15th Triennial World Congress, Barcelona, Spain

THE INTELLIGENT PRODUCT IN MANUFACTURING CONTROL AND MANAGEMENT

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Abstract: The authors are involved in a major, industrially-funded, research project which is connecting manufactured components and products to the internet. The Auto-ID project will enable unique information about a particular item to be stored, retrieved, communicated to others and even used in automated decision making relevant to that item. In this way we begin to build a specification for an *intelligent product* – one whose information content is permanently bound to its material content. This paper will begin to explore the impact of such developments on manufacturing shop floor control and management and will in particular, examine the way in which so called distributed, intelligent manufacturing control methods can be enhanced. *Copyright © 2002 IFAC*

Keywords: manufacturing control, automatic identification, distributed systems, holonic manufacturing, multi-agent systems

1. INTRODUCTION

The term *intelligent* has been applied to a wide variety of recent developments in manufacturing systems technology[1]. According to the Oxford English Dictionary (Thompson, 1996) an *intelligent device* or *machine* is one which is "able to vary its behaviour in response to varying situations and requirements and past experience". In this paper we closely follow this definition and examine what is required for typical objects in manufacturing operations – namely products and resources (i.e. machines, vehicles) – to be considered *intelligent*. We will particularly examine the requirements for the development of an *intelligent product* - a manufactured item which is equipped with an ability to monitor, assess and reason about its current or future state and if necessary influence its destiny.

The ramifications for such a capability in a manufacturing environment are significant, even in the near term, with benefits in terms of product tracking accuracy, reduced inventory levels and automated inventory management possible simply through the availability of real time product data. In the longer term, benefits from the ability to rapidly customise products and to develop self-organising production, distribution and inventory systems will lead to a paradigm shift in the manufacturing organisation of the future.

[1] By way of example, refer to the wide range of projects reported on the Intelligent Manufacturing Systems web site www.ims.org

A parallel but related development is the emergence of methodologies for designing distributed, intelligent manufacturing control – so called *multi-agent* control systems and *holonic manufacturing systems* are two such developments. A key feature of these approaches has been to replace conventional centralised decision making programmes with distributed but interacting decision making software modules (software agents) which correspond one for one with the physical products and resources in the manufacturing environment. Control strategies (e.g. routing selection, scheduling, planning) are resolved by negotiations between these distributed software entities acting on behalf of their physical counterparts. Such approaches permit increased adaptability of the control system in the face of disruptions or reorganisations and promise to provide a "deregulated" control system for supporting the rapidly customised products and self-organising production, distribution and inventory systems discussed earlier.

Clearly, for such systems it is vital that the location and state of the physical products and resources be available, and to date, an important shortcoming of these approaches has been the lack of a standardised means for linking the product software modules to their physical counterparts. In this paper we will propose that the development of so called automatic identification (*auto-id*) technologies combined with software agents can provide the means of constructing intelligent products and hence enabling truly distributed and intelligent manufacturing control and management systems. In Section 2 we will explain the basic concepts of automatic identification and introduce the Auto-ID project. In Section 3 we will briefly review manufacturing control and in particular distributed, intelligent control and then in Section 4 we consider the role an intelligent product can play in enhancing existing distributed, intelligent control systems.

2. THE AUTO-ID PROJECT

2.1 Overview

Auto-ID – short for Automatic Identification - in its simplest form involves merging information networks (bits) and material flows (atoms) together to form one seamless network that interacts with the real world in real time. (See Figure 1.) Specifically, physical objects will have embedded intelligence that will allow them to communicate with each other and with machines, businesses and consumers. Auto-ID represents a logical extension to the *bar code* and in particular offers benefits of unique item identification, non line-of-sight reading as well as a standardised network architecture which connects ID information to the internet.

The Auto-ID Center[2] based initially at MIT and now also at Cambridge has the mission of developing Standards, Infrastructure, Applications for the networking of physical objects with an initial focus on products in the retail supply chain. The Auto-ID Project currently involves a consortium of more than 30 companies - comprising both end users and vendors who also work actively on the developments at the two sites. Additional research centres in Asia and South America are planned for 2002.

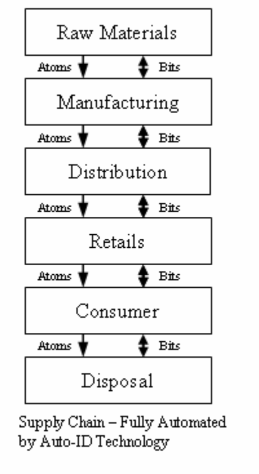

Figure 1 Material and Information Flows

2.2 Auto-ID Infrastructure

An Electronic Product Code (ePC) is embedded onto individual products and physical objects on memory chips known as "smart tags" that connect objects to the Internet. Auto-ID technology will allow the Internet to extend to everyday objects. Everything will be connected in a dynamic, automated supply chain that joins businesses and consumers together in a mutually beneficial relationship.

A 96-bit code of numbers called an Electronic Product Code (ePC) is embedded in a memory chip (smart tag) on individual products. Each smart tag is scanned by a wireless radio frequency "reader," which transmits the product's embedded identity code to the Internet, where the "real" information on the product is kept. That information is then communicated back from the relevant data repository to provide whatever information is needed about that product.

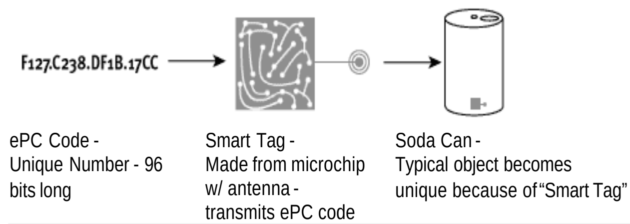

Figure 2 Unique Identifier for Soda Can

The ePC works together with a Product Markup Language (PML) and an Object Naming Service (ONS). PML is a new standard "language" for describing physical objects to the Internet in the same way that HyperText Markup Language (HTML) is the common language on which most Internet web sites are based. The ONS tells computer systems where to find information about any object that carries an ePC code, or smart tag. ONS is based in part on the Internet's existing Domain Name System (DNS), which routes information to appropriate web sites. The ONS will likely be many times larger than the DNS, serving as a lightening fast "post office" that locates data for every single one of trillions of objects carrying an ePC code.

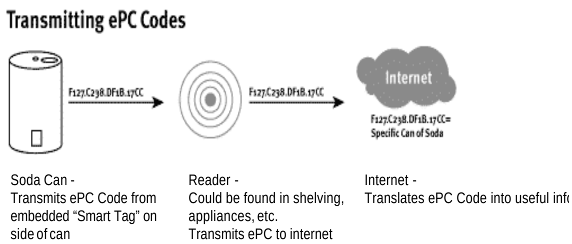

Figure 3 Network Connection for Tagged Product

2.3 Benefits from Auto-ID Technology

Auto-ID technology is forging a path for a new generation of real time global supply and demand. Auto-ID technology can identify more than 268 million manufacturers, each with more than one

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[2] refer to www.auto-id.org for more details on the Auto-ID Centre

million individual products, directly linking businesses to consumers in a dynamic and mutually beneficial supply and demand relationship. Less products will be wasted and manufacturers will be able to develop environmentally friendly products based on real time feedback from each element of the supply chain cycle. Auto-ID technology will change the world by merging bits and atoms together to form one seamless network that interacts with the real world in real time. Some of the specific benefits that can be expected in initial applications of Auto-ID technology within the retail supply chain are:

- Better replenishment
- Counterfeit protection
- Identification of diversion
- Easier logistics for custom products
- Inventory management
- Theft prediction
- Faster checkouts
- Recycling

Clearly many of these benefits will be achieved through integrating Auto-ID systems with other developments and we address this for the case of manufacturing control in the next two sections.

3. DISTRIBUTED, INTELLIGENT MANUFACTURING CONTOL SYSTEMS

In this section we briefly introduce some key concepts in distributed, intelligent manufacturing control. We begin by over viewing a conventional view on manufacturing control

3.1 Conventional Manufacturing Control

Conventional manufacturing control is typically hierarchical in nature (see Figure 4), where customer orders are integrated into a single factory planning process from which detailed schedules are developed. These in turn are passed on to the shop floor where the schedules are executed (shop floor control) on pre assigned resources. Bills of materials generated in planning are used to prepare the appropriate sets of raw materials / sub components required for the manufacturing process. This orderly process is very efficient under relatively steady operating conditions, but – as has been reported by numerous authors (see for example Zweben and Fox (1994), Baker (1998), Bongaerts et al (2000), McFarlane and Bussmann (2000)) – a centrally managed, hierarchical control strategy is unresponsive in the face of disturbances such as rush orders, breakdowns, supply stockouts, line reconfigurations. It is for this reason that a number of researchers have pursued more distributed solutions in which decisions about planning,

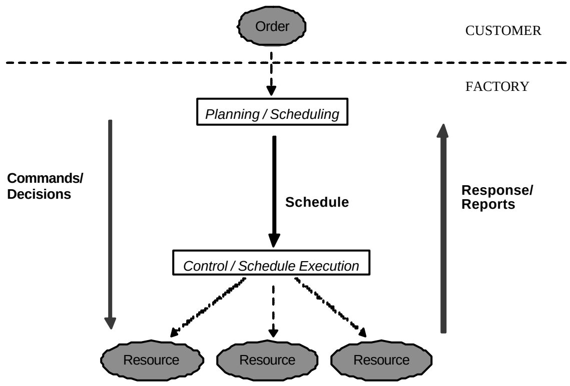

Figure 4 Conventional (hierarchical) Manufacturing Control

scheduling are made closer to the execution of production and control of the flow of materials. We discuss two approaches using these concepts next.

3.2 Agent Based Manufacturing Control

As discussed earlier, a *software agent* is an interactive decision making software module, which is more formally defined as:

A distinct software process, which can reason independently, and can react to change induced upon it by other agents and its environment, and is able to cooperate with other agents.

The reader is referred to O'Hare and Jennings (1996), Ferber, (2000) for introductory material on software agents. Agents have been applied in the manufacturing control domain for over ten years (see the references in Zweben and Fox, 1994, Prosser et al, 1996), and an important class of these applications are those in which software agents correspond on a one-to-one basis with *each* machine and product (representing all or part of customer orders) in the manufacturing environment. Using the appropriate distributed control algorithms, the individual machine and product agents can make *their own* manufacturing control *decisions* relating to scheduling, resource allocation, prioritisation etc using an automated form of "negotiation". The key benefit of such an approach is that if production is disrupted or reorganised in some way, the same negotiation process still takes place, albeit with different machines or products making the decisions, and hence the system is relatively robust to change. Such algorithms have been described in Baker (1998), Bussmann (1998), Peeters et al (2000), McFarlane et al (2001), Zhang and Norrie (1999), Valckenaers et al (2000), and their operation is illustrated conceptually in Figure 5. Algorithms implemented in multi agent software environments have been developed for planning, scheduling and shop floor control applications.

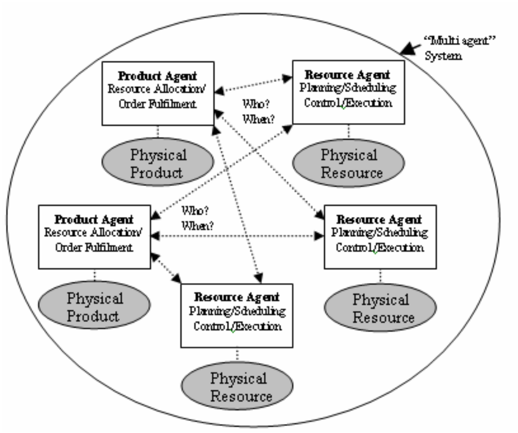

Figure 5 Multi Agent Manufacturing Control System

3.3 Holonic Manufacturing Systems

The field of holonic manufacturing systems has developed over the last ten years as an approach for designing and operating autonomous, flexible, interchangable manufacturing modules referred to as *holons*. (Refer to Suda 1989, Christensen, 1994, Van Brussel, 1994 for background details.) It is a systems engineering methodology rather than a solution to a specific control problem, and is referred to as a *bottom up* approach because overall plant control is developed through the integration of these flexible, interchangable manufacturing modules. This is in direct contrast with conventional *top-down* methodologies for designing and specifying manufacturing control systems (e.g. Computer Integrated Manufacturing or CIM) in which a computer control systems hierarchy is centrally devised to support the planning, scheduling and shop floor control processes illustrated in Figure 4. *The discriminating value of holonic manufacturing is that it represents the only methodology for control system design which manages short and long term changes in the manufacturing environment as "business as usual".*

We emphasise here that holonic manufacturing is not an *alternative* nor an *identical* approach to multi agent control but rather it is *complementary* in that it represents a systems engineering approach to the development of manufacturing control systems infrastructure, rather than a solution mechanism for solving individual manufacturing control problems. In fact, most developments of holonic systems to date have deployed multi agent like solvers as a means of resolving planning, scheduling and shop floor control issues.

However, while multi agent systems represent purely software environments, a holonic system encapsulates both the physical and information based aspects of the manufacturing environment. Hence a *resource holon* for machining, might contain a machine tool, sensing and actuation, a local controller, a network connection and one or more coordinating software agents located either locally or on the network. (See Figure 6.)

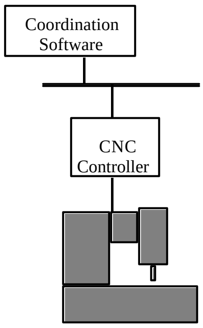

Figure 6 Machining Resource Holon

Of critical importance here is the control network which connects the physical machining operation to the software that coordinates it, because the algorithms used for developing real time control actions rely on up-to-date information about the state of the machine. However, in the case of a *product holon*, it is far more difficult to achieve and maintain a network connection between a physical component or product and the software agent and developments to date have relied on indirect tracking data provided by local detection sensors in the production environment. These can be ambiguous or erronious.

Returning to the soda can example, we summarise – over simplistically - the current state of holonic manufacturing in Figure 7 in which two production lines (i.e. resource holons) are directly connected to a network (and hence their corresponding agent software) but individual product holons are *decoupled* from their corresponding software environments.

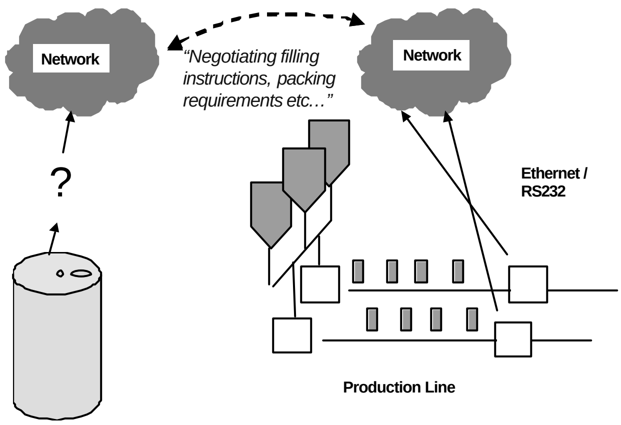

Figure 7 Incomplete Communication Between Product and Resource Holon

It is here that we now introduce the Auto-ID developments into the context of distributed, intelligent manufacturing control.

4. INTELLIGENT PRODUCTS IN MANUFACTURING OPERATIONS

In this section we will use the terms *product holon* and *intelligent product* interchangably, and introduce the role of an intelligent product in a manufacturing control environment.

4.1 Definition

We first formalise the concept of an intelligent product with the following working definition:

An <u>*intelligent product*</u> *is a physical and information based representation of an item for retail which:*
(1) possesses a unique identification
(2) is capable of communicating effectively with its environment
(3) can retain or store data about itself
(4) deploys a language to display its features, production requirements etc...
(5) is capable of participating in or making decisions relevant to its own destiny

In the case of the soda can, the corresponding intelligent product is illustrated in Figure 8 in which the soda can is connected to a network and thus to both information stored about it and also to a software agent acting on its behalf. Clearly the intelligent product is an extension of the product identification provided by the Auto-ID system outlined in Section 3.

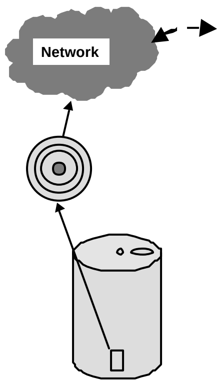

Figure 8 "Intelligent Soda Can"!

4.2 Intelligent Product Driven Manufacturing Control

In addition to the potential for ready adaptation to disturbances, an attractive feature of the holonic approach to operating a manufacturing plant is that – potentially – a customer's order specification – embodied within one or more product holons – can be enabled to directly influence the speed, cost and quality of production of that order[3]. However, although the holonic software environments already developed for this, the successful execution of the customer order is only as good as the accuracy of information about availability, location, state of raw materials or wip. The authors believe that, with the improved materials tracking capability provided by the Auto-ID environment, the full implementation of customer driven manufacturing control can be enabled

[3] Conversely, the benefit to the manufacture is that the resources in the factory are essentially open to market forces, so that a rush job would incur clear penalty costs for a customer.

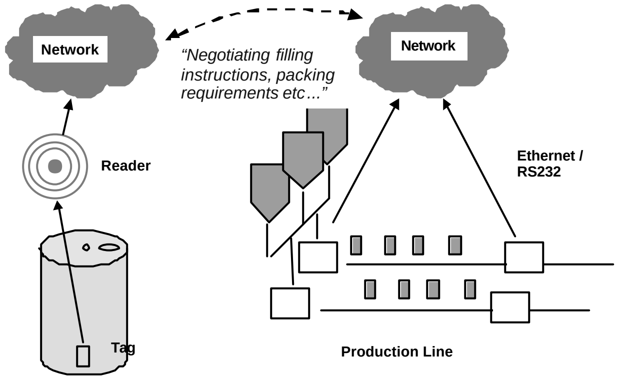

Figure 9 Intelligent Product Driven Manufacturing Control

4.3 Example - Intelligent Product Driven Manufacturing Control

To illustrate the way in which an Auto-ID based intelligent product might operate in a holonic production environment, an holonic assembly cell system (see Chirn and McFarlane, 1999, 2000) has been adapted to reflect how Auto-ID capabilities might be integrated. We will simply describe this system which will be demonstrated during the presentation of the paper.

The job of the robot assembly cell illustrated in Figure 10 is to complete the assembly of a simple electrical meter box. A robot arm with vacuum suckers is employed to pick and place parts among buffers. A rotary table equipped with two jigs is made to turn through 180 degrees for swapping the position of each jig. A cartesian robot which has an automatic screwdriver attached is designed to assemble together two separate parts in the jig. A flipper unit with two rotating clamps is utilised to hold a part and then flip it upside-down.

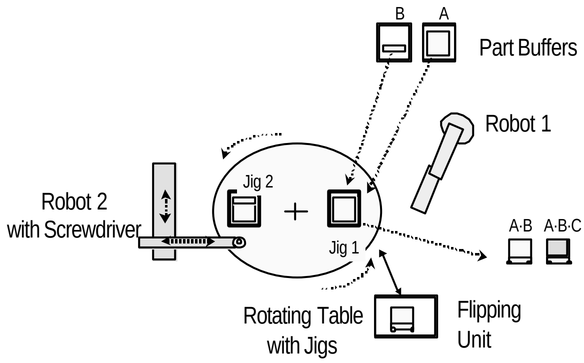

Figure 10 Layout of Simple Assembly Operation

Three kinds of components, annotated as Parts A, B, and C, are used to assemble the two kinds of products. One is denoted as *Product AB,* which is assembled from Parts A and B. Part A is the main housing of the meter box. Part B is a small access cover. Product AB is assembled by putting part B on top of part A and screwing B into A with a single screw. The other product, referred to as *Product ABC,* is assembled by attaching a transparent plate to product AB using a further four screws. The four screws attaching the transparent plate are fed in from the opposite side of the box to the single screw attaching the access cover. For this reason, it is necessary to flip Product AB during assembly using the flipper unit. Hence the two products require a different resource set to perform their respective assembly needs.

In the existing holonic control environment (implemented using largely conventional computer control hardware) the system has been show to be more readily reconfigurable than a conventional control system and capable of automatically dealing with frequently changing orders (Chirn, 2001). We emphasise that there is no predetermined schedule or control for this holonic cell.

In the Auto-ID enhanced environment the customer order generates product specification/recipe software (as in the original holonic case), but in addition, tagged components required for the assembly are scanned and automatically synchronise with product software which updates during production. Hence the components effectively *belong* to the customer from this point on. Next, the product holon drives its own manufacturing sequence via negotiation with production resources (as in the original holonic case also) but because of the Auto-ID system in place it is possible to track the product (and its sub components) through the different stages of assembly which makes reorganisation of production simple both in terms of the information & control systems and also the physical operations. In trials, the system has been shown to readily handle the following scenarios:

(1) *multiple simultaneous orders* – orders for two customers were produce simultaneously with near identical parts without any ambiguity in component identification or assignment

(2) *quality error* – a semi completed product was erroneously placed on the incoming components conveyor. The Auto-ID system detects from the order history that the product is part complete and rejects it from production

(3) *real time customisation* – a late order interrupt is received requesting a customisation to the AB product (adding Part C). The order profile is updated and the product holon negotiates additional resources to complete the revised assembly.

These simple descriptions illustrate the potential benefits of combining Auto-ID technology with advanced manufacturing control systems.

4.4 Towards Intelligent Products in the Manufacturing Supply Chain

Many of the features described in Sections 4.1 and 4.2 have ready analogs in inventory management and supply chain logistics. The role of the intelligent product in these situations is currently under investigation.

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