New Shop Floor Control Approaches for Virtual Enterprises

Luís Ribeiro (ldr@uninova.pt)
Faculty of Science and Technology, New University of Lisbon

José Barata (jab@uninova.pt)
Faculty of Science and Technology, New University of Lisbon

Abstract

The virtual enterprise paradigm seems a fit response to face market instability and the volatile nature of business opportunities increasing enterprise's interest in similar forms of networked organisations.

The dynamic environment of a virtual enterprise requires that partners in the consortium own reconfigurable shop floors. This paper presents new approaches to shop floor control that meet the requirements of the new industrial paradigms and argues on work re-organization at shop floor level.

Introduction

The emergence of the Virtual Enterprise (VE) paradigm comes as a response to the continuously changing socio-economic challenges that modern enterprises have to deal with in order to maintain competitive. Rather than an isolated concept, the VE paradigm is part of a natural sequence of the process restructuring in the traditional industrial paradigms that has been observed in recent years (Camarinha-Matos and Afsarmanesh, 2005a) and is supported by the most recent developments in networking and ubiquitous computing technologies.

Although the concepts and definitions regarding the VE paradigm are evolving and a common terminology is far from being agreed, there are some running examples of such organizations (Camarinha-Matos and Afsarmanesh, 2005a).

Recently the focus of the development effort concerning VE has been directed towards global integration of complex autonomous and heterogeneous systems (Camarinha-Matos and Afsarmanesh, 2005a). Nevertheless there are important integration issues at shop floor level that remain unsolved.

In fact, the dynamic nature of a VE imposes that the participating enterprises have themselves a dynamic and reconfigurable infrastructure at shop floor level. The traditional control methods and devices are not robust enough to cope with fast shop floor or process reconfigurations.

Most of the industrial device manufacturers are incorporating processors into their products and supporting software interaction among devices in a tendency that is shifting them towards intelligent components.

To take full advantage of these technologically advanced devices an innovative approach to control is needed. Distributed control fits the robustness requirements of the modern shop floor activities while modern networking software can help to attain an easily reconfigurable shop floor. In this context technologies such as Multi-agent Systems and WebServices can provide some interesting base infrastructures.

The introduction of sophisticated software technology at shop floor level is likely to change the way workers operate the system as well as their knowledge and competencies.

Virtual Enterprises

Virtual Enterprises and Collaborative Networks

A Collaborative Network (CN) can be defined has "a variety of entities that are largely autonomous, geographically distributed, and heterogeneous in terms of their: operating environment, culture, social capital and goals" (Camarinha-Matos and Afsarmanesh, 2005b).

This sort of networks can be further sub classified according to their goals and level of collaboration. According to (Camarinha-Matos and Afsarmanesh, 2005b) several variants of CN's exist, in the context of this work the following worth mention:

- Virtual Enterprise (VE) – "a temporary alliance of enterprises that come together to share skills or core competencies and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks".
- Virtual Organization (VO) – "a concept similar to a VE, comprising a set of (legally) independent organization that share resources and skills to achieve its mission/goal, but that is not limited to an alliance of for profit enterprises".
- Extended Enterprise – "a concept typically applied to an organization in which a dominant enterprise extends its boundaries to all or some of its suppliers".
- VO Breeding Environment (VBE) – "represents an association or pool of organizations and their related supporting institutions that have both the potential and the will to cooperate with each other through the establishment of a base long-term cooperation agreement and interoperable infrastructure. When a business opportunity is identified by one member, a subset of these organizations can be selected and thus forming a VE/VO".

From the descriptions above its clear that the broadest concept is a CN being the others sub specializations as shown in Figure 1

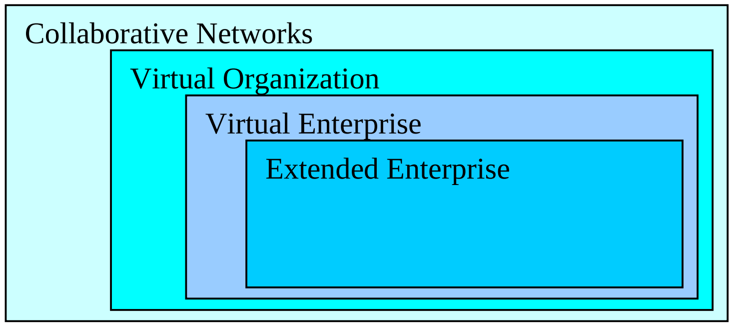

Figure 1. Examples of CN's adapted from (Camarinha-Matos and Afsarmanesh, 2005b)

Virtual Enterprise Life Cycle

A typical VE presents the following life cycle (Camarinha-Matos and Afsarmanesh, 2003b):

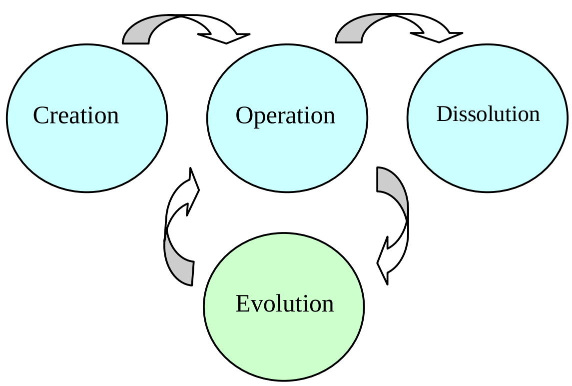

Figure 2. The VE lifecycle

- Creation - the first step in the establishment of a VE is the identification of a business opportunity after which partners search and selection and role definition takes place.

- Operation – The activities in a VE are normally divided among members according to their core competencies. In the operation phase all the activities must be coordinated in order to achieve the goal established earlier. During operation the VE is required to cope with unexpected changes at all levels. Failing to do so can pose a serious threat on the success of the process

- Evolution – dealing with changes includes being prepared to admit new partners and releasing old ones or role switching inside the VE. This happens typically during evolution phase.

- Dissolution – in the end risks, profit, product maintenance, etc has to be divided amid participants.

Figure 2 clearly shows that changes in a VE like environment are part of its natural development therefore participating entities must be able to cope with these dynamic interactions at all levels.

A new industrial/business Paradigm

Industrial/business Paradigms have historically evolved to face market needs increasing enterprise competitiveness. In (Barata, 2003) there is an extensive review on industrial/business paradigms change over time.

As costumers become increasingly demanding, enterprises must seek for innovative forms of organization. In recent years advances in the information technologies (IT) have been playing an important role in enterprise restructuring towards increased multilevel flexibility, integration and easy reconfiguration.

Rather than an isolated concept the VE paradigm falls within this restructuring process. Among the advantages that emerge from joining a VE like organization are worth mention (Camarinha-Matos and Afsarmanesh, 2003a):

- Agility – "the ability to recognize , rapidly react and cope with unpredictable changes in the environment in order to achieve better response to opportunities, shorter time-to-market, and higher quality with less investment".

- Complementary roles – "enterprises seek for complementarities that allow them to participate in competitive business opportunities and new markets".

- Achieving dimension – the VE concept is especially interesting for small and medium size enterprises (SME's). Working as partners SME's can exploit business opportunities beyond individual capabilities.

- Competitiveness – proper task division among specialized partners shortens time response increasing cost effectiveness.

- Resource Optimization – picking the right partners prevents waste of resources.

- Innovation – working as a network provides an environment for knowledge exchange.

Figure 3 shows the evolution the evolution of business paradigms and the business environment along time.

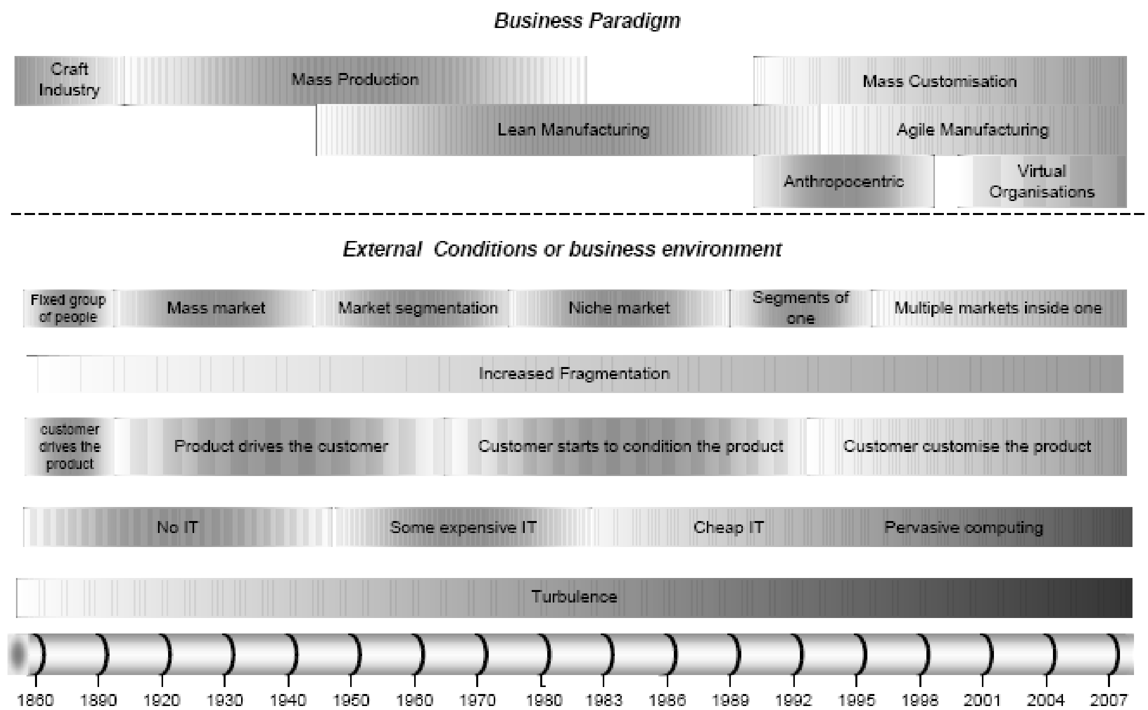

Figure 3. Business Paradigm and Business Environment over time (Barata 2003).

Again, taking advantage of participating in a VE comes at a price of owning a suitable IT infrastructure and being able to deal with changes at all levels including the shop floor.

Shop Floor Requisites of Virtual Enterprises

Achieving agility requires comprehensive multilevel system integration starting from the cell level where basic hardware resources and their controllers must be able communicate in order, to complete a certain task, on to shop floor level where the various cells must be provided a mean to warrant that the production process runs properly. Further integration is possible inside an enterprise this includes integrating the shop floor with other departments.

The VE/VO concept represents an additional step regarding system integration since it requires that all IT infrastructures of the partners are harmonized and functional. Once this difficult task is accomplished the VE is ready to start operating. Normally this task is time consuming and by the time a VE is ready the business opportunity may no longer be viable. In (Camarinha-Matos, 2005) some design and development issues are analyzed.

If an enterprise is willing to joint a VE or a VBE it must be agile not to compromise the VE agility requirements. As previously seen there is an increased demand for customized products. Especially as part of a VBE an enterprise may be part of several VE’s this has tremendous requirements for agility, plug-ability, flexibility and robustness at shop floor level.

Technologies for Shop Floor Control

Shop Floor Control Reference Architectures

Control architectures for shop floor control have evolved through time from centralized master-slave solutions to fully distributed solutions. Figure 4 shows this evolution:

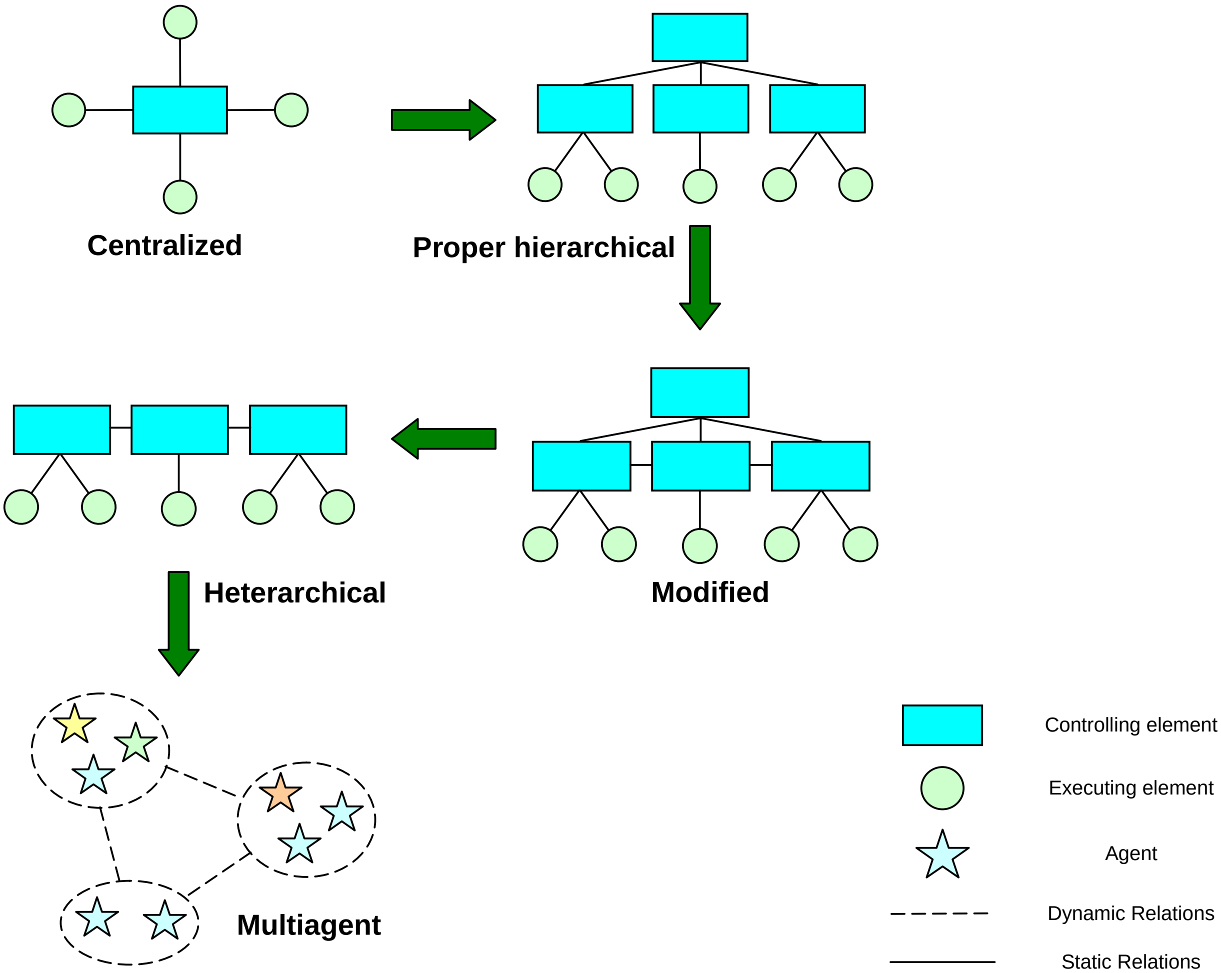

Figure 4. Evolution of Shop Floor Architectures (Barata 2003)

Centralised Control

The most basic type of control architecture is centralized control where a central node controls the entire system using master slave relations. The advantages and disadvantages are depicted in Table 1

Table 1. Advantages and disadvantages of the centralized approach (Barata, 2003)

Advantages	Disadvantages
• Simpler coordinating algorithms	• Difficult to modify – any modification implies big changes in the program • Difficult to extend – the introduction of a new element implies changes in the program • Complex control logic – a central control node with complex control logic for the entire system • Error Prone/ Lack Robustness – due to the dependence of the central node

Proper hierarchical

The control attributed to the central node is decentralized over several sub nodes.

Table 2. Advantages and disadvantages of the proper hierarchical approach (Barata, 2003)

Advantages	Disadvantages
• Reduces the functionality and complexity of each individual control • It is possible to integrate new nodes on existing layers • Works near optimal performance under stable conditions • Adaptive Behaviour. It is possible to obtain feedback from lower level control and use it to close the feedback loop	• Difficult to introduce new layers – structural rigidity. • Difficult to evolve due to its structural rigidity • Bad response to unstable situations • Poor fault tolerance

This control scheme has been implemented in the following architectures:

- AMRF – Automated Manufacturing Research Facility (Jones and McLean, 1986);
- PAC – Production Activity Control (Bauer, Bowden, Browne, Duggan and Lyons, 1991)
- FACE – Flexible Assembly Control Environment (Onori, 1996)

Modified hierarchical

The control attributed to the central node is decentralized over several sub nodes these nodes can communicate vertically or horizontally, the decision takes place it the node containing enough information do deal with it rather than a higher level node. This approach releases the overload from higher level nodes.

Table 3. Advantages and disadvantages of the modified hierarchical approach (Barata, 2003)

Advantages	Disadvantages
• Reduces information overload • Faster reaction to abnormal situations	• Increased node complexity • The same as proper hierarchical architecture

Implementations of the modified hierarchical model can be found in:

- NASREM – NASA/NBS Standard Reference Model for Telerobot Control System Architecture (Albus, Lumia, Fiala and Wavering, 1989).
- CCP's Manufacturing Cell Controller (Leitão and Quintas, 1997).

Heterarchical

In this approach all hierarchical design is abolished each node behaves like an autonomous cooperative entity and abstracts a resource or task of the shop floor. All the decision takes place at entity level and decisions that fall beyond each entity scope are subject of negotiation between the participating nodes.

Table 2. Advantages and disadvantages of the proper heterarchical approach (Barata 2003)

Advantages	Disadvantages
• Node autonomy reduces the overall system's complexity • Reacts faster to abnormal situations • Improved fault tolerance since the failure of a node does not have impact on the control strategy • Higher scalability since the addition or removal of a node is simpler and does not affect significantly the remaining nodes	• Difficult to reach optimized solution due to lack of global information • Chaotic behaviour can occur without central control • The system's performance depends on the negotiation rules • It is better implemented in applications that have an homogeneous set of resources

Current Industrial Control

Industrial control still uses nowadays hierarchical approaches. The typical scenario in a manufacturing plant is, upon a process change, the reprogramming of the totality or a considerable part of the controllers present in a certain station, cell, line, etc. This is an expensive and time consuming operation. Most of the current control is also tied to aged PLC limitations.

Nevertheless some industrial equipment manufacturers are incorporating processors in their devices and supporting software interaction among them in a shift towards intelligent equipment.

New control approaches should take the best advantage of the increasing processing power that is being built in the new devices.

New Shop Floor Control Approaches

Supporting Technologies

Recent approaches to shop floor control are close to the heterarchical model. Therefore they are based on the idea of independent autonomous nodes (abstracting resources, tasks, humans, etc) that interact with each other regarding the achievement of local goals from which emerges the global expected behaviour.

This high level approach to control requires sophisticated software platforms and devices that are able to implement the advanced control concepts and metaphors of the new approaches. Amid the existing architectures multi-agent and service oriented are promising ones to support new control architectures.

Although the existence of these platforms their connection to the hardware world is not straightforward and depending on the device's support for software can become a serious system integration task. Typical industrial applications run on programmable logic controllers (PLCs) that do not support high level programming languages and concepts. There is fortunately a growing effort for incorporating heavy processing capabilities in industrial devices. In fact, the industrial environment is slowly turning in direction to the exploitation of intelligent devices as PC-based control and Ethernet/TPC/IP gain incorporation in automation. To fight the industrialist's resistance to state of the art automation technology a new concept of device is emerging. The programmable automation controller (PAC) is a mix between a classical PLC and an industrial PC. This acronym is being used simultaneously by PLC vendors to designate their high end systems and by PC control companies in an effort to sell intelligent devices in a language fit for industrialists.

There is a wide range of manufacturers selling these technologies: Beckhoff, GE Fanuc Automation, OPTO 22, Bosch Rexroth, Siemens, etc.

These sorts of devices are leading hardware technologies to support enterprise agility at shop floor level if a sophisticated matching control approach is taken.

State of the Art Control Architectures

Most of the architectures hereby present are prototypes. Although they show promising results there are several barriers to their implementation in real scenarios:

- Base technology is resource consuming in terms of system memory and processing power.
- Even though decentralised and distributed architectures are the base for robust, agile and reconfigurable shop floors they do not present an optimal solution.
- Existing decentralised and distributed platforms are not designed for industrial use nor meet industrial requirements.
- Most industrialists do not foresee the need to implement such a technology.

HCBA

The Holonic Component-Based Architecture (HCBA) (Chim and McFarlane, 2000) uses a pool of separated unorganized holons representing resources. A special holon is waiting for manufacturing orders. Upon receiving the orders this holon updates its production plan and generates from time to time agents to warrant the accomplishment of the manufacturing orders.

An interesting aspect of this architecture is that rather on focusing only on shop floor control also implements diagnostic. The approach taken for diagnosis is based on the autonomy of the holons, by interchanging error messages they are able to take alternative measures to cope with system failures.

ADACOR

ADACOR architecture (Leitão and Restivo, 2002) focus on the set up and maintenance operations and is a distributed approach to manufacturing shop floor control. It uses the holon metaphor to represent manufacturing entities. The holons are implemented via agent based technology.

The basic entities/holons for this architecture are operational are the following:

- Product – contains data related to the product and is responsible for process planning.
- Task – represents a manufacturing order and is responsible for the execution of that order.
- Operational – represents the physical resources.
- Supervisor – coordinates operational and supervisor holons.

This architecture presents an innovative approach to control according to two different states: steady and transient states. In the steady state operational holons are coordinated by supervisor holons in a hierarchical federated scheme. The system is in the transient state when it needs to react to disturbances. Whenever this occurs the systems reorganizes it self temporarily increasing local autonomy and shifting to heterachical control. Once it has recovered from the error the system returns to the steady state.

CoBASA

The CoBASA (Barata, 2003) architecture is an agent-based approach to improve shop floor agility. While most of the architectures focus only on control, CoBASA also aims to ease shop floor re-configurability. Being based on coalitions of agents the control system becomes robust and reactive to changes in the environment typically these changes are the introduction of new devices or abnormal situations.

ABAS

The ABAS agent based architecture (Lastra, 2004) uses the metaphor of assembly actors to model assembly operations. Clustering assembly actors enables the realization of complex operations. Subjacent to this model is the idea of task accomplishment through interactions inside a society of agents.

Reactive multi-agent System for assembly cell control

In (Tang and Wong, 2005) a control system for an assembly cell based on reactive agents is presented. The advantage of using reactive agents is that they require less memory to implement and are reactive to changes in the manufacturing control environment. Concerning the architecture it is implemented a scheme were supervisor agents coordinate the activities of groups of agents.

iShopFloor

The iShopFloor framework is presented in (Shen, Lang and Wang, 2005). This is a multi-agent control approach that uses a XML based message system and aims at achieving a plug and play operation environment. While most of the systems are set to work on local area networks the iShopFloor is being developed to function over the internet, this represents an interesting feature towards enterprise system integration and agility.

SIRENA

The SIRENA project (SIRENA, 2006) developed a service oriented framework applicable to different domains such as: automation, automotive electronics, home automation and telecommunications systems. The advantages of the service oriented architecture (SOA) are discussed in (Jammes and Smit, 2005). The SOA architecture implements local intelligence on the devices using web services. It is worth mentioning that this project was awarded the ITEA Achievement Award 2006.

Decentralised Control

The architectures previously described are distributed / decentralised. There is a never ending ongoing discussion among experts regarding whether decentralized control is more efficient or less likely to fail that the typical centralized approach. In (Rusmevichientong and Van Roy, 2003) the problem of decentralized decision making is studied. The authors of the paper focused on the analysis of situations were coordination between agents is not possible and have established quantitatively the performance differences between decentralized decision schemes and centralized strategies. Although centralized strategies perform better there are situations where they are virtually impossible to apply, typically dynamic networked structures. The paper also suggests that stochastic decentralized strategies perform closer to centralized ones than decentralized deterministic strategies presenting also the advantage of being independent of the problem's dimension. This reinforces the idea that it is possible to benchmark the performance of decentralized strategies for very complex dynamic environments which is a key argument against the statement that decentralized systems present unpredictable behaviour.

The interest in decentralised approaches to control is growing as its advantages begin to be understood. Challenging areas such as the one of micro assembly are adopting this sort of control. The ongoing EUPASS project (EUPASS, 2006) targeting at the development of evolvable, cost effective ultra-precision manufacturing solutions that maximize equipment re-usability is a clear example of the previous statement.

Work re-Organization at Shop Floor Level

Normally new approaches to control tend to abstract humans as agents. In practical terms this means that there will be agents acting on behalf of shop floor workers. Since agents are pieces of software, a properly designed agent can ease workers tasks. Routine complex tasks can therefore run almost automatically being performed by agents commanded by under-specialized workers. In (Pitt, 2004) the advantages, pitfalls and legal issues of using agents acting on behalf of people are discussed in the information society context.

At shop floor level these technologies impact is:

- Improve workers mobility - since a software agent can autonomously page workers requiring assistance.
- Improve workers rotation – since no specialized technicians are needed, workers can periodically switch functions.
- Cut costs in specialized personnel – requiring their intervention only when necessary.
- Open the door for remote diagnosis and predictive maintenance – as processing power grows within devices and fault prediction schemes are implemented factory owners may decide to completely outsource real time complex monitoring and diagnosis.

Conclusions

As markets become increasingly demanding for customized and low cost goods, enterprises must seek for new organizational paradigms to keep competitive. In the last years information technologies have opened the door for the establishment of borderless profitable associations. The virtual enterprise concept seems a promising metaphor to business associations. Nevertheless in order to participate in such an organization enterprises must be agile. The agility problem can be addressed at different levels. Although the VE concept focuses on inter-enterprise agility it sets some requirements for shop floor agility.

A truly agile shop floor must be built upon state of the art control architecture. Unfortunately industrialists are resistant to change and unwelcome the concepts related to heterarchical approaches despite the fact that existing prototypes show interesting results. There is although a tendency for change as PC-based solutions for automation start to prove themselves both efficient and powerful.

New methods for shop floor control have a direct impact in work organisation at that level. As the component's autonomy grows, less skilled workers are required to operate them and the intervention of specialized technicians can be optimized.

The new technological developments allow modern enterprises to explore new business opportunities. Nevertheless they are simultaneously setting higher requirements in term of agility and competitiveness and customers are becoming more exigent. Minimizing nowadays the importance of the new control approaches can lead to severe competitiveness drawbacks in the future.

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