A MANUFACTURING CELL CONTROLLER ARCHITECTURE

António Quintas [1] , Paulo Leitão [2]

[1]Professor Associado do DEEC da Faculdade de Engenharia da Universidade do Porto, Rua dos Bragas, 4099 Porto Codex; Tel: 351.2.2041844; email: aquintas@fe.up.pt
[2]Assistente da ESTG do Instituto Politécnico de Bragança, Quinta S^{ta} Apolónia, Apartado 134, 5300 Bragança; Tel:351.073.3303083; email: pleitao@ipb.pt

ABSTRACT : Worldwide competition among enterprises has lead to new needs in the area of manufacturing to answer for price, quality and delivery time. The improvement of productivity and flexibility in manufacturing systems by the introduction of new concepts and technologies, and by the appropriate integration of the different resources, may constitute a key factor for the solution towards the success.
This paper describes the specification and implementation of a Manufacturing Cell Controller integrated into the demonstration pilot of an ESPRIT Project.
Special attention is given to the control structure, communication system, information system and the way the integration was done using the MMS (Manufacturing Message Specification) communication standard. Be also important, an analysis of the performance and costs of the solution is discussed together with alternative development platforms and technologies to achieve a better one.

1. INTRODUCTION

Worldwide competition among enterprises lead to a need for new control systems, which perform the control and the supervision of the manufacturing through the integration of the resources. The implementation of these technologies is the answer to the improvement of productivity and the quality, and the decrease of the price and the delivery time.
The control systems used to integrate and to control the resources of a manufacturing or assembly cell, is called by Cell Controller [1]. Mainly, the Cell Controller must allow the following functions [1,2]:

- the integration of the cell resources;
- the manufacturing control and supervision;
- real time scheduling of cell production, based upon the real time cell capacities;
- the storage and the download of the NC and the RC programs;
- the reaction to fault conditions.

The design and the implementation of a Cell Controller is a complex task, involving real time control restrictions and the manipulation of different operating systems, different

communication protocols and machines supplied from different vendors. The specification of a Cell Controller architecture results into the definition of two main points: control structure and communication system.
The control structure is a key factor for the final performance of the Cell Controller and it can be performed with some basic control architectures: centralized, hierarchical and heterarchical [3]. With the powerful PCs, inexpensive and widely available, the architectures evolued from centralized architecture to the distributed architectures, allowing the improvement of the Cell Controller performance.
The communication system is crucial to implement the integration of the cell resources, as to transfer to them the NC and RC programs and also to control these devices. There are several protocols available to implement the communication system: MAP (Manufacturing Automation Protocol) /MMS, FieldBus, serial link, TCP/IP. The choice of a communication protocol depends upon the costs, the standardization, and the control degree available.
Following the paper, a Cell Controller architecture solution is described, with the analysis of his performance. Then, other platforms and technologies for the Cell Controller are discussed and a comparative performance evaluation is presented.

2. MANUFACTURING CELL CONTROLLER

2.1 Flexible Manufacturing Cell

The 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 [4].

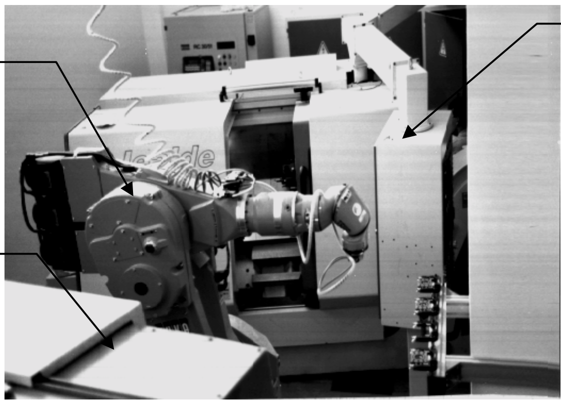

Figure 1 *- Manufacturing cell layout*

The Cell Controller was developed and implemented in a Sun SparcStation 10 workstation with Solaris 2.4 Operating System. This workstation has a network card with two stacks:

- **TCP/IP stack**, for the communication with the Shop Floor Controller and the Project Department. This network allows the transmission of NC and RC programs from fileserver to the industrial machines;
- **OSI MAP stack**, for the communication with industrial machines, like NC machines and robots.

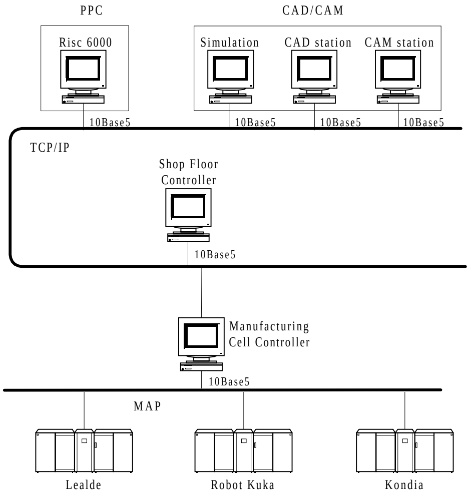

Figure 2 - Shop Floor communication infrastruture

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.

2.2. Manufacturing Cell Controller architecture

The Cell Controller architecture implemented in the manufacturing cell is a set of several modules, that share information stored in a local database [4]. The definition of control structure for Cell Controller was done keeping in mind two important aspects:

- **modular structure**, which allows the future expansion of the control system, for instance, if the number of machines grows up;
- **real time requirements**, to guarantee that control system is able to execute all required functions performing the time restrictions, for example the cooperation between machines.

The specified architecture for this Cell Controller is based in the hierarchical architecture; the initial control system is decomposed into individual subsystems, and each one of these subsystems can be updated as necessary without affecting the rest of the system.
This structure has three hierarchical levels, being each one responsible for the execution of control functions. The first level, the Manager Module, is the brain of the Cell Controller, and it is responsible for the control and the supervision of the production process of the manufacturing cell and also for the management of cell resources. The main functions of this module are:

- Start the Cell Controller, verifying if it is a normal or abnormal start;

- Receive and process the messages from the Shop Floor Controller;
- Receive and process the results of services executed by the Device Controllers;
- Determine for each order, the next operation to be executed and dispatch these orders to the Device Controllers;
- Notify the Shop Floor about the evolution of the orders and whenever an alarm occurs;

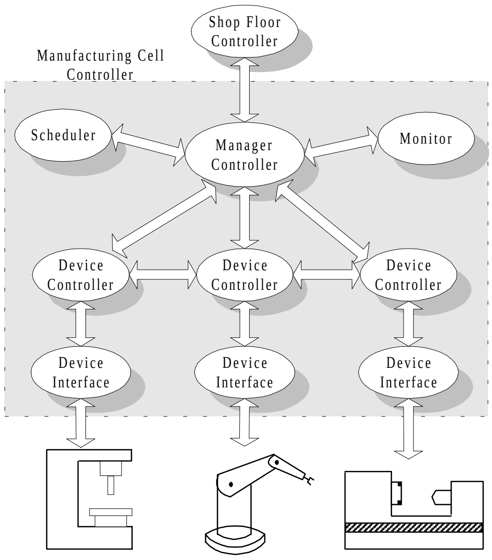

Figure 3 - Cell Controller structure

The management of the manufacturing cell is based upon information stored in the cell database. This database contains information about orders, resources, cell buffers and tools stored in the industrial machines of the cell. In the second level, there are several modules to control industrial machines. Each of these modules, designated by Device Controller, is customized to the industrial machine and it has the responsibility for the execution of the jobs in the machines. Finally, the last level, the Device Interface, contains the interface between the Cell Controller and each of the industrial machines, implemented with the MMS protocol.
All Cell Controller code is written in C language and the communication between modules, inside the Cell Controller, is implemented with a Unix Operating System functionality, called pipes, which is made up of files to exchange the messages.

2.3 MMS, A Standard Protocol

Flexibility and open systems concept lead us to the application of an open systems communication standard protocol at the manufacturing process control level. MMS is a standardized 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. MMS is the international standard ISO 9506 [5], based upon the OSI (Open Systems Interconnection) networking model - it’s a protocol of the application layer of the OSI model. It runs on the top of an OSI stack providing a set of 80 services distributed for ten MMS functional classes.
The MMS protocol implements the interface communication between the Cell Controller and the industrial devices. The key features of MMS are:

- **the “Virtual Manufacturing Device” (VMD) model**. The VMD model specifies the objects contained in the server, and with MMS services it is possible to access and manipulate these objects;
- **the client/server model**. The client is a device or application that requests data from the server; the server responds with data requested by the client.

There is a distinction between a real device (e.g. PLC, CNC, Robot) and the real objects contained in it (e.g. variables, programs), and the virtual device and objects defined by the VMD model. Each developer of a MMS server device or MMS server application is responsible for “hiding” the details of their real devices and objects. The executive function translates the real devices and objects into the virtual ones defined by the VMD model.

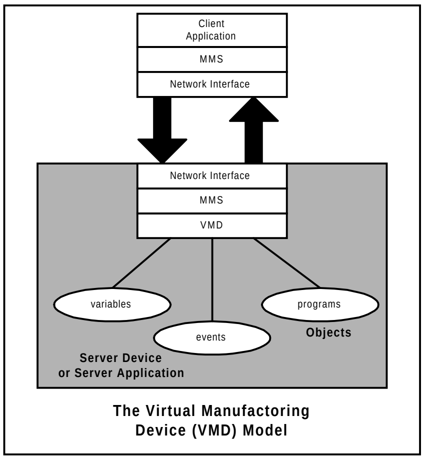

Figure 4 - The VMD model

In many cases, the relationship between the real objects and the virtual ones can be standardized for a particular class of device or application (PLC, CNC, Robots, PCs). Developers and users of these real devices may decide to define more precisely how MMS is applied to a particular class of device or application - the result is a Companion Standard.
It is possible to note the missing of some implementations that would be useful from the control application point of view. There is a gap between the MMS functionalities specified in ISO 9506 [6] and the objects and services provided by the MMS server applications for the controllers we work with. As an example the end of execution of a NC/RC program can be asynchronously reported by the server application by means of an event notification unconfirmed MMS service. This feature is only implemented in the MMS server application for the *Sinumerik* NC controller. The MMS server application for the *GE FANUC* NC controller reports this occurrence with an unsolicited status unconfirmed MMS service. In the case of the robot MMS server application there is no mechanism for the reporting of this occurrence which implied the development of a polling function with the associated lost of efficiency.
It has also been possible to note different solutions in the modeling of some real objects to MMS objects for the MMS server applications related to the two NC controllers. We expect that in the future this problem is solved with the application of MMS Companion Standards.

3. PERFORMANCE ANALYSIS

3.1 Data Transmission rates

The execution of a program in a industrial device requires the existence of this program inside the device memory. Due to the memory capacity limitation, it is necessary to transfer the program to the device whenever it will be necessary. This operation is performed by the Cell Controller with the MMS Download service. During the Cell Controller implementation tests, and with a network analyzer, it was possible to work out the transfer speed: 10 kbits/s. This speed is very slow and origines the Cell Controller lost of efficiency. For example, the Cell Controller spends approximately 30 seconds to download a NC program with 50 kbytes! This time is not profitable in the processing tasks, and causes the lost of productivity in the manufacturing cell.

With this slow transfer speed, it was necessary to know where the problem was located. After several tests, it could be concluded that the problem was not associated with MMS protocol, because two MMS applications, running at SUN worksation, could communicate with 10 Mbits/s transfer speed; thus, the problem is related to the internal machine problems. In fact, when a machine receives a program, this is analyzed inside the machine, line by line, to detect errors inside the program. This procedure causes the reduction of data transmission from 10 Mbits/s to 10 kbits/s.

For increasing the Cell Controller efficiency, it is necessary to do the management of the NC programs inside the machines memory and download the needed NC programs into the Cell Controller, making use of it´s dead times. This is a complex solution to be implemented, and requires the introduction of Artificial Intelligence techniques inside the system control.

5.2 Costs of the solution

The cost is an important factor that will be decisive for the viability of a solution. It is possible to quantify the cost associated with this Cell Controller architecture solution, by analyzing the costs of the several platforms and interface boards used to implement the Cell Controller. These costs can be divided into three main areas: the communication software, the interface boards and the developing platform.

The cost of the MAP/MMS interface boards is around $6000 (US dolars) each one. In this application, the number of MAP/MMS interface boards is 4 (3 servers/machines and 1 client), so it is necessary to spend $24000 to provide all cell resources with MAP interface boards. The price of the MMS software (MMSEASE from SISCO in this case) is around $6700. The cost of the developing platform is $15340, due to the cost of the SUN SparcStation 10 and the developing software SUN SparcWorks.

For a better perception of this cost value, it is possible to make a comparation with the cost associated with the resources of the cell (two NC machines and one robot). The cost of these three machines is around $333300. So, the communication system cost value is approximately 9,2% of the costs associated with the resources of the cell, and the cost of Cell Controller is approximately 13,8%. However, taking into consideration the cost related with the developing phase, it can be assumed the reduction of this percentage (9,2%), due to the less effort allocated to this phase when the MMS solution is adopted.

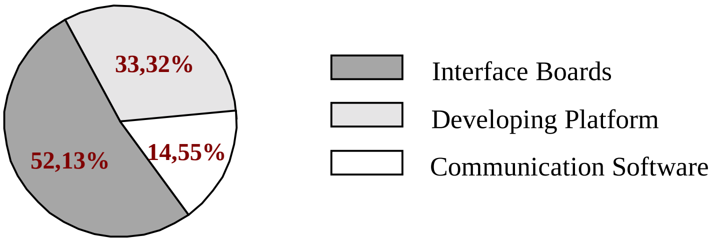

Figure 5 - Cost of the Cell Controller architecture

Even so, with this scenario, it can be concluded that it is expensive to use a standardized communication protocol like MAP/MMS, basically because of the price of the interface boards quite high. In alternative, other communications protocols, such as the FieldBus, could realise the communication system. The need also for new platforms like Windows NT suggests even higher costs not supportable by the generality of SMEs (Small and Medium Enterprises)

4. NEW TRENDS OF THE CELL CONTROLLER ARCHITECTURES

Actually, the questions around the design and the implementation of the Cell Controller solutions are focused in the new technologies and methodologies, to increase his performance and to decrease the developing time of the solution. What is the best communication protocol? What is the adequate developing platform? What is the best control system to be implemented? The answers to these questions require the analysis of the technologies and the methodologies available, together with the requirements of the specific problem.
The trends of the Cell Controllers can be characterized in the following points:

- distributed and user-friendly developing platforms, which allow a quick, easy and also a cheap solution;
- communication protocols, like MMS and Fieldbus, which must allow the easy integration of the resources supplied by different vendors;
- new programming and control paradigms, such as object oriented and Artificial Intelligent methods, which allow the improvement of the solution performance;
- new generation of manufacturing systems, such as holonic, biological and fractal systems, which allow the rapid development and the flexibility needed for the manufacturing systems.

The following points will dispute the application of these technologies and methodologies, with the special attention to the manufacturing systems requirements.

4.1 Developing Platforms

Newish PC operating systems, such as Windows NT, offer the same features of the Unix systems, with the advantages of low setup, administration effort and cost. These operating systems present a platform windows compatible, a good market penetration, an inexpensive platform and a wide range of development tools available.
An important problem with the Unix platforms is the monitoring or graphical interface is very complex to implement. The use of Visual C++, for instance, allows the reduction of development costs and a more quick implementation of the solution for the desired application, using all the potentialities of these programming tools. The Windows NT platform allows the

reduction of hardware costs and the use of more user-friendly programming tools, like Visual Basic or Visual C++.

4.2 New Programming and Control Paradigms

Due to the complexity and diversity of the problems to be solved, it is necessary to use new programming paradigms, such as Object Oriented, instead of traditional programming. The traditional programming should be used only if combined with artificial intelligence methods, such as knowledge based systems.

The Object Oriented paradigm is a new approach, which increases the potentiality of the programming tools. Object oriented programming is a paradigm for a software design and implementation, which is organized as a collection of objects, that operate by exchanging each other, messages of services request. [7]. An object is simply something that makes sense in an application context, and it is characterized by encapsulating his data, designated by attributes, and offering a set of services, designated by methods, to access the data.

Another ongoing research area in the Cell Controller design and implementation is the artificial intelligence methods. The application of the artificial intelligence methods allows the resolution of complex control tasks, such as the faults recover and the resources control. There are several AI methods available to be implemented in the Cell Controllers solutions, such as Expert Systems, Neural Networks and Fuzzy Logic.

The knowledge-based systems use the human and the specialist experience to solve the problems. The knowledge is stored in a database, which can be updated through the system learning, and a so-called inference engine can make decisions with a higher efficiency.

4.3 Communication Protocols

The integration of the industrial resources, using a Cell Controller, interfers with the lower levels of the ISO model: cell, equipment and sensors.

The implementation of the RS232 or RS485 protocol is very cheap, but it requires the development of an API (Application Program Interface) for each industrial resource, customized to the resource funcionalities. For a higher number of resources, this task is complex due to the different functionality of each resource. Thus, the RS232 is acceptable for applications with low degree of control and when it is only necessary to transfer the NC and RC programs to the industrial resources. Applications to control a lot of resources (supplied from different vendors) and with some control and supervision tasks, need a standard communication protocol, such as MAP or Fieldbus.

The MAP architecture is based upon the OSI reference model, specifying an ISO protocol for each layer. In the application layer, two important protocols are specified: MMS for the remote control and monitoring of the industrial resources, and FTAM (File Transfer Access Management) for the files remote access. The advantages of this architecture are the suppliers independence, the decrease of developing cost and the decrease of maintenance cost.

The CNMA project [5], developed under the ESPRIT programme, is compatible with the MAP architecture, and additional specification of the RDA (Remote Database Access) protocol in the application layer. These architectures are a good solution for applications with a large number of different resources (from different suppliers); nevertheless, in situations, which require temporal restrictions, these architectures are to heavy. Other additional disadvantage is the cost of the interface boards, which dissuades the expansion of this communication protocol in the industrial market.

The Fieldbus networks are traditionally used to interconnect sensor and actuator devices, localized in a small local area. These industrial networks only implement three layers: physical, data link and application layers. The physical layer uses the RS485 protocol, adequate to the industrial communications due to the good noise immunity, and also it has the possibility to implement the MMS protocol in the application layer. These networks are characterized by the good adaptation to adverse ambients, an easy update of new resources and the low cost of the interface boards and the maintenance.
The limitative factor to the expansion of the Fieldbus networks is the lack of the standardization in this architecture. In fact there are several standards for the Fieldbus [8]:

- **FIP (Factory Instrumentation Protocol)**, supported by the french manufacturers;
- **PROFIBUS (Process Fieldbus)**, supported by Siemens, Bosh and Kloeckmer-Moeller;

The FiCIM project [9] was an effort to create an unique fieldbus standard, but the aim of the project wasn't reached.

4.4 New Generation of Manufacturing Systems

Manufacturing industry comprises the manufacture of a variety of products in small sized lots, with a small delivery time. These requirements imply the development of new manufacturing control systems with more autonomy and more intelligence, able to handle to the changes and disturbances much better than the actual control systems. There are several theories for the manufacturing systems, which involve a decentralized control system, characterized by intelligent and cooperate nodes, such as holonic, biological, fractal and genetic manufacturing systems. These theories have some similar concepts, but they can be distinguished by their origin: mathematics for the fractal, nature for biological and social organization for holonic.
The Holonic control system is based upon a structure with several holons, each one being autonomous and able to cooperate with the other holons. An holon is a particle or module, and it can represent a physical or logical activity, such as a machine, an order or an operator. The holonic paradigm consists in broking complex tasks into a several sub-tasks, which in turn could be broken into further sub-tasks, which allows the reduction of the problem complexity [10].

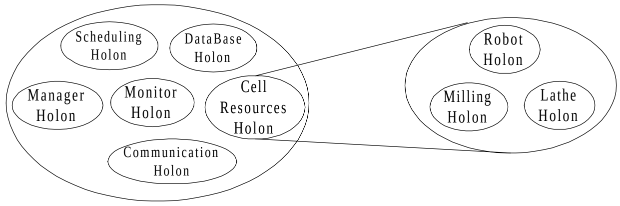

Figure 6 - Holonic system architecture

This structure presents the following benefits:

- fast reconfiguration in response to the system strategical exchange;
- increase of the system flexibility, because it is possible to consider the operator as a holon;
- increase the capability for the expansion of the system, because it is easier to do.

One approach which derives from the Distributed Artificial Intelligence is the multi-agents systems concept. The multi-agents architecture could be defined as a set of nodes, designated by

agents, that represent the manufacturing system objects, such as resources and tasks. The agents are autonomous and intelligent, and they can communicate together to perform the required tasks. In this architecture, the negotiation between different agents is one of the most important problem to solve. This negotiation can be implemented using the Contract Net Protocol [11].
The dissemination of these theories will allow the future implementation of modular, flexible and intelligent Cell Controller architectures, with the advantage of flexibility and the improvement of the manufacturing systems intelligence.

5. CONCLUSIONS

The cell controller architecture presented in this paper is now working well. The two major aspects of a Cell Controller specification were focused: the control structure and the communication system. In the control structure, the use of decentralized architectures is growing up, mainly due to the increase of the computing system capacities and the reduction of the prices. The control structure presented in the Cell Controller solution is an hierarchical architecture, allowing the flexibility and the modularity of the application. The communication system is implemented with the MAP/MMS protocol due, basically, to it´s standardization and the simplicity of it´s implementation.
With the analysis of the MMS implementation, it was possible to conclude that the costs of the MMS interface boards may be the limiting factor to the implementation of MMS protocol in the integrated applications. Nevertheless, the MMS protocol is a good solution for applications which require a total control of resources, or when the integration involves a great number of resources with high degree of complexity.
The trends of the Cell Controller technologies and methodologies, look for Cell Controller architectures with low cost and with short developing time, which can be afford by SMEs. The cell controllers for the next future are mainly based upon four points: developing platforms, new generation of manufacturing systems, communication protocols, new programming and control paradigms. The development and implementation of these new concepts will allow the increase of the Cell Controllers performance, operationality, and also the decrease of their cost.

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