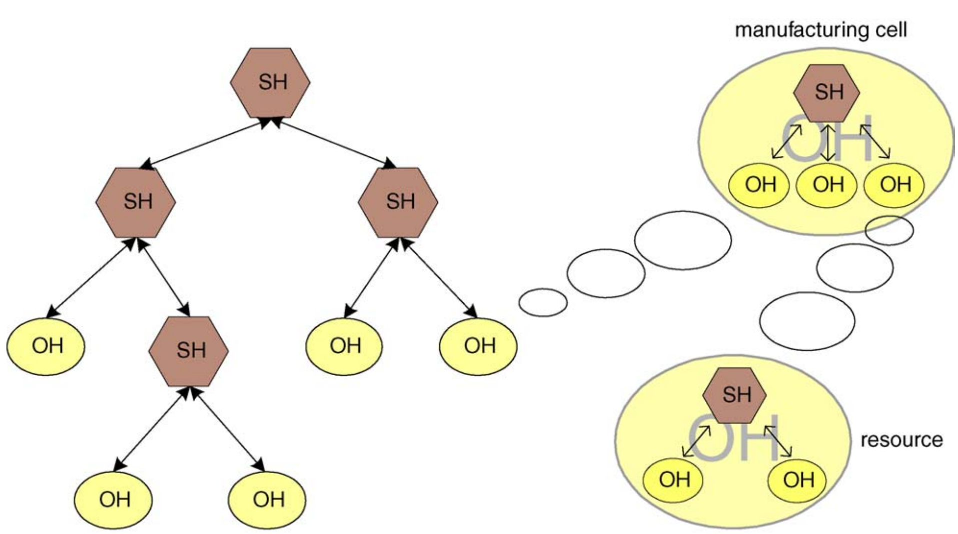

Fig. 3. ''Fractal'' feature in ADACOR approach.

3. Interaction among ADACOR holons

In distributed manufacturing environments, each holon is autonomous and has a partial knowledge of the problem. The manufacturing control emerges, as a whole, from the interaction among the distributed holons, each one contributing with its local knowledge.

In the ADACOR architecture, during an order life cycle, there are different types of interactions between ADACOR holons, according to the interdependencies between the holon classes, as illustrated in Fig. 4.

The product holons, placed at the process planning level, interact with task holons, placed at the management level, to exchange product and process planning information. Additionally, product holons interact indirectly with operational and supervisor holons during the elaboration of alternative process plans, since it is necessary to verify which operational holons are available at the factory plant.

The task holons interact with the operational holons, placed at the operational level, aiming:

- plan execution (regulating the execution of the defined plan for the production order);
- monitoring (querying about the progress of the plan execution);
- elaboration of dynamic and distributed (re-)scheduling (allocating operations by direct interaction with the resources using an auction mechanism).

Additionally, for global and optimised coordination, task holons interact with supervisor holons, placed at the coordination level. In these coordination processes, supervisor holons propose to the task holons the execution of operations in an optimised manner, exchanging information related to the resource allocation and monitoring the execution of those operations. The presence of the coordination level, i.e. the existence of the supervisor holons interacting with the task and operational holons, is optional and exists only in stable scenarios with the system running as planned, without the occurrence of unexpected disturbances.

The operational holons interact between themselves allowing the synchronisation of their activities. Additionally, during disturbance handling, operational holons interact between themselves and with supervisor holons to enable the re-organisation of the control structure, and with the task holons to achieve an alternative plan that minimises the impact of the occurrence of the unexpected disturbance.

The identified types of interactions between distributed ADACOR holons are modelled using AUML interaction diagrams, which is an extension of the UML's sequence diagrams for the multi-agent systems. As an example, Fig. 5 illustrates the interaction diagram for the task allocation process using a completely decentralised control structure.

4. Adaptation by self-organisation

The adaptive ADACOR mechanism emerges in a bottom-up approach, built upon the individual self-organisation of manufacturing holons. The dynamic adaptation of each holon to unexpected situations contributes to the agile adaptation of the system as a whole to the emergence.

The self-organisation mechanisms require local and global driving forces to support the adaptation. In ADACOR architecture, the local driving forces are the autonomy factor

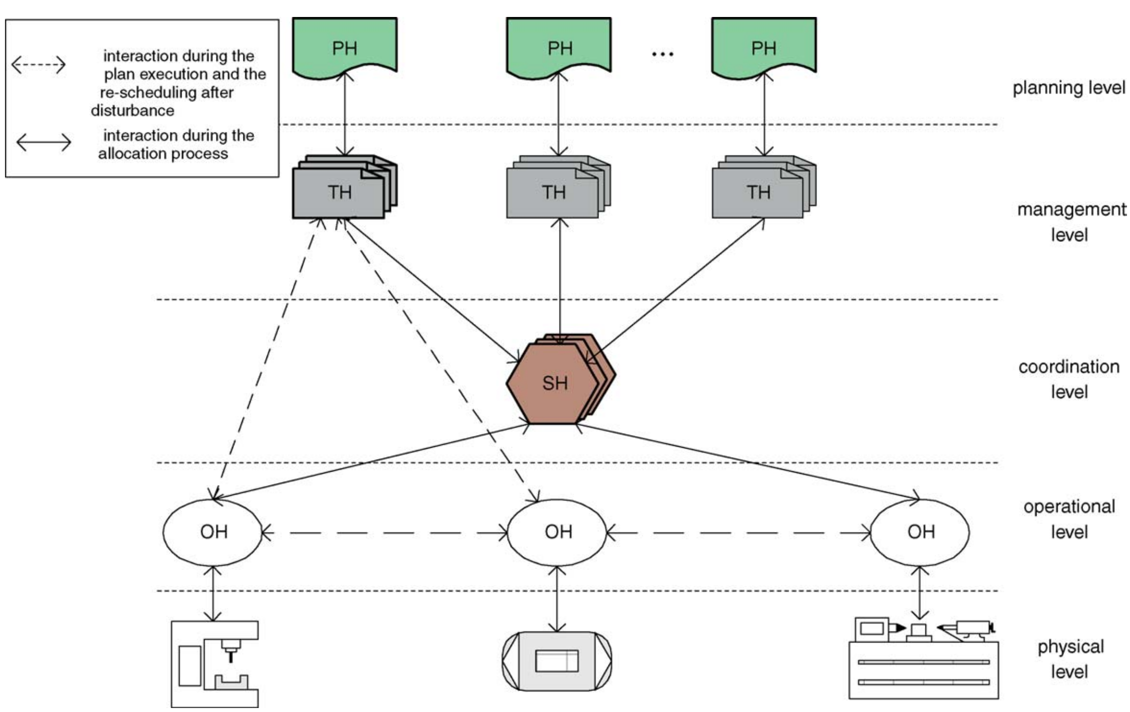

Fig. 4. ADACOR Holon classes, with interactions.

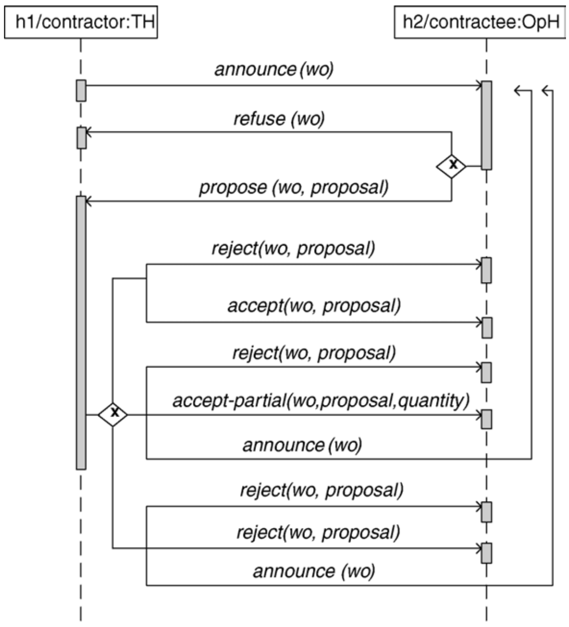

Fig. 5. Task allocation interaction diagram.

and the learning capability, which are inherent characteristics to each ADACOR holon; the global self-organisation of the system is achieved through the interaction between local individual holons, propagating the emergence and the need for re-organisation.

4.1. Autonomy factor

The autonomy factor, α, associated to each operational holon, is a parameter that reflects the degree of autonomy of each holon. The autonomy factor is a continuous or discrete variable, regulated by a decision mechanism, that evolves dynamically in order to adapt the holon behaviour to changes in the environment where it is placed.

Normally, the operational holons have low autonomy factor, following the supervisor holon coordination and accepting its schedule proposals [12]. The supervisor coordination introduces global optimisation in the system, since it has a wider view of the system than the operational holons under its coordination domain.

An emergency, normally the occurrence of an unexpected disturbance, triggers the adaptive behaviour that determines the evolution of the autonomy factor associated to each operational holon, according to a set of rules. The new value of the autonomy factor is a function of its current value, of the reestablishment time, that is the estimated time to recover from the current disturbance, and of the pheromone parameter, a parameter that is an indication of the level of impact of the disturbance.

The degree of efficiency of the self-organisation is dependent on how the learning mechanisms are implemented, and on new knowledge influences the decision parameters.

The cardinality of the numerical set associated to the autonomy factor may have strong impact in the dynamic of the adaptation mechanism: on one side, the higher is the number of values, the more gradual will be the adaptation procedure, but on the other a high number of values makes the adaptation mechanism more complex, requiring the implementation of more complex decision mechanisms, and the response times longer.

4.2. Propagation mechanisms

The propagation of emergence in ADACOR uses a pheromone-like spreading mechanism to distribute global information. In case of occurrence of an unexpected disturbance, the need for re-organisation is propagated through the deposit of a certain quantity of pheromone in the neighbour supervisor holons, proportional to the estimated reestablishment time, forecasted according to the type of disturbance and to the historic data.

The holons associated to each supervisor holon receive the need for re-organisation by sensing the pheromone and propagate this need to neighbour holons. The intensity of the odour associated to the pheromone becomes smaller with the increase in the number of the levels of supervisor holons (similar to distance in the original pheromone techniques), according to a defined flow field gradient.

The propagation of the emergence and the need for re-organisation, using pheromone-like techniques, is suitable for the dynamic and continuous adaptation of the system to disturbances, supporting the global self-organisation, reducing the communication overhead and improving the reaction to disturbances.

5. Adaptive production control

The control architecture is a key factor for the performance of the manufacturing control system, playing a critical role in the system performance in terms of response to change and capability to learn.

The use of heterarchical control architectures introduces good reaction to disturbances but degrades the global production optimisation; on the other hand, the hierarchical approach presents good global optimisation but weak reaction to disturbances. The objective is to develop a dynamic and adaptive control approach that improves the agility and reaction to unexpected disturbances without compromising the global optimisation.

The self-organisation capability of ADACOR holons is the key concept that allows balancing the control between different control structures, reaching an adaptive control approach that combines the agile reaction to disturbances with the global optimisation.

5.1. Dynamic evolution of the control structure

The ADACOR control structure is neither completely decentralised nor hierarchical, but balances between a more centralised and a more flat approach, passing through other intermediate forms of control, due to the adaptive and dynamic evolution of the autonomy factor of each ADACOR holon.

The proposed adaptive production control shares the control between supervisor and operational holons, and splits the control evolution into two alternative states: a stationary state, where the system control uses coordination levels and the supervisor role to get global optimisation of the production process, and a transient state, triggered by the occurrence of disturbances and presenting a behaviour quite similar to the heterarchical approach in terms of agility and adaptability.

Fig. 6 shows the dynamic evolution of the control structure for a scenario that contains a factory plant (controlled by SH_1) with two manufacturing cells (controlled by SH_2 and SH_3), one comprising three machines and other two machines (each one controlled by one operational holon).

In the *stationary state* the holons are organised in a hierarchical structure, with the supervisor holons representing cell controllers and/or shop floor controllers, interacting directly with the task holons during the operation allocation process. The supervisor holons elaborate optimised schedule plans that propose to the task holons and to the operational holons within their coordination domain. In this state, each operational holon has a low autonomy factor and sees these proposals as advices, following the proposals sent by the supervisor holon, although they have enough autonomy to accept or reject the proposed schedule.

After the allocation of the manufacturing operations, the task holons interact directly with the operational holons during the execution of the operations (e.g. to ask for availability of space in the buffer). When an operational holon rejects one or more proposed operations, the supervisor holon must re-schedule the production operations, trying to find alternatives. The learning mechanisms allow that information related to the rejections may be used in future to reach better optimised schedules.

If, for any reason, the system deviates from planned, due for example to a machine failure that provokes the destruction of the part that has been processed, or to an external change, the control system enters in the *transient state*. The transient state is characterised by the re-organisation of the holons required by the transition from the hierarchical control architecture to the heterarchical control architecture, responsible for the agile reaction to disturbances of this control structure.

In the case of a machine failure, as illustrated in Fig. 6, the operational holon which detects the disturbance tries to recover locally from the failure, by analysing the symptoms and making a self-diagnosis, but if it cannot recover from the failure, it increases its autonomy factor parameter and propagates the need for re-organisation to the other holons in the system, through its supervisor holon. Each ADACOR holon should have generated knowledge to forecast the impact of the disturbance in the actual plan, to maintain the system stable and to handle the reaction to disturbance. The neighbour holons also sense the pheromone and increase their autonomy factors according to the intensity of the pheromone and their local knowledge, re-organising themselves into a heterarchical structure.

In this transitory state, the task holons interact directly with the operational holons in order to achieve an alternative

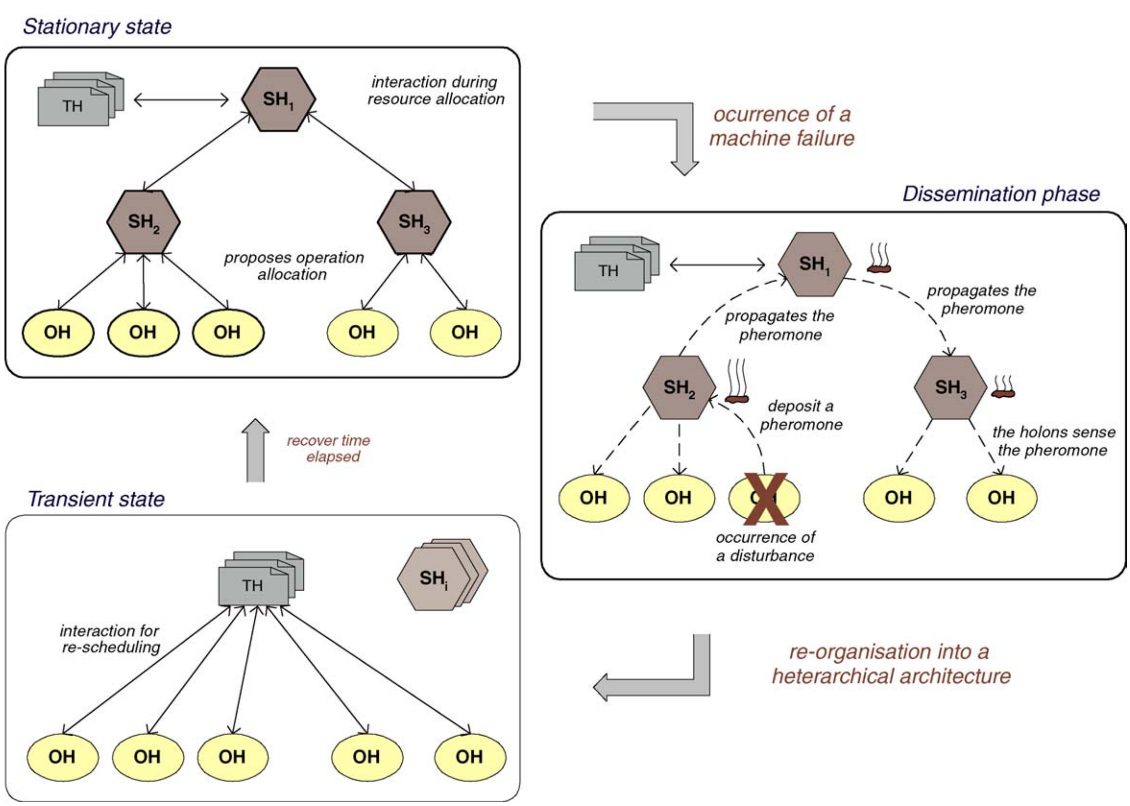

Fig. 6. Dynamic re-organisation in ADACOR approach.

schedule plan. During this state, the supervisor holons can continue elaborating and proposing the allocation of work orders to the operational holons, but since these now have high values of autonomy factors, they will probably reject the proposals.

The holons remain in the transient state during the reestablishment time, the period of time estimated by the operational holon that detected the disturbance for its recovery. When this time elapses, they verify if the pheromone odour is already dissipated or remains active. If the pheromone remains active, the operational holons stay in the transient phase during an additional reestablishment time, until the pheromone is dissipated.

After the recovery from the disturbance, the operational holon ends the reinforcement of the pheromone, and the reestablishment and recovery times are adjusted using the learning mechanisms. When the other holons do not sense anymore the dissemination, they reduce their autonomy factors, the system evolving to a new control structure (often returning to the original one), according to the learning capabilities embedded in each holon. The supervisor holon returns to its coordination function, re-scheduling if necessary the work orders of the new local agendas to synchronise the local and central schedules. The new schedules are sent to the operational holons, which have again low autonomy factor and accept the advised schedules.

5.2. Equilibrium in the adaptation mechanism

In dynamic and complex systems it is important to guarantee that the self-organisation of individual entities maintains the system in a stable and correct state. The stability concept is concerned to the condition in which a slight disturbance in a system does not produce a significant disrupting effect on the system.

In ADACOR approach, the stability in the adaptive production control structure can be affected by several factors, including the number of holons present in the system, the probability of occurrence of a disturbance, the recovery times and the estimated reestablishment times.

The reestablishment times must be adjusted dynamically, using learning mechanisms, to improve the stability of the system. A short reestablishment time is better in terms of stability but is worse in terms of guaranteeing the completion of the disturbance recovery within the forecasted time interval.

6. Implementation of ADACOR concepts

The proof of correctness and validation of the ADACOR concepts was performed through the implementation and test of a prototype production control system. The application was completed as a part of the doctoral thesis of one of the authors [15] and is described in [16].

Multi-agent technology was used to implement the holons, taking advantage of the autonomy, intelligent and cooperative behaviour, modularity, decentralisation and components re-use inherent to software agents. Since the development of multi-agent systems requires the implementation of features usually not supported by programming languages, such as message transport, encoding and parsing, yellow and white pages services, ontology for common understanding and agent life cycle management services, it was decided to adopt a general purpose agent development platform, to make the development of the application easier and to reduce the programming effort. The agent development platform chosen to implement the ADACOR prototype was Java Agent Development Framework (JADE) [17] because it provides a set of system services and agents in compliance with the Foundation for Intelligent Physical Agents (FIPA) specifications.

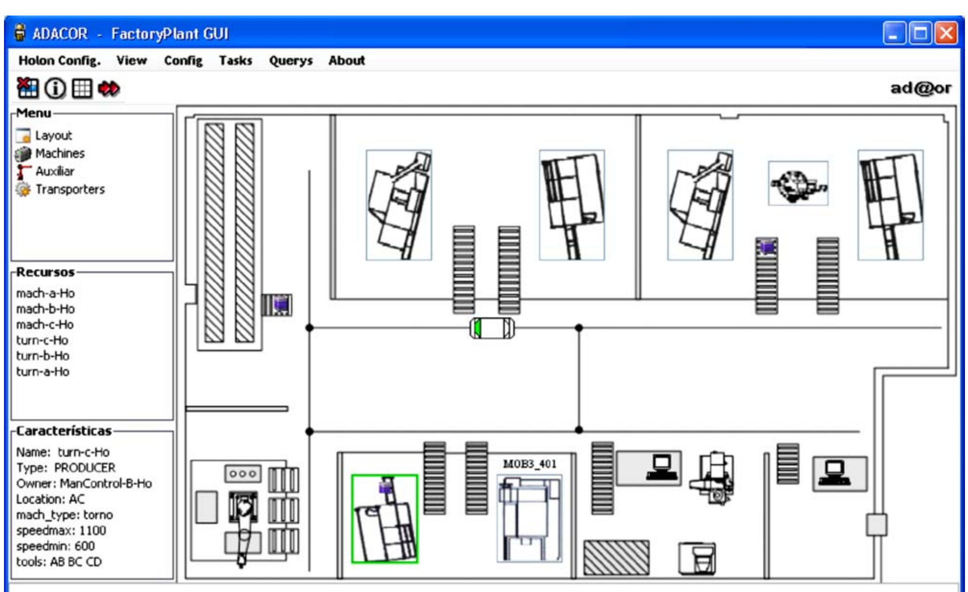

Fig. 7. Screenshot of ADACOR control system.

ADACOR holons are Java classes that extend the agent class provided by the JADE framework extended with features that represent the specific behaviour of each ADACOR holon class [16]. The behaviour of each ADACOR holon uses multi-threaded programming. The communication between the distributed holons is done over an Ethernet network, using TCP/IP protocol, and the messages are encoded using the FIPA-ACL communication language.

The main element in the decision component of each ADACOR holon is a rule-based system, developed using the JESS (Java Expert System Shell) tool, that regulates the holons behaviour [16]. ADACOR prototype adopted a very simple binary autonomy factor and takes care of all the operations in the shop floor, from order entry to product delivery, including disturbance management.

Fig. 7 illustrates a screenshot of the developed ADACOR-based control system for a case study pilot installation. The pilot installation is a semi-virtual laboratorial platform that includes the flexible manufacturing system from CIM Centre of Porto [15], extended with two virtual manufacturing cells, that provide redundancy and flexibility in achieving alternative solutions in the production planning.

The flexible manufacturing system platform consists of three turning machines, two milling machines, one drilling machine, one tool calibration machine, two anthropomorphic handling robots, one SCARA assembly robot, one automated storage/retrieval system (AS/RS) system and one auto-guided vehicle (AGV). In this pilot plant, four different products have to be produced: base, body, cover and handle.

The experience gained during the prototype implementation, debugging and testing, and the success of this application under an extensive range of tests demonstrates the applicability of ADACOR concepts to real life flexible manufacturing system control.

7. Conclusions

The manufacturing companies at the beginning of 21st century live in dynamic environments where economical, technological and customer trends changes rapidly, requiring the increase of flexibility and agility to react to unexpected disturbances, while maintaining productivity and quality. The traditional manufacturing control systems do not react automatically to these changes, and must be adapted on a case-by-case basis, requiring expensive and huge time-consuming efforts to develop, maintain or re-configure.

The proposed ADACOR holonic manufacturing control architecture addresses the improvement of the performance in industrial scenarios characterised by the frequent occurrence of unexpected disturbances at the shop floor level, and is based on a set of autonomous and cooperative holons, with self-organisation and learning capabilities. The supervisor holon, coordinating several operational and supervisor holons, and introducing global optimisation in otherwise decentralised control systems, is an innovative aspect of the ADACOR approach.

The supervisor holon and the self-organisation capability associated to each ADACOR holon are the basis of the adaptive production control, allowing to balance the production control between stationary (presenting a hierarchical-like control structure) and transient (presenting a heterarchical-like control structure) control states, combining the global production optimisation with the agile reaction to disturbances. In normal operation, the supervisor holons supervise and regulate the activity of the operational holons under their coordination domain, while when a disturbance occurs, operational holons have to find their way without the help of the supervisor holon.

The experimental implementation of ADACOR concepts in a flexible manufacturing system case study demonstrated the applicability of the ADACOR concepts to real environments and the merits of the ADACOR collaborative/holonic approach.

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