Towards The Next Level of Abstraction- The Autonomous Decentralized Systems-An overview

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Abstract: The last five decades have witnessed a tremendous growth in computer applications. This increase by any means can be approximated to an exponential growth. The human cognitive abilities on the other hand have not kept pace with the gigantic leap in computer applications. Such a mismatch has forced us to look for abstract models of systems to reduce the number of elements we have to consider simultaneously for system comprehension. This necessity created the need for subsystems that are autonomous in nature and perform a specified task independently irrespective of disturbances occurring in the system. The control and information subsystem design evolved over recent years in a manufacturing environment is a typical case in reference. Distributed computing has totally changed the computing paradigm in recent times resulting in rapid employment of these design trends in the manufacturing sector. An important variable in the equation determining the trend of manufacturing technologies is the consumer choice and preference which has become dynamic recently. To address these heterogeneous user demands, the Autonomous Decentralized System (ADS) concept was introduced two decades ago. The ADS has been a significant development incorporated in modern manufacturing systems and have been standardised as the de-facto standard for factory automation. These systems hold the promise for on-line system maintenance, timeliness and assurance, ensuring greater productivity and cost benefit emerging as the system of choice in automated manufacturing systems. This paper reviews the ADS from its inception, its application to a manufacturing system as a case example, assesses the state of the art and discusses the future trends.

Keywords: Autonomous decentralized systems, manufacturing systems, distributed computing.

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1. Introduction

The advances in the Information and Communication Technology (ICT) have altogether changed the socio-economic landscape of present times. The fast pace of technology has opened new avenues of experimentation and research into new paradigms catering for the heterogeneous and ever changing nature of information services.

As the new paradigms are implemented, researchers are faced with new challenges to optimise the management of two key ingredients of the modern information service system, i.e., the Information and control subsystems. With respect to manufacturing systems, these have kept pace with the advances in Large Scale Integration (LSI) and the ICT. Until recently, the two important components of a modern manufacturing system, i.e., the coordination and control subsystems were implemented centrally resulting in low flexibility and adaptability. Due to increased connectivity to the internet and the blooming of e-commerce, the user demand and trends have become highly unpredictable and heterogeneous in nature. As a result of these developments, manufacturing systems have incorporated drastic quality changes to replace changes in production volume. Mass production of items has gradually been replaced by the user demand-oriented items. In addition, the conventional and planned multiple and small lot production gave way to variable-types and variable-volume production. In such a situation it became mandatory to respond to user needs rather than providing the volume and types of products required. In order to respond to the changing customer trends and advances in ICT, manufacturing organizations are moving towards distributed and decentralized architectures [1]. These stringent demands therefore provided new impetus to the already on-going research effort to integrate the two essential computing subsystems of a manufacturing system, i.e., coordination (information) and control systems to address the new challenges faced by the manufacturing enterprise [2-6]). An effort was made initially to devise a new methodology for hierarchical control of the manufacturing systems [7-8]. Over the period of time, various new manufacturing paradigms emerged to optimize a manufacturing organization within the context of integrating the coordination and control functions like the bionic manufacturing system [9,10], the fractal factory architectural concept [11,12], the holonic manufacturing concept [13-15], the Net man frame work for decentralized manufacturing [16]. An entirely new class of manufacturing paradigms also emerged based on the agent technology. Multi-agent technology can be surveyed elsewhere [18-21].

These paradigms outline the foundations of the design of distributed manufacturing systems. However, the classification schemes used in these manufacturing paradigms for coordination and control functions tends to be too generic or may be too restrictive [22]. They proposed a new scheme to take into account the shortcomings of the existing schemes. In the context of intelligent agents, a multi-agent approach for part dynamic routing in flexible manufacturing systems has been reported recently [23]. However, the issues related to agent mobility within a network environment have not been addressed. In all these developments the problems posed by the distributed networked environment have not been taken into account.

The requirements for optimum functioning of a modern production system are trivial in nature. It should have the capability to continue its operation while new components are either added or removed from the main system in response to changing requirements for production. Also it should be possible to analyze and debug faults while the system is operational so that the system down-time is minimized.

Autonomous Decentralized System concept was introduced in Japan to address the design issues facing the manufacturing systems in the wake of advances in ICT [24]. The ADS architecture transformed the traditional client-server computing paradigm of the manufacturing systems to an efficient decentralized paradigm taking care of the on-line expansion, fault tolerance and on-line testing of these systems. The ADS has attracted a lot of research effort around the world since its proposal. The first symposium on ADS technologies was held in 1993, second in 1995, third in 1997 followed by the most recent in 2003. All these symposiums are referred to as ISADS followed by the year in which they were held. The ADS is an important area of research in the "Intelligent Manufacturing System" project of the Ministry of International Trade and Industry of Japan [25]. The ADS architecture was eventually approved as a de-facto standard for factory automation by international consortium of factory automation [26].

In this paper ADS technology will be reviewed with reference to its application in a manufacturing environment. Being an overview paper, it will encompass the current state of the technology and the possible directions it will take in the future. An effort has been made to make a mention of all the possible application domains of the ADS. The paper is organised as follows: The basic concept of ADS will be described in the next section. Section 3 will consider the mode of communications used by the ADS among various modules in the architecture. Section 4 will describe the general requirements of manufacturing systems. Section 5 will outline the layout of typical ADS. Section 6 will encompass the ADS application outside the manufacturing environment whereas section 7 will look at the current state of the art of this technology and its future prospects. The paper will be concluded in section 8.

2. The Autonomous Decentralized System Concept

The Autonomous Decentralized System (ADS) was proposed two decades ago in 1984. The concept was derived from an analogy to living organisms. Every living thing is composed of cells. Each cell is independent of other cells in the body and is totally self sufficient for the information for its living and multiplication.

None of these cells is involved in any master-slave relationship. The cells are therefore totally autonomous in their survival and function. Similarly the organisms in the living thing are performing their own function in unison with other organs in the body. The functions of the organs in the body can be characterised to be heterogeneous compared to the homogenous functions of cells. Any communication that takes place between cells and the organs does not violate their basic autonomy. In case an organ malfunctions, its function may be moved to other organs. Thus the living body carries out its function of living and growth through its cellular structure while ensuring assurance, agility, mobility and autonomy.

The ADS was proposed with two underlying assumptions with respect to the information system, i.e., the computing system will invariably have faulty parts and that it will undergo the transition of various stages of its operation including maintenance and future expansion.

In case of a homogeneous system, following are the important characteristics of the ADS:

1. Fault tolerance: The partial failure of the system does not hinder the system operation in any way. The normal designed operation of the system is possible to be carried out with the added advantage that the fault will not propagate to the rest of the system.

2. On-line expansion: The system operation is not affected in any way when additional subsystems are added or removed.

3. On-line maintenance and testing: Routine maintenance and testing operations are possible to be carried out on the system without with out stopping system operation.

n ADS has to satisfy the following properties if it is employed in a heterogeneous system:

1. System agility: The changing environment should be matched to the dynamics of the system flexibility

2. Mobility: The functional behaviour of the system should incorporate mobility whereby it may be able to migrate to other systems in response to changing conditions around the system.

3. Assurance: Under evolving conditions, the system should be able to collaborate with other systems in the event that it is unable to perform that function alone.

hese properties of the ADS are analogous to the cells and organs in a living body. The ADS has to satisfy ie characteristics of autonomous control and autonomous coordination with respect to its analogy to living rganisms. Coordination and control function is the key in the assurance of on-line property. The addition, eletion or failure of any subsystems in the main ADS does not jeopardize the operation of the main system. 'he subsystems can coordinate with each other to perform their functions being totally autonomous at the ame time. Each subsystem is also autonomous and does not engage in any master-slave relationship with ny other subsystem. Thus all the subsystems are equal in function. The management of each subsystem to arryout its function is local and any coordination with other subsystems is based on local information only. 'herefore the condition of locality is met. Moreover the structure of each subsystem is uniform and self ontained. This property makes the subsystem totally autonomous. It has then the autonomy to mange itself nd carries out the necessary coordination with other subsystems. Thus the condition of uniformity is met.

3. Mode of Communication

The deviation of ADS from conventional systems warrants a totally different approach for communication vithin the main system. The conventional communication methods cannot be used in ADS.

3.1. Communication in Homogeneous Systems

The ADS employs a unique method of communication referred to as content code communication. Two mportant components of this communication technique are the data field (DF) and the message. There is no central authority in the system. The subsystems are managed by their own processors called autonomous control processors (ACP). The subsystems communicate through a common data filed whereby the message is broadcast to the DF with the appropriate content code specifying its destination. The message is received by the intended subsystem through the DF and rejected by other subsystems. The content codes of the messages are pre-registered in the ACP of each subsystem. The comparative message passing scheme is shown in Fig.1 for both conventional and ADS messages.

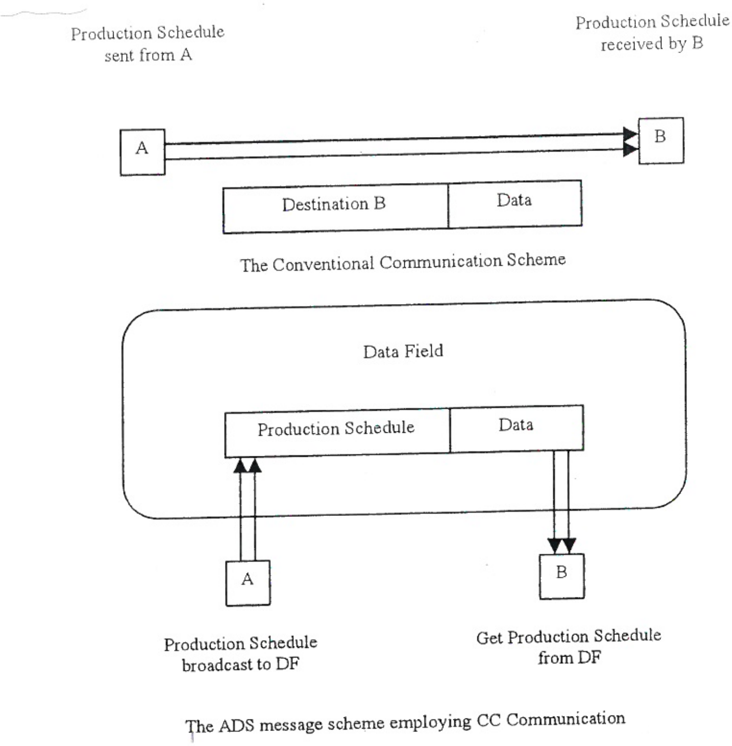

Figure 1: Comparison of Conventional and Content Code Communication Schemes.

The broadcast message is deleted by the originator after it is sent to the DF. The application software module installed in a subsystem starts the execution of its function only after all the required user data is received. Thus the subsystems in ADS are loosely coupled modules of a major system operating autonomously and executing their individual function. The DF architecture is depicted in Figure 2.

3.2 Communication in a Heterogeneous System

In case of a heterogeneous system employing ADS technology, various application systems are integrated together through gateways [27]. In such a scheme, every application system is connected to its own DF to retain its own characteristics. They retain their designed functions but cooperate with other subsystems. A heterogeneous system connecting its application modules through a gateway is shown in Fig. 3. Here, the data from various DFs belonging to various subsystems can exchange data through the gateway node. The gateway node only relays the required data to other DFs since the contents of data are known a priori to the gateway node. For example the details of sales in a sales department DF can be relayed to the production department DF on required basis.

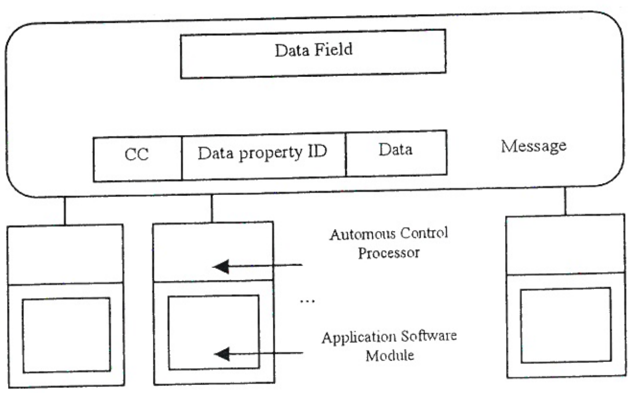

Figure 2: The Data Field Architecture.

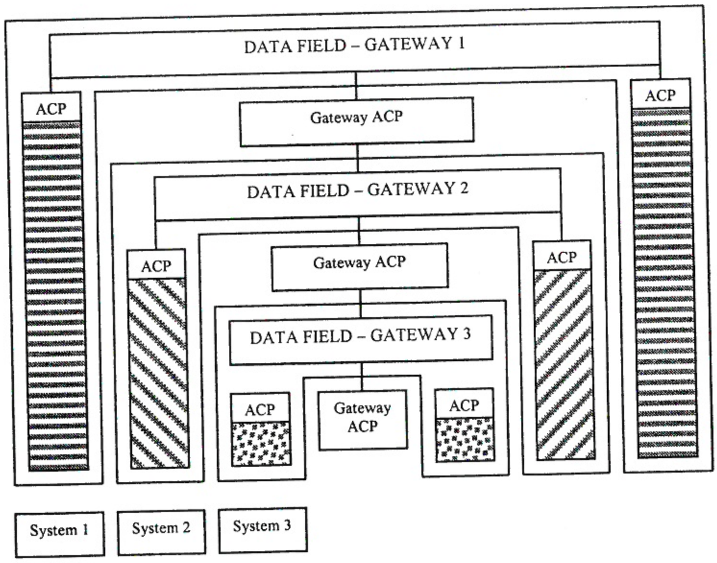

Figure 3: The gateway Mechanism Connecting Various Application Systems in a Heterogeneous System.

4. Manufacturing System Requirements

Conventional manufacturing systems have a hierarchical structure and therefore they lack the much needed flexibility. The very nature of such systems is complex and it makes any modification in the system an arduous task for the engineers. The hardware and software structures of these systems tend to be complex since the two important entities of the system, i.e., information and control subsystems are prone to generate more communication traffic as the manufacturing systems are getting more information- intensive. In case of any addition/deletion in the main system, the engineers have to comprehend the whole system function as it has tightly coupled parts. The function of one is dependent on the other. Thus the ADS provide on-line expansion facility to address this problem.

4.1.1 System Expansion/Modification

Companies invest heavily in the installation and commissioning of manufacturing systems. When a need arises to modify part of the system, the whole system has to be shut down resulting in the loss of valuable time. Therefore a system capable of on-line expansion and on-line maintenance/test would be highly desirable [28-29].

It is therefore imperative that the system modifications and additions are carried out on-line, during its operation. In addition, when any new part of the system is added to the main system, it becomes necessary to carry out its functional checks to ascertain as to whether the new subsystem can carry out its designed task. Thus on-line testing and on-line maintenance of these manufacturing systems should be possible.

4.1.2. Customer Demand-driven Manufacturing Enterprise

Businesses are required to monitor customer trends/demands and then quickly adjust the production process to meet these demands in today's competitive environment. Conventional manufacturing involves set patterns of mass produced items managed by a central computing facility. Both the information and control subsystems perform independently. The information system manages the production scheduling, pricing, sales and accounts while the control system regulates the control of machines. The production schedule is better comprehended by workers on the factory floor and they are in a better position to modify the schedule according to the state of machines serviceability coupled with information regarding customer's trend/demands. Thus the integration of information and control is fruitful to boost productivity.

4.1.3 Flexibility Function

A number of machines work in unison to manufacture a product. In order to regulate the working of these machines and the operators, appropriate scheduling needs to be carried out. Due to changes in demand and essential maintenance and repair to be carried out on these machines, the scheduling function needs to be flexible to cater for these requirements.

5. Application in Production Systems

A typical application of this concept applied to production systems has been in the newspaper production [30]. Such a system allows immediate changes in format and volume according to article contents, as well as coordinated production between locally distributed printing plants. The architecture allows flexible change of the production schedule while ensuring reliability. However in this section,

The ADS application in highly reliable steel manufacturing systems will be discussed in this section as a reference to highlight the technical concepts of this technology [31]. The requirements of steel production are in line with the provisions of the ADS. The successful implementation of ADS in steel production is due to two main reasons. In the first case a feedback control system is used to monitor the data from sensors and management modules of the plant. The actuators, monitors and sensors though incorporate artificial intelligence, these are still device dependent. Their functions can be capsulated which correspond to the ADS subsystems [31]. Secondly, these capsules are inter-connected via the data itself, not according to the process situation. The capsule data can be uniformly defined both for the input and output.

In the ADS, the subsystems initiate their work after getting complete data from the ADF. These capsules are thus ideally suited for ADS application. The interaction among three functional layers of a steel production unit is depicted in Fig. 4.

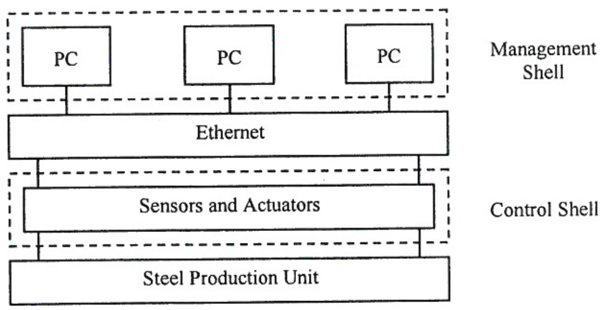

Figure 4: A symbolic Representation of a Steel Production Unit

The on-line maintenance and test provision in the aforementioned steel production plant boosted the productivity by 30% [31]. However, extensive manpower training is required to be carried out in a system employing the ADS technology. Also actuators and switching devices are tending to be incorporating artificial intelligence. This allows these devices to be capsulated and therefore could be connected in an ultra distributed system involving thousands of such devices [31].

The degree of freedom in motion control in production systems can be enlarged if the machines in the production line receive the electrical energy through wireless power transmission in addition to being controlled in a decentralised fashion by through wireless transmission of the control and feedback data. The practical problems for realization of wireless transmission of power and information needed for the proposed ADS were clarified by Junji et al [32]. They also presented the practical solutions to these problems.

A material handling system forms an important component of a autonomous decentralized manufacturing system. Particularly an automatically guided vehicle (AGV) plays a central role in the intelligent material handling system. A new method to overcome the problems of navigation and collision avoidance in such a system setting has been proposed recently [33]. They verified their AGV guidance approach based on Q-learning through experimental results.

6. Applications outside the Production Domain

The ADS have been applied to a number of applications that involve the management of information and control function in an adaptive information service system. The concept has been successfully applied in transportation traffic control and information systems. A typical example is the Tokyo Metropolitan Train affic Control System [34]. Train management data is broadcast in the data field where the current formation on all trains and stations is kept as data flow. Thus, any information under any circumstances is ailable to passengers in real-time at any time. Filtering technology has been developed in order to aintain separation and integration of the control and information subsystem concurrently. elecommunications-based information services are another beneficiary of ADS technology. A lecommunication system essentially can be divided into three main subsystems

Network service providers: These are responsible for the end-to-end connection of calling and called parties at the basic level of services by providing the underlying infrastructure and the associated technologies.

End users: The end users are the customers or corporations who utilise the information services for personal and business use.

Service Providers: The end user is serviced by these providers in return for payment for the usage.

he ADS technology can be applied to constructing telecommunication service platform that consists of end isers, network service providers and the service providers. The ADS conforms to the heterogeneous user lemands of information service under evolving conditions with utmost quality of service.

The applications of ADS envisage any independent subsystem that provides services across a well specified nterface. The subsystem can decide autonomously how the specified service is realized under the given circumstances. In a general may exhibit a large number of responses that cannot be well anticipated by the system designers in the design phase. To address this issue, the subsystems must have the ability to adapt to the changing environment autonomously in order to select the best response to a specific service request. The subsystem is therefore autonomous in the selection of most appropriate course to deal with the given situation.

A typical example would be the braking system of an automobile. The braking system receives the input to reduce the speed of the vehicle by a certain amount. The subsystem then decides the means to reduce the speed by employing the most appropriate method out of a number of choices, i.e. by reducing engine power, by the application of conventional brakes, by using secondary emergency brakes and so on. The driver thus specifies the effect of the function to the system and the system in turn selects the best course autonomously top achieve the goal.

7. The Current State of the Art and Future Trends

ADS have progressed to data intensive system applications since their inception. The major thrust of research effort has been to integrate the information and control functions in the conventional manufacturing systems [35]. The ADS in the integrated form realizes the goal of on-line development and maintenance [36]. There is a dire need to provide a software architecture that is capable of controlling correct synchronization, reconfiguration and reliability [37-39]. Functional reliability of manufacturing systems employing ADS is equally important. Autonomous successive construction technology without stopping system operation for a real time system has recently been reported [40]. The authors demonstrate that the optimal method for system construction is through small subsystems. The functional reliability and on-line functional availability have been characterized to be the best index for system assurance indication.

Recently the ADS has been given a new impetus by the unpredictable market forces as new endeavours are made in the field of information technology, i.e., LSI and optical fibre in addition to heterogeneous market requirements [41]. Thus the major advancement in ADS technology has been LAN-centric manufacturing. However, in the near future, the overall cost of ADS based manufacturing systems will be reduced by up to 80% of its IT component as both the computing resources and the underlying communication will be organized as an infrastructure community [41}. This community will be managed as autonomous community components thus relieving the human resource from managing the computing systems. Therefore autonomous community technology is one of the latest paradigms of ADS.

8. Conclusion.

The ADS aims to achieve the properties of on-line expansion, fault tolerance and on-line maintenance under partial system failures, system expansion and modification. The ADS concept is characterised by the integration of its subsystems to realise its intended goals. Since their inception, these technologies have been applied in the control and information fields with success and some of these technologies have been approved as the de-facto standards of Open Device Net Vendor Association (ODVA) and Object management Group (OMG).

The ADS concept has been reviewed in this paper through a specific example of a steel manufacturing system. Distributed systems that include many autonomous entities can benefit from the ADS technology. The ADS is an integrated set of subsystems that can be modified and tested on-line in addition to being fault tolerant. Telecommunication-based information service systems are envisaged to expand in the future giving rise to more intelligent networks. The network centric computing is already operational where conventional manufacturing trends have been identified to be giving way to dynamic volume production systems in response to user trends and demands. The future of ADS is seen to be associated with autonomous community concept where each component of the community will be autonomously handled. The ADS have been instrumental in boosting productivity and lowering costs in manufacturing systems and have been approved as the de-facto standard in factory automation.

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