A Layered Approach to Distributed Manufacturing

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Abstract

World-wide competition forces enterprises to achieve new cooperations and arrangements with other enterprises in order to share skills, using the virtual enterprise concept. The virtual enterprise introduces the distributed manufacturing concept, which can be expanded and zoomed to other distributed layers, such as multi-site and interacting units.

The development and implementation of distributed manufacturing control systems, based in new distributed manufacturing paradigms, plays a key factor in the improvement of the enterprises capacity to react to market and organisation changes.

This paper gives an overview of manufacturing paradigms and describes the evolution of control architectures, from the classical approach to the distributed approaches. The new paradigms for distributed manufacturing control, in order to prepare the next generation of manufacturing systems requirements, are also presented, with special attention to three concepts: Holonic, Biological and Fractal Manufacturing Systems.

1. Introduction

World-wide competition among enterprises led to the need for new systems to perform the control and supervision of distributed manufacturing, through the integration of information and automation islands [1,2]. The market demands should be fulfilled by manufacturing enterprises to avoid the risk of becoming less competitive.

The adoption of new manufacturing concepts combined with the implementation of emergent technologies, is the answer to the improvement of productivity and quality, and to the decrease of price and delivery time.

Nowadays, the distributed manufacturing organisational concept, e.g. the virtual enterprises, requires the development of decentralised control architectures, capable to react to disturbances and changes in their environment, and capable to improve its performance maintaining the robustness and flexibility.

A brief history of the evolution of manufacturing paradigms is presented, and some new ideas towards future research in the distributed manufacturing control area and ways to generalise this architecture, are also discussed. These new paradigms in distributed manufacturing control are the key for the development of distributed shop floor applications for next century.

2. Brief History of Manufacturing Paradigms

In the beginning of 20th century, Henry Ford introduced the revolutionary concept of mass manufacturing, characterised by the production of the same product in large scale. At the time, everybody could have a Ford T car of any colour as far as it was black!

During several years, this paradigm was widely accepted and implemented, but in last decades it could not respond to the challenges of modern, dynamic and worldwide business. The globalisation of markets brought to the companies in the production area the necessity to become strong competitively, in order to fulfil the requirements of the market for the reduction of prices, better product quality, minimum time of delivery, diversity of offer, etc..

The mass manufacturing, idealised by Henry Ford was a strap down system, incapable to treat variations in the type of product. This rigidity started to be an obstacle and with the worldwide competitiveness the mass manufacturing became viable only in some products. In this way, the mass manufacturing emerged from the era of manufacturing to the era of mass customisation.

Nowadays, each product has several models, and each model can be highly customised in order to fulfil the requirements of the customers (a good example is the automobile industry), which requires the job shop type of production and in some cases the one-of-a-kind production.

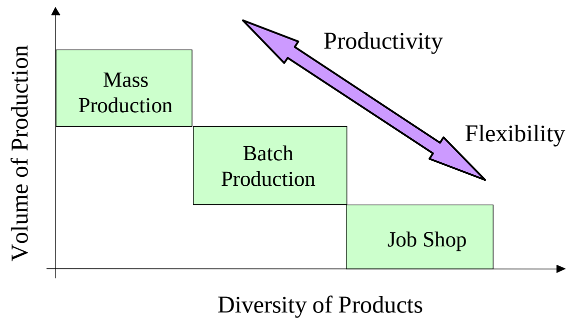

***Figure 1** – Types of Production*

The companies were obliged to use new technologies and new manufacturing concepts in their different activities to avoid the risk to becoming less competitive or obsolete.

In the 80s, Japanese companies introduced in its business process a new paradigm, called Lean Manufacturing, which idea is to shorten the time line between customer order and shipment, by eliminating waste. Lean Manufacturing is an extension of Just in Time concept, which consists in having the right material at right place at right time, eliminating stocks, and using very simple control and scheduling systems.

The aim of Lean Manufacturing is to achieve manufacturing products with less of time to design, less inventory, less defects, reduction of setups, etc. The three main areas in Lean Manufacturing are [3]:

- manufacturing management excellence,
- organisation learning,
- principles and practices of lean manufacturing.

The USA response to this paradigm is the Agile Manufacturing. Agile Manufacturing is the ability to adapt quickly and profitably to continuos and unexpected changes in the manufacturing environment.

Agility impacts the entire manufacturing organisation, including product design, customer relations and logistics, as well as production, and it has been expressed as having four underlying principles:

- deliver value to the customer;
- ability to react to changes;
- value of human knowledge and skills
- ability to constitute virtual partnerships.

While the first three principles can be found in the Lean Manufacturing paradigm, the fourth principle makes the difference between Lean and Agile Manufacturing: in Agile Manufacturing the companies form temporary alliances with other companies, even competitors, to react to unexpected situations, with mutual benefits for both companies [3]. Finally, in Agile Manufacturing it is important to consider that human factors and organisational knowledge are just as important as advanced technology.

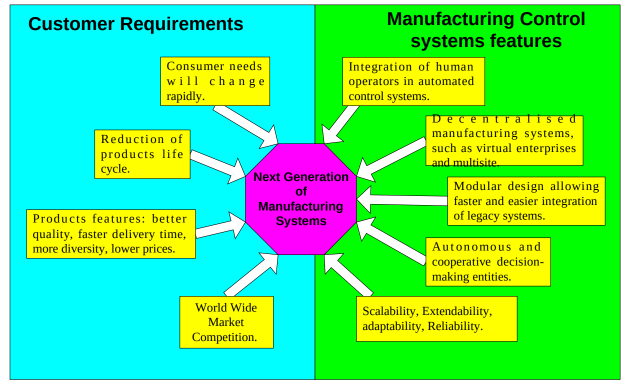

***Figure 2** - Requirements and Features of Future Manufacturing Systems*

Today, the worldwide market competition, implies that manufacturing enterprises can no longer be seen acting stand-alone, forcing them to reconsider how they are organised and introduces the Virtual Enterprise concept. The Virtual Enterprise is a paradigm that can be defined as a temporary alliance of enterprises that come together to share skills and resources in order to better respond to business opportunities and whose co-operation is supported by computer networks [4].

The term Virtual Enterprise is used because in spite of having all the attributes of an enterprise, it would not be a permanent organisation (for example, a joint venture is one type of Virtual Enterprise, where some enterprises group together in order to achieve a particular and common goal).

One approach to Virtual Enterprise modelling is to consider it as a multi-agent system, where each node in the network is an intelligent agent [4].

An example of Virtual Enterprise paradigm is the Boeing company that established a virtual co-operation with several companies in order to produce its 777 aeroplanes. Boeing designs, assembles and markets the aircraft, while an international network of suppliers makes the components.

The Virtual Manufacturing paradigm is a relatively new concept of executing manufacturing processes in computers as well as in the real world. Virtual Manufacturing uses simulation tools and computer models to simulate different aspects of a manufacturing levels, such as the manufacturing processes, previously, without using the real facilities, and by this way to accelerate and optimise the design (and re-design) and production of a manufacturing product in real manufacturing systems.

3. Classical Architectures for Development of Control Systems

The control architecture is a key factor for the final performance of the application system. Some basic control

architectures are centralised, hierarchical and heterarchical [5]. With the powerful PCs, inexpensive and widely available, the architectures evolved from centralised architectures to the distributed architectures, allowing the improvement of the manufacturing control systems performance.
The centralised architecture is the oldest architecture and is characterised by a single decision node, where all the planning and processing information functions are concentrated [5].
This architecture has the advantage of a better management and control optimisation. Despite this advantage, there are some important disadvantages:

- reply time, mainly when are involved high volume of information;
- the increase of system dimension reduces the efficiency and increases the control complexity of the system;
- the tolerance to faults is bad, mainly when the supervisor breakdown.
- The expandability of the system are a hard task, because it requires a deeply modification of the control system.

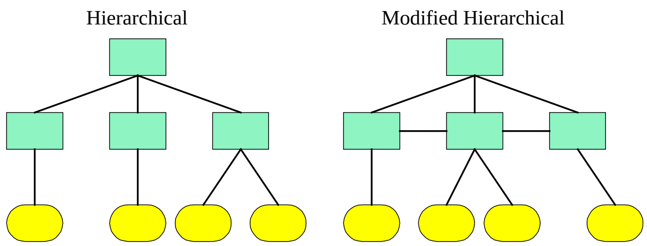

***Figure 3** – Hierarchical Architectures*

In the Hierarchical architecture, a complex problem is decomposed in several simpler and smaller problems, and distributed among multiple control layers. This architecture is characterised by the existence of some control levels, distributed in a pyramid structure, allowing the distribution of decision-making among these hierarchical levels. The relations between hierarchical levels are based on the master-slave concept.
The main advantages of this architecture are the robustness, the predictability and the efficiency that is better than in centralised architectures. However, the appearance of disturbances in the system reduces significantly its performance.
This type of architecture presents the additional advantage to facilitate the development of the control system, as well the possibility to implement it gradually.
The modified hierarchical architecture tries to find a solution to the reaction to disturbances problem, maintaining all features of hierarchical architecture and adding the interaction between modules at the same hierarchical level. This interaction allows the exchange of information between modules improving the reaction to disturbances.
The expandability of the system is easier than the hierarchical architecture due to the interaction at same control level feature.
The heterarchical architecture is characterised by a high level of autonomy, and co-operation of modules and the client-server structure with fixed relations are no more applied [5].

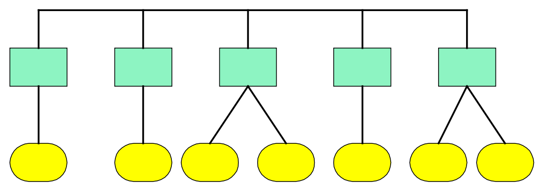

***Figure 4** – Heterarchical Architecture*

These features allow a high performance against disturbances, but the global optimisation is reduced, because decision making is local and autonomous, without a global view of the system. The expandability of the system is an easier task, because it is enough to modify only the modules where it is desired to modify its functioning or add new modules to the control system.
The implementation of heterarchical control requires the use of negotiation protocols, allowing the co-operation between modules.
The control architectures mentioned before are the classical approaches to the development of manufacturing control systems that require flexibility, robustness, reaction against disturbances, etc. Some important research in the area of Cell Controller and Shop Floor Control Architectures is being carried out, using these classical control architectures. In the following, some of the relevant control systems architectures are listed:

- *COSIMA (Control Systems for Integrated Manufacturing)*

  The ESPRIT project 447, COSIMA [6], has developed functional software architecture for cell and shop floor levels. It consists of five well-defined functional modules, grouped into a Production Activity Control (PAC) concept, that controls one manufacturing cell. The PAC architecture modules are:
  - Scheduler, which plans the manufacturing resources according with long term tactical plans and resources capacities.
  - Dispatcher, which is the heart of control system and acts in real time control over the manufacturing environment.
  - Monitor, which collects shop floor data to give a logical view of actual states in the manufacturing environment.

– Producers and Movers, who controls the shop floor resources.

The co-ordination between PAC systems is performed by the FC (Factory Co-ordination) module.

- *CHAMP (Chalmers Architecture and Methodology for Flexible Production)*

  Champ is a modified hierarchical reference architecture, for model the control software of manufacturing cells, developed at Chalmers University of Technology. It is elaborated upon the experiences made from implementations of control systems based on the PAC architecture and its extensions, PAC+ and PAC++. The CHAMP architecture includes functions for scheduling, dispatching, resource control, monitoring and error handling [7].

  The main features of this architecture are the separation of product and resource information, and the physical separation of generic functions from specific functions of the products and the resources currently in use.

- *FACE (Flexible Assembly Control Environment)*

  FACE is an architecture developed at the Royal Institute of Technology, Sweden, and aims to simplify and speed up programming and control of flexible automatic assembly cells [7]. The FACE concept consists of the following modules: off-line control, on-line control, error recovery and databases.

- *RapidCIM*

  The RapidCIM was a joint venture project between Texas A&M University, Penn State University and Systems Modelling Corporation. The RapidCIM objective is to facilitate the process of developing full-automated computer controllers for Flexible Manufacturing Systems (FMS). The basic components of the RapidCIM concept are the Shop Floor Architecture (based in the hierarchical architecture), Factory and Process Plan Model, Formal Models of Execution and associated tools (for development of execution software) and Simulation for Real Time Control. [8].

- *MOSCOT (Modular Shop Control Toolkit for Flexible Manufacturing)*

  This architecture is characterised by two main parts: a kernel, which contains the common modules (objects) to all shop floor applications and the shells, which are developed or customised according to the specifications of each applications [9]. Examples of shells are the scheduler, P&PC interface, Graphical User Interface, Data Collection, etc. Other innovation associated to this architecture is the SCAPI (Shop Control Application Program Interface), which acts like an operating systems for shop control applications developers.

- *CCP´s Manufacturing Cell Controller*

  CCP´s Manufacturing Cell Controller Architecture, developed and implemented for the Flexible Manufacturing Cell of CIM Centre of Porto platform will be presented in detail in the next chapter.

4. Manufacturing Cell Controller Architecture

The shop floor of CCP platform is a set of four cells: Material Storage and Transportation Cell, Palletising and Calibration Cell, Assembly Cell and Flexible Manufacturing Cell. Each cell of shop floor area has a control system which objective is to integrate and manage their resources, and only has communication with Shop Floor Control.

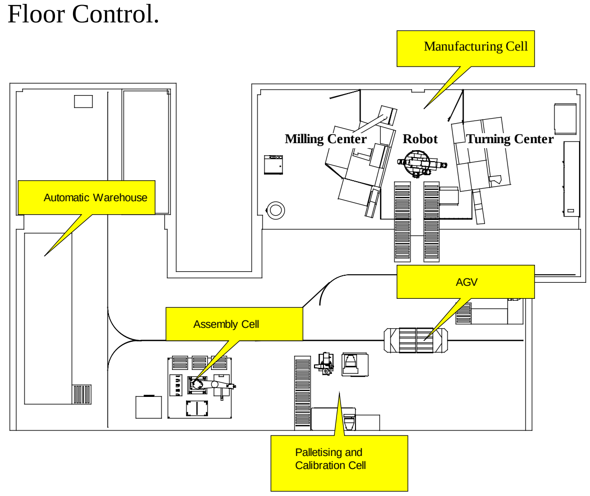

***Figure 5** –CCP´s Shop Floor Layout*

The flexible manufacturing cell has two CNC machines and an anthropomorphic robot for the load/unload of the machines. One of these machines is a turning center *Lealde TCN10*, with a SIEMENS *Sinumerik 880T* controller; the other machine is a milling center *Kondia B500* model, with a FANUC *16MA* numerical control. The robot is a KUKA *IR163/30.1* with a SIEMENS *RC3051* controller. The manufacturing cell has two transfer tables for the containers loading and unloading. These containers bring the material to be operated into the cell and take away the pieces produced.

The manufacturing cell is connected to the controlling room by a LAN with a bus structure topology, based on a base band transfer media (10Mb/s). The LLC protocol used is 802.3 (Ethernet CSMA/CD). All the machines have MAP interface boards. These interfaces are: **CP 1476 MAP** for Siemens Sinumerik 880T machine controller, **CP 1475 MAP** for Siemens Sirotec robot controller and **GE FANUC OSI-Ethernet Interface** for GE Fanuc 16MA numerical controller.

The CCP´s Manufacturing Cell Controller Architecture uses a modified hierarchical architecture approach [10].

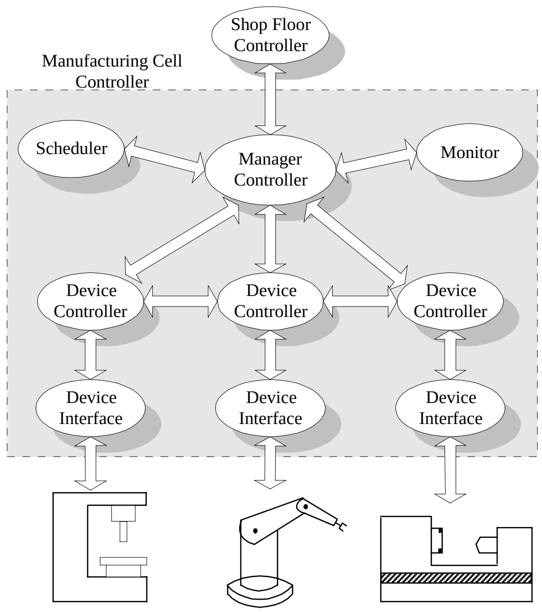

***Figure 6** –Manufacturing Cell Controller Architecture*

The Cell Controller architecture is a set of several modules, whose brain is the Manager Module, which is responsible for the control and the supervision of the production process of the manufacturing cell and also for the management of cell resources.

Each real device has an module, designated by Device Controller, which is customised to the industrial machine, such as production or handling equipment, and it has the responsibility for the local control of the machine, and for the execution of the jobs requested by the high level module.

The interface between the Cell Controller and each of the industrial machines is implemented using the MMS (Manufacturing Message Specification) communication protocol. MMS is the international standard ISO 9506 [11], and define a standardised message system for exchanging real-time data and supervisory control information between networked devices and/or computer applications in such a manner that it is independent from the application function to be performed and from the developer of the device or application.

5. Brief Approach to Distributed Manufacturing

The Virtual Enterprise environment is characterised by the distributed co-operation between different enterprises, with different functions in the network: suppliers, manufacturers/assemblers, distributors and customers. The data exchanged between the companies, over the communication platform, are basically commercial data, using an EDI (Electronic Data Interchange) format, like EDIFACT, and product data, using the STEP protocol or a similar one.

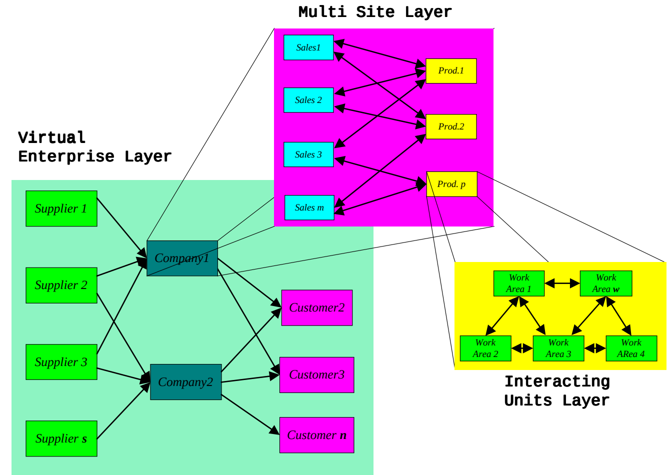

***Figure 7** – Distributed Manufacturing Layers*

A similar environment is found within each manufacturing enterprise. Zooming into an enterprise shows another distributed manufacturing layer, called the multi site case, where it is possible to find the co-operation between geographically distributed entities, which normally are the sales offices and the production sites.

Zooming again into the production sites shows the interacting units layer, where the distributed manufacturing control within a production site or shop floor can be found. Interacting units have some distributed work areas working together and in co-operation, in order to fulfil all orders allocated to the shop floor, respecting the due dates.

The distributed manufacturing systems aim to be the best solution to respond to the challenge of world wide competition and to customers requirements, that demand quality, delivery time, prices and diversity. The implementation of distributed manufacturing systems deal with some problems that are being subject of research during the last years. The main problems are the following:

- **Data Translation**. The implementation of decentralised manufacturing systems, and in particularly the virtual enterprise requires the need of data exchange between two or more companies. These data are concerned to business information, product information, project information, etc.

  The way to represent and understand the information is different in each company. The STEP protocol tries to define a standard protocol to exchange product data. The data model consists in generic data and a set of AP´s (Application Protocol), which define exchange data standards for each kind of industry. Recently, the XML (eXtensible Markup Language) is pointed as the standard for the exchange of data.

- **Decentralised Planning and Scheduling**. The planning and scheduling for a company, working stand alone, is a hard task, due to the high number of constraints involved. However, in a distributed environment, it is necessary to link the planning and scheduling systems of a company with the planning systems of its suppliers. This decentralised planning and scheduling requires the synchronisation of local planning and scheduling systems and a decentralised platform to support the global optimisation.
- **Decentralised Architectures**. Available commercial products for the distributed manufacturing problem, such as SAP APO, Baan Supply Chain, and I2 Rhythm, are based in centralised architectures, which imply that the software system become heavy, slow, and difficult to maintain and to configure. In order to improve the performance of the systems, it is necessary to develop mechanisms for the decentralised co-operation and decision-making.

6. Multi-Agent Architecture

One approach, which derives from the Distributed Artificial Intelligence, is the multi-agent system concept. In fact, the Distributed Artificial Intelligence scientific area has two different approaches to Intelligent Manufacturing Systems: Distributed Problem Solving and Multi-agent systems [12]. The Distributed Problem Solving is characterised by a set of modules co-operating to solve a specific problem, each one with a part of knowledge about the problem.

The multi-agent systems can be defined as a set of nodes, designated by agents, that represent the objects of the system. An agent can be defined as a component of software and/or hardware that is capable of acting in order to accomplish tasks. In the manufacturing systems domain, an agent is a software object, that represents manufacturing system objects, such as resources and tasks. The agents are autonomous and intelligent, and they can communicate together in order to perform the required tasks.

The agents can be classified by several different points of view:

- Mobility, which is related to theability that an agent has to move around some network. There are the static and mobile agents.
- Deliberative or reactive, related to the capacity of response of the agents. The reactive agents act using a stimulus/response type of behaviour by responding to a state.
- Ideal attributes, that are characteristics that an agent should exhibit. Examples of these attributes are the autonomy, the co-operation and learning.

The software necessary to develop each agent is much shorter and simpler than it would be required for a centralised approach, and as a result it is easier to write, debug and maintain [13].

In the Multi-agent systems, there are a clear distinction between problem solving and co-operation, where the co-operation process between autonomous agents assumes an important aspect of Multi-agent systems. In this way it is possible to find the following sub-systems in the agents architecture:

- **Information**, which deals with the mechanisms to store, manipulate and visualise the information about the production environment. These mechanisms include the security facility (backup and access levels), data distribution, data entry, data definition, data monitoring, etc.
- **Decision making**, which deals with the algorithms and problem solving rules.
- **Communication**, which deals with the specification and implementation of a communication platform to support the co-operation and exchange of data between the agents.

In this architecture, the negotiation between different agents is one of the most important problems to solve. This negotiation can be implemented using the Contract Net Protocol [14].

Many hardware vendors, such as Allen-Bradley, Honeywell, Mitsubishi and Echelon, are developing small controllers and bus-like communications architectures that are designed based in autonomous agents concept. Another example is Digital Equipment Corporation that has developed agent-based network management mechanisms [13].

7. New Paradigms for Distributed Manufacturing Control

The distributed manufacturing environments and the flexibility and reaction to disturbances requirements are crucial reasons for moving to new distributed paradigms that solve these problems and requirements.

The traditional manufacturing control systems have low capacity to adapt and react to the dynamic changes of its environment, such as the reaction to disturbances. Next generation of manufacturing control systems comprises the high adaptation and reaction to the occurrence of disturbances and to external/internal environment changes. On the other hand, these control systems should optimise the global performance of the system, which require a global view of entire system. These requirements imply the development of new manufacturing control systems with more autonomy, robustness against disturbances and more intelligence, able to handle to the changes and disturbances much better than the actual control systems.

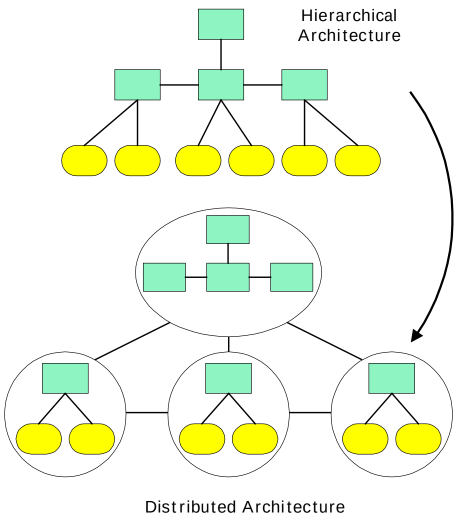

Figure 8 *– Decomposition of a Hierarchical Architectures in Distributed Architectures*

The new paradigms should have the ability to respond promptly and correctly to external changes, and they differ from conventional approaches due to their inherent capability to adapt to changes without external interventions.

There several theories for the next generation of manufacturing systems, which involve a decentralised control system, characterised by intelligent and co-operative nodes, such as holonic [15], biological [17] and fractal [18] manufacturing systems.

An additional approach to distributed manufacturing control systems is based in the behaviour of colonies of ants. The entities act quite independently, but continuously adapt to changes in their environment. The individual co-operative actions of the entities bring a collective behaviour, where the local adjustments and adaptation counteract perturbations in the environment.

Tharumarajah et al. [19], present a new approach to the scheduling task, in the distributed manufacturing environment, based in the ants behaviour.

The concepts of each paradigm are yet quite general and are currently being developed by different research communities further to implement their practical potential.

7.1 Holonic Manufacturing Systems

History

In the middle of the sixties, Arthur Koestler introduced the word holon to describe a basic unit of organisation in living organisms and social organisations. The word holon is a combination of the Greek word *holos*, which means *whole*, and the suffix *on*, which means *particle*.

The Holonic Manufacturing Systems is a new paradigm developed in the Intelligent Manufacturing Systems programme and translates the concepts that Koestler developed for living organisms and social organisations into a set of appropriate concepts for manufacturing industries [11].

Description

The HMS is a holarchy that integrates the entire range of manufacturing activities. A holarchy is a system of holons that can co-operate to achieve a goal. A holon is an autonomous and co-operative object of a manufacturing system, and it can represent a physical or logical activity, such as a robot, a machine, an order, a Flexible Manufacturing System, or even an human operator. The holon have an information processing part and often a physical processing part [16].

A holon can be part of another holon, e.g., a holon can be broken into several others holons, which in turn can be broken into further holons, which allows the reduction of the problem complexity. An example is the representation of a shop floor control system, which have a holon designed by *Manufacturing Cell Holon*. This holon can be a set of three other holons: *Robot Holon*, *Machine 1 Holon* and *Machine 2 Holon*.

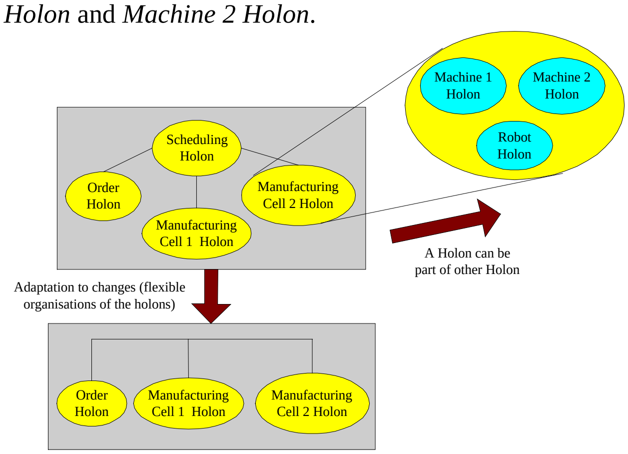

Figure 9 *– Holonic features: adaptation and holon expansion*

The Holonic Manufacturing Systems paradigm is the next generation of distributed control, and introduces the hierarchical control within the heterarchical structure. This innovation makes available the combination of robustness against disturbances, presented in heterarchical control, with the stability and global performance optimisation, presented in hierarchical control. The implementation of this concept requires that decision power must be distributed between the central and local

holons (switch between hierarchical control and heterarchical control).
The function of central holons is to advise the local holons. When the disturbances occur the autonomy of holons increase and the local holons ignore the advises of central holon. During normal functioning, the autonomy of local holons decrease and they follow the advises of central holons (for example, the scheduling plans).
The Holonic Manufacturing Systems are implemented with multi-agents systems, consisting of autonomous and co-operative units (the holons).

Actual Status

Currently the HMS concepts are being implemented through the development of a set of manufacturing holons, such as:

- machining holon;
- assembly cell holon;
- transportation holon;
- continuous processing holon.

Additionally, the development of shop floor architectures based in the HMS concepts are going on, such as PROSA (Product Resource Order Staff Architecture). This architecture is based in the holonic manufacturing systems concept and defines three basic holons: Product, Order and Resource. Additionally, exist the staff holons, whose mission is to give advises to other holons; an example of Staff holon is the scheduler. This architecture combines the predictability and the robustness of the hierarchical control with the high reaction to disturbances of heterarchical control.

7.2 Biological Manufacturing Systems

History

The Biological Manufacturing Systems is a new paradigm developed in the framework of the Intelligent Manufacturing Systems (IMS) programme, within the Next Generation of Manufacturing Systems initiative.
The Biological Manufacturing Systems tries to translate to the manufacturing world the concepts of biological nature: self-organisation and evolution mechanisms.
In Biological Manufacturing Systems, the autonomous entities are the manufacturing cells that have the capacity to self-organise in case of disturbances or in case of changes on demand [17].

Description

The biological cell is autonomous and controls its local behaviour based on the surrounding environment and genetic code. These biological units are represented by the following information:

- ***static***, genetic information found in DNA;
- ***adaptive***, learned information found in brain neurons.

The biological manufacturing is developed under the biology ideas and concepts, and assumes that the manufacturing companies can be built upon open, autonomous, co-operative and adaptative units, which can evolve. By analogy to biological cells, the manufacturing units have associated information represented by a code with static information and adaptive information.
The dynamic functionality of the biological manufacturing system, to implement the resource allocation, is based in the attraction fields concept.
In the self-organisation, each autonomous entity is described by the capability to create attraction fields, and by the sensivity to these attraction fields. In the manufacturing world, these autonomous entities are manufacturing units, such as manufacturing cells, assembly cells and transporter units (containing products).
Each manufacturing cell generates attraction fields according to its attributes, which represent the manufacturing cell capabilities. On the other hand, each product generates sensivity fields according to its attributes, which are self-modifiable and describe the processing requirements. The attraction and sensivity fields are self-modifiable, and the value of the field depends of several parameters, such as the type, capabilities (or requirements) and actual status of the autonomous entity.
The products are allocated to the manufacturing cell when the capabilities and the requirements are matched, according to the attraction fields. In this case, the attraction field of manufacturing cell and the sensivity field of transport (which transports the product) are turned off, in order to guarantee that both the resource and product could not be allocated to another unit.
In case of disturbances, for example resource breakdown, the attraction field is turned off.
The definition of these attraction and sensivity fields allows the simulation of self-organisation in Biological Manufacturing Systems.

Actual Status

At the moment, it is starting the implementation of Biological Manufacturing Systems concepts in several pilot sites, located in Japan.
Some of the largest Japonese industrial companies, such as Honda, Sony, Komatsu, Fijitsu and Fuji Electric, are experimenting the Biological ideas on how to adapt a biological approach to the factory floor and into a product´s life cycle.

7.3 Fractal Manufacturing

History

The Fractal Company introduces a set of new concepts which aim is to solve the organisation lack of flexibility to react to external and/or internal changes [18].

Description

The Fractal Company is an open system, which consists of independent self-similar units, the fractals, and it's a vital organism due to its dynamic organisational structure.
The fractal manufacturing uses the ideas of mathematical chaos: the companies could be composed by small components or fractal objects, which have the capacity to react and adapt quickly to the new environment changes.
A fractal object has the following features:

- ***self-organised***, which means that doesn't need external intervention to reorganise itself.
- ***self-similar***, which means that one object in a fractal company is similar to other object. In other words, self-similar means that each object contains a set of similar components and shares a set of objectives and visions.
- ***self-optimised***, which means that continuously increase its performance.

The explosion of fractal objects into other fractal objects, has the particularity of generating objects which possess organisational structure and objectives similar to the original ones.

Actual Status

The fractal manufacturing concepts are being implemented in several applications in the former East Germany.
An example is the Regensburg-SAS Automotive Systems, a 50/50 joint venture company formed by Siemens AT and Sommer Allibert, which has launched a fractal automotive factory. The factory produces an average of 350 complete cockpits daily for Skoda Octavia.

7.4 Comparation of Concepts

The three distributed manufacturing control paradigms, described in previous points, have some similar concepts and characteristics but they can be distinguished by their origin: mathematics for the fractal, nature for biological and social organisation for holonic. Additionally, each one of these paradigms emphasises a different set of issues and characteristics.
The concepts of these paradigms are unified in proposing distributed, autonomous and adaptative manufacturing systems. The concepts of each paradigm differ in their approach to design of these features. The biological manufacturing and specially the holonic manufacturing fit well into some existing methodologies, such as object-oriented. Instead, the definitive approaches may not be suited for fractals that require a multi-dimensional approach [22].
The behaviour of these paradigms is more open, autonomic and co-operative when compared with the traditional manufacturing systems. The cells, in biological manufacturing, react to inputs and outputs of other cells in their environment, and the holons, in holonic manufacturing, cooperate and negotiate with other holons, in order to plan and make decisions about their tasks. The fractals, in fractal manufacturing, pursue concurrent and iterative goal formation.
At other level, it is possible to compare the Holonic Manufacturing Systems and the Multi-Agents Systems, which have similar concepts. However, it is possible to find some different features [15]:

- The Agents are a general concept while the Holons are focused in the manufacturing area.
- The Holonic Manufacturing Systems can be implemented using the Multi-Agent Systems, with the additional possibility to combine hierarchical structures with heterarchical structures.
- Holons include the physical objects that are managing, and consider also the human integration.
- A holon can represent simultaneously a whole and a part of the whole. Thus a holon can be made up of other holons. An agent doesn't supports this feature.

8. Negotiation Mechanisms for Distributed Manufacturing

In the architectures where it is necessary that the some entities interact between themselves, such as distributed architectures, it is crucial the existence of a process of co-operation, through the negotiation between entities. Negotiation approaches among agents have been developed using various heuristics rules.
Since each entity is totally autonomous, it will be able to refuse or accept one given message, from the knowledge that has of its state. This feature will have to be kept or to be safeguarded during the negotiation process.
The well-known negotiation protocol and widely used to implement the co-operation process is the Contract Net Protocol [14]. Basically, this negotiation process allows the allocation of entities that are qualified to execute one given range of tasks. The negotiation has four important components:

- local process ,that does not involve central control;
- swap of information in the two directions;
- each part of the negotiation evaluates the information from its point of view;
- final agreement is reached by mutual selection.

Each entity can take two designations, as the execution of the individual tasks: contractor or contracted. A priori, each one of the entities is not assigned by any of the two.

The contractor is responsible for the monitoring of the execution of the task and the processing of results of its execution. The contracted one is responsible for the execution of the task.

During the negotiation, the distributed entities will exchange messages, through the follow negotiation schema:

1. **Announce of the task** - the entity that creates the task, normally initiates the negotiation, announcing it to the other entities, indicating in the sent message the set of specifications that the entities will have to satisfy;
2. **Reply** - when an entity receives a message announces of task, verify if the required specifications, can be satisfied by itself, and in affirmative case it sends this message indicating its capacities to carry through the task;
3. **Adjudication** - after analysed all the responses, the contractor sends a message to the entities that have been selected.

If the manager knows exactly which the entity is appropriate to execute the task, it does not send one announce of task, but a adjudication message directly to this entity.

The Contract Net based co-ordination approach may clearly lead to sub-optimal scheduling solutions. The main reasons for that are the short one-step planning horizon and the very limited information that agents can use while negotiation task allocation [20].

The Contract Net based approach are spatial and temporal myopic. Spatial myopy means that the information of the state of others contractors is not used during the construction of a bid, while the temporal myopy means that the information of sub-sequent tasks is not used either in bidding or in award selection.

Some researchers have proposed modified versions of Contract Net, such as Extended Contract Net Protocol and B-Contract Net, that extended the Contract Net with additional features. For example, Shen [21] proposed an CNP, that allows that in bidding and negotiation process, the contractor keeps the indication of resources not selected as alternatives in case of unforeseen situations such as a machine breakdown.

In the decision-making process, there are some particular problems that negotiation should solve, such as indecision and renegotiation problems. The indecision problem can be characterised by the indecision of an agent to choose between two announced tasks overlap on time frame. The agent can reply to both of tasks announcements which is a bad decision if both tasks will be acknowledged to the agent. On the other hand, if the agent only replies one of task the decision is bad if that task will not be allocated to the agent.

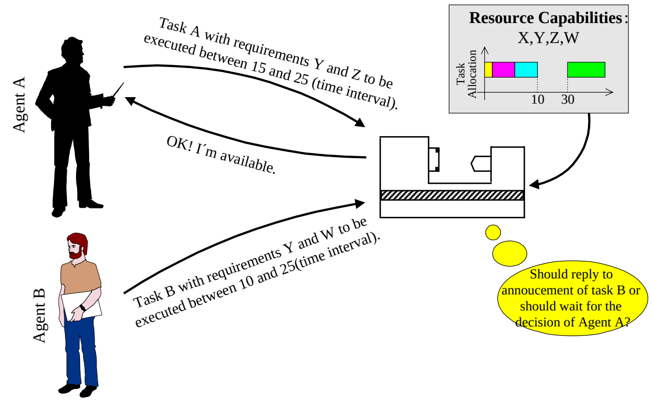

Figure 10 *- Indecision problem in the concurrent task case*

There are some basic solutions approaches to this problem, such as pessimistic and optimistic approaches, and other more intelligent approaches that requires some information about the global state of the system [20].

The renegotiation problem is the procedure that should be performed after the occurrence of a disturbance, such as the machine breakdown.

The Constraint Satisfaction approach and the Simulation based approach are alternatives to the Contract Net approach.

9. Conclusions and Future Work

The development and implementation of flexible, intelligent and co-operative control systems is the key factor to improve the competitivity of an enterprise. This paper presented some research on traditional architectures for development of manufacturing control systems, with special focus to CCP´s flexible manufacturing cell controller architecture developed using the modified hierarchical control structure. The requirements of manufacturing systems of next century, for example, the virtual enterprise concept, show that it is necessary to evolve to the implementation of new paradigms for manufacturing distributed control.

The development and dissemination of the new decentralised control systems theories will allow the future implementation of modular, flexible and intelligent control systems architectures, such as the Cell Controllers and Shop Floor Controllers, with the advantage of flexibility, global optimisation and robustness against disturbances of the manufacturing systems intelligence.

10. References

[1] M. P. Groover , "Automation, Production Systems and CIM", Prentice-Hall, 1987.

[2] U. Rembold, B.O. Nnaji, "Computer Integrated Manufacturing and Engineering", Addison-Wesley, 1993.

[3] Paul Kidd, “Agile Manufacturing: Forging New Frontiers”, Addison-Wesley, 1994.

[4] L. Camarinha-Matos, R. Carelli, J. Pellicer, M. Martín, “Towards to the Virtual Enterprise Food Industry”, in Proceedings of International Conference on Integrated and Sustainable Industrial Production, Edited by Luis Camarinha-Matos, Chapman & Hall, Lisboa, Maio de 1997, pp 73-84.

[5] D. Diltis, N. Boyd, H. Whorms, “The evolution of control architectures for automated manufacturing systems”, in Journal of Manufacturing Systems, Vol. 10 Nº1, 1991,pp 63-79.

[6] A. Bauer, R. Bowden, J. Browne, J. Duggan and G. Lyons, “Shop Floor Control Systems - From Design to Implementation”, Chapman & Hall, 1991.

[7] B. Janusz, L. Bongaerts, P. Gullander, P. Klingstam, L. Monostari, P. Jordan, “Shop Floor Control Architectures”, Proceedings of ASI 97 (Advanced Summer Institute of the Network of Excellence on Intelligent Control and Integrated Manufacturing Systems), Budapest, 14-17 July, 1997, pp 9-16.

[8] RapidCIM WWW Pages,
http://wimpy1.psu.edu/rapidcim/doc2.html

[9] G. Teunis, P. Leitão, M. Madden, “A New Architecture for Flexible Shop Control Systems”, in Proceedings of Integration in Manufacturing Conference, Gotengorg, 6-8 October 1998, pp 699-709.

[10] A. Quintas, P. Leitão, “A Manufacturing Cell Controller Architecture”, Proceedings of Flexible Automation and Intelligent Manufacturing Conference, Begell House Inc, ISBN:1-56700-089-4, Edited by William G. Sullivan and M. Munir Ahmad, Middlesbrough, June 1997, pp 483-493.

[11] ISO/IEC 9506-1, Industrial Automation Systems - Manufacturing Message Specification, Part 1 - Service Definition, 1992.

[12] Paulo Sousa, Carlos Ramos, “A Distributed Architecture and Negotiation Protocol for Scheduling in Manufacturing Systems”, in ASI 96 **???**, pp 311-318.

[13] H. Van Dyke Parunak, “Applications of Distributed Artificial Intelligence in Industry”, in Foundations of Distributed Artificial Intelligence, Wiley Inter-Science, 1994

[14] R.G. Smith**, “**The Contract Net Protocol: High-Level Communication and Control in a Distributed Solver, *IEEE Transactions on Computers*, Vol. C-29, Nº12, pp 1104-1113, 1980.

[15] Luc Bongaerts, Integration of Scheduling and Control in Holonic Manufacturing Systems, PhD thesis, Katholieke Universiteit Leuven, 1998, Belgium.

[16] M: Winkler, M. Mey, “Holonic Manufacturing Systems”, in European Production Engineering, October 3-4, 1994.

[17] N. Fujii, J. Vaari, K. Ueda, “Potential field based simulation of self-organisation in Biological Manufacturing Systems”, in Proceedings of Manufacturing System Design, May 14-16, 1997, Magdeburg, Germany.

[18] J. Bischoff, "The Fractal Company - Success Factors of a High-performance Organisation", in Proceedings of Integration in Manufacturing Conference, Gotengorg, 6-8 October 1998, pp 257-265.

[19] A. Tharumarajah, A. Wells, A. Wirth, “Scheduling in Distributed Production Systems, in Proceedings of Conference ICME 95, Melbourne, Australia, 1995.

[20] Ilkka Seilonen, “Distributed and Collaborative production management systems in discrete part manufacturing: A review of research and technology”, VTT Research Notes, Espoo, 1997.

[21] Weiming Shen, Douglas Norrie, “Hybrid Agent-Oriented Infrastructure for modelling Enterprises”, in Proceedings of KAW´98 Conference, Banff, Canada, 1998.

[22] A. Tharumarajah, A. Wells, L. Nemes, “Comparison of the Bionic, fractal and holonic manufacturing systems concepts”, in International Journal of Computer Integrated Manufacturing, 1996, Vol.9, nº3, pp 217-226.