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THE INTELLIGENT PRODUCT IN MANUFACTURING CONTROL

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Abstract: The authors are involved in an industrially-funded research project which is establishing connections between manufactured components or products and the internet using automated identification - *or Auto ID* - technologies. This will enable accurate, timely information about a specific item to be stored, retrieved, communicated and even used in automated decision making or control functions 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, and which can influence decisions made concerning its destiny. This paper specifically explores the impact of such developments on manufacturing shop floor control and management and in particular examines the way in which distributed, intelligent manufacturing control methods can be enhanced by the availability of accurate, timely, item-level information.

Keywords: manufacturing control, intelligent manufacturing systems, 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. 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.

A parallel but related development has been 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 both 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. Conclusions are briefly given in Section 5.

2. AUTO ID TECHNOLOGIES

2.1 Overview

Automatic Identification (Auto ID) in its most abstract 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 both unique item identification and non line-of-sight reading as well as a standardised network architecture which connects product ID information to the internet.

The Auto ID Center with laboratories currently at Massachusetts Institute of Technology (MIT) in the USA, University of Cambridge in Europe and University of Adelaide in Australia 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 Center currently involves a consortium of more than 50 companies - comprising both end users and vendors who also work actively on the research developments at the different laboratories. Additional laboratories in Asia and South America are planned for 2002 and 2003.

In the next section we briefly overview the systems produced by the Auto ID Centre to date.

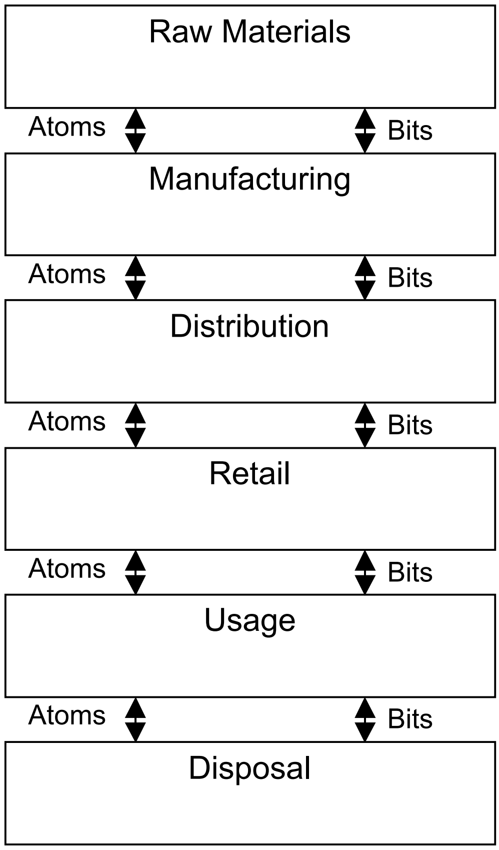

Figure 1 Material and Information Flows

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.

Referring to Figure 2 and Figure 3, 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. An obvious extension of this model is for more of the information regarding the product to be stored directly onto the tag itself (see Bajic and Chaxel, 2002 for an example). The system in Figures 2 and 3 is simply the minimal tag memory model which is likely to be deployed with very low cost products such as simple retail items.

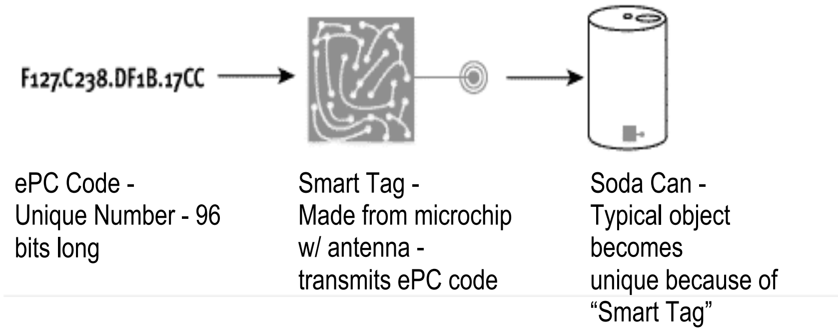

Figure 2 Unique Identifier for Soda Can

The ePC works together with a Product Markup Language (PML) to provide a rich and dynamic data repository for a product. PML is a proposed standard "language" for describing physical objects to the Internet based closely on developments in extensible mark-up language (XML). An Object Naming Service (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.

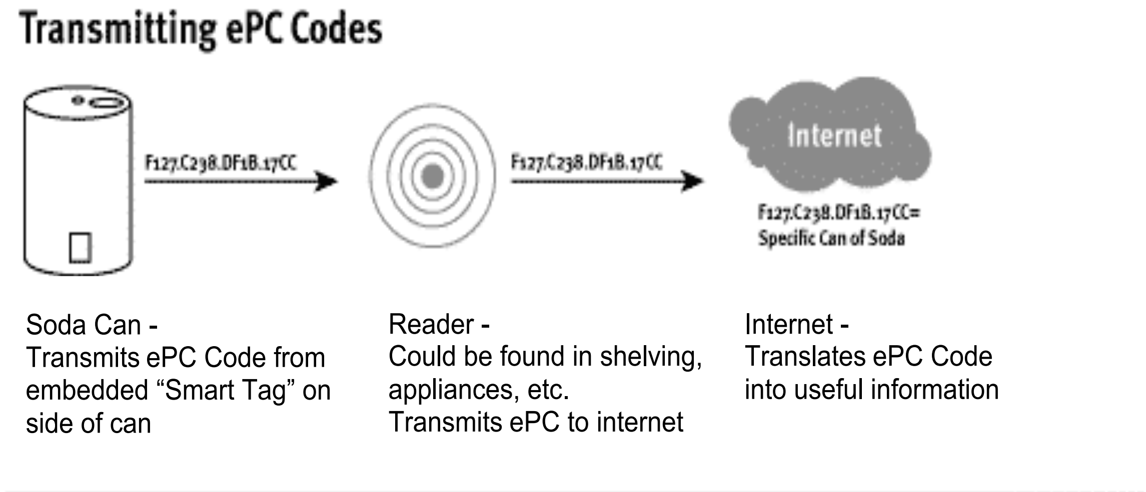

Figure 3 Network Connection for Tagged Product

When deployed within a feedback control system, the introduction of Auto ID data provides the possibility of product data – identity, instructions, state - to be used in conjunction with typical operational data – temperature, position, velocity, equipment status. This is illustrated in Figure 4 and the general role of Auto ID in feedback control systems is discussed at length in McFarlane (2002).

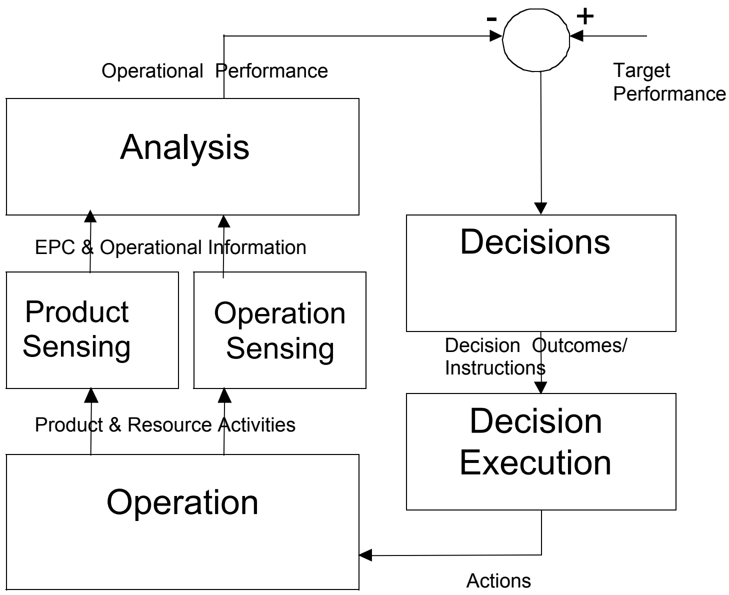

Figure 4 Typical Feedback Control System with Product Information

2.3 Benefits from Auto ID Technology

Auto ID technology provides a means to support real time global supply and demand. Auto ID technology can uniquely identify more than 268 million manufacturers, each with more than one 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 merge physical and information flows into 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 in the short term are:

- Greater inventory and product tracking accuracy
- Better replenishment
- Counterfeit protection
- Identification of diversion
- Theft detection
- Faster retail checkout systems

In the longer term, as more sophisticated software is developed to exploit Auto ID based data, the following further benefits are anticipated.

- Easier production control and logistics management for customised products
- More responsive supply chain operations
- Efficient inventory management

- Intelligent theft prediction
- Intelligent and remote maintenance and service provision
- Simplified Product Lifecycle management including reuse, rework and recycling of goods

(We note that many of these benefits will be achieved through integrating Auto ID systems with other developments)

Next we consider the role of manufacturing control systems and in particular we introduce another recent development relevant to the future deployment of Auto ID systems – that of *distributed, intelligent manufacturing control system*.

3. CONVENTIONAL AND DISTRIBUTED, INTELLIGENT MANUFACTURING CONTOL SYSTEMS

We begin this section by overviewing the conventional approach to manufacturing control – focussing on the nature of decision making and the information required to make the decisions. We introduce key concepts in distributed, intelligent manufacturing control.

3.1 Conventional Manufacturing Control

Conventional manufacturing control is typically hierarchical in nature (see Figure 5 for a simplified view of the decision making processes involved), where customer orders are integrated into a single factory planning process from which detailed schedules are developed. The diagram can be viewed as a series of four cascaded control loops each driven by a higher level decision, each providing actuation/instructions to a lower level operation (on the right hand side) and each providing a sensing function (on the left hand side) collecting status reports on the progress of the operation. We emphasise that in general, the sensing function is system oriented, and little direct information regarding the products is collected. Bills of materials generated in planning are used to prepare the appropriate sets of raw materials / sub components required for the manufacturing process. Raw material and resource schedules are in turn are passed on to the shop floor where the schedules are executed (shop floor control) on preassigned resources according to preassigned timings. Task execution is typically carried out by distribution of automated instructions to computer controlled machines and materials handling systems whose actions are driven by devices and actuators. We note that off the four nested feedback control loops in Figure 5 only the lowest refers to a *continuous or discrete time* control system – the remainder are very much *event* driven processes. As will be discussed in Section 4, it is in discrete event situations that the impact of Auto ID information has greatest effect.

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. In simple terms, the decoupling of the scheduling and planning functions from the (dynamically changing) state of physical shop floor operations means that there is often little or no correspondence between planned and actual production. It is for this reason that a number of researchers have pursued more distributed solutions in which decisions about planning and scheduling are more closely aligned to the execution of production and control of the flow of materials.

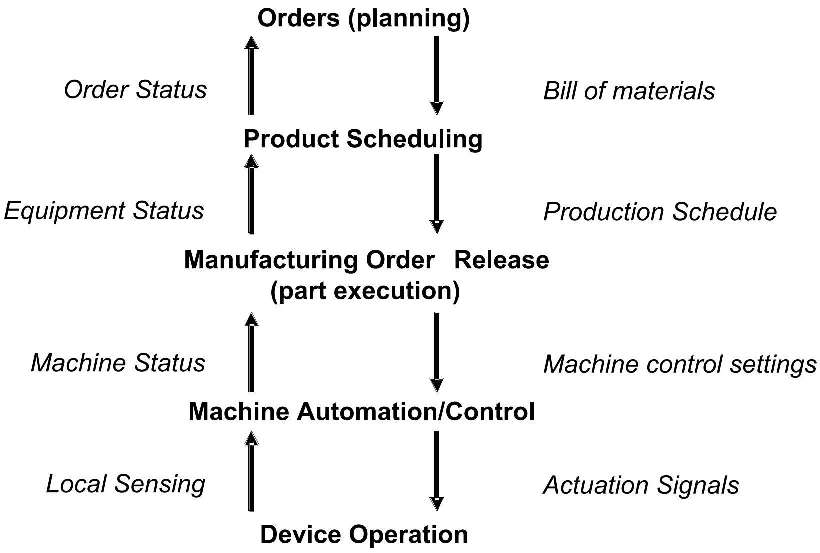

Figure 5 Conventional (hierarchical) Manufacturing Control

Although there have been numerous efforts in addressing this decoupling problem, we focus here particularly on the distributed, intelligent manufacturing control approach, which is introduced next.

3.2 Developments in Distributed, Intelligent Manufacturing Control

Distributed, intelligent manufacturing control systems in the context of this paper refer to the class of manufacturing control systems in which

1. Control system decisions (e.g. for planning, scheduling, routing, task execution etc) are determined by more than one decision making element
2. The decision making elements – typically so called software agents interact collaboratively and flexibly to arrive at a decision
3. No one decision making element has access to all of the information required to make an effective decision
4. Decision making elements are typically linked to physical elements in the manufacturing domain – namely machines, products, parts and customer orders

In this category we will refer specifically to two closely related developments in distributed, intelligent control in a manufacturing context, namely, multi-agent based manufacturing control and holonic manufacturing control. Both of these use a common core component – a software agent. A *software agent,* in the context of a manufacturing control system, is an interactive decision making software element, 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.

For introductory material on software agents, the reader is referred – for example - to O'Hare and Jennings (1996), Ferber, (2000). In the context of distributed, intelligent control the software agent is used as a distributed software programme, which utilises interactive communication protocols to determine and reserve appropriate tasks for execution.

3.2.1 Multi Agent Based Manufacturing Control

Agents have been applied as a means of developing distributed decision making solutions 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 (1999), McFarlane et al (2002), Zhang and Norrie (1999), Valckenaers et al (1995), and their operation is illustrated conceptually in Figure 6. Algorithms implemented in multi agent software environments have been developed for planning, scheduling and shop floor control applications.

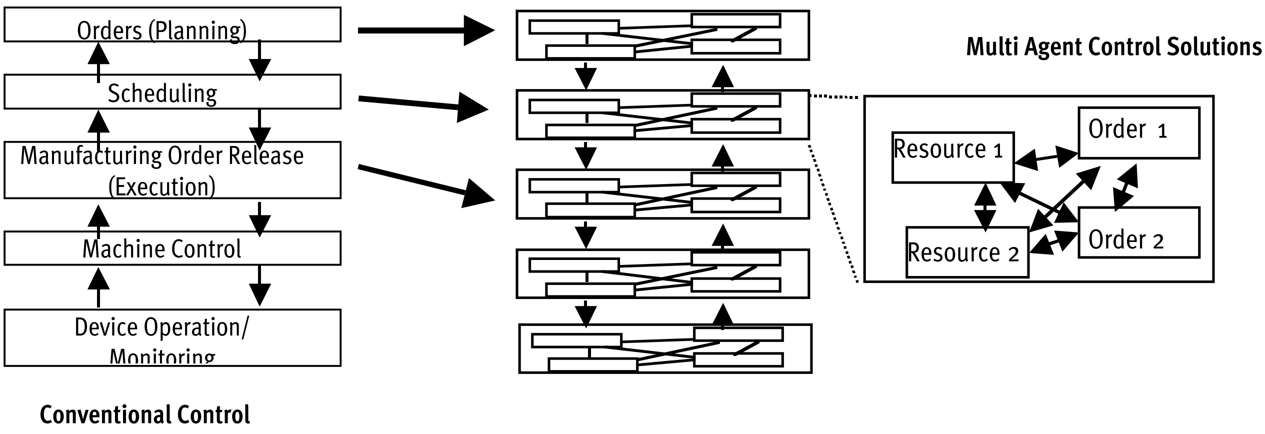

Figure 6 Conventional vs Multi Agent Based Manufacturing Control System

3.2.2 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, 1998 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 5. 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. Most developments of holonic systems to date have deployed agent-like solvers as a means of resolving planning, scheduling and shop floor control issues.

However, while multi agent based control 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, for example, 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 7.)

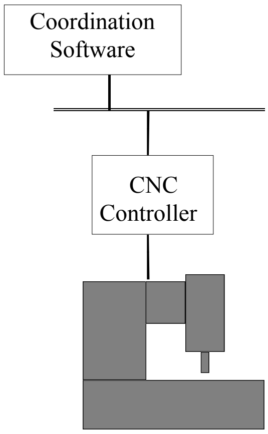

Figure 7 Machining Resource Holon

The integration of the physical resource or product to the different control processes in a holonic environment is illustrated in Figure 8

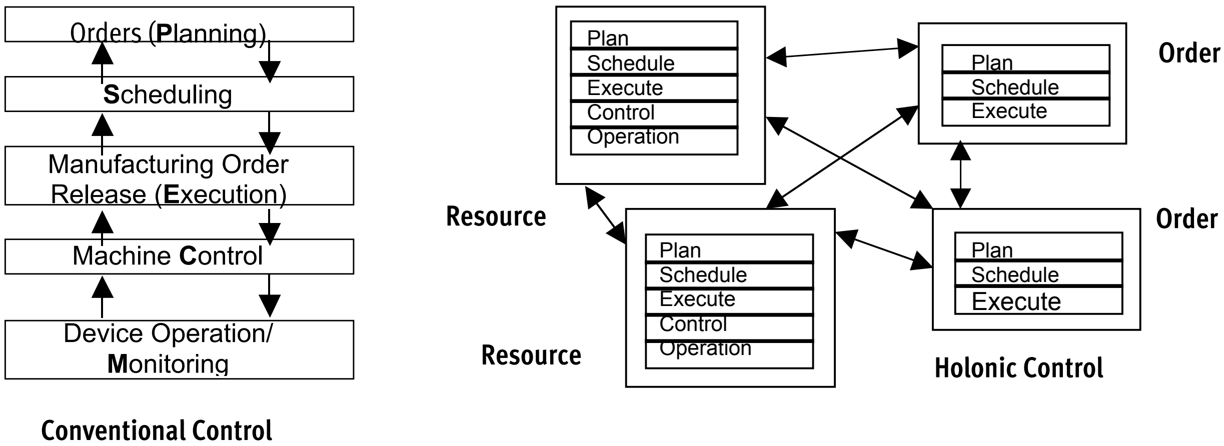

Figure 8   Conventional vs Holonic Manufacturing Control System

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 sometimes be ambiguous or erronious.

Returning to the soda can example, we summarise – over simplistically - the current state of holonic manufacturing in Figure 9 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.

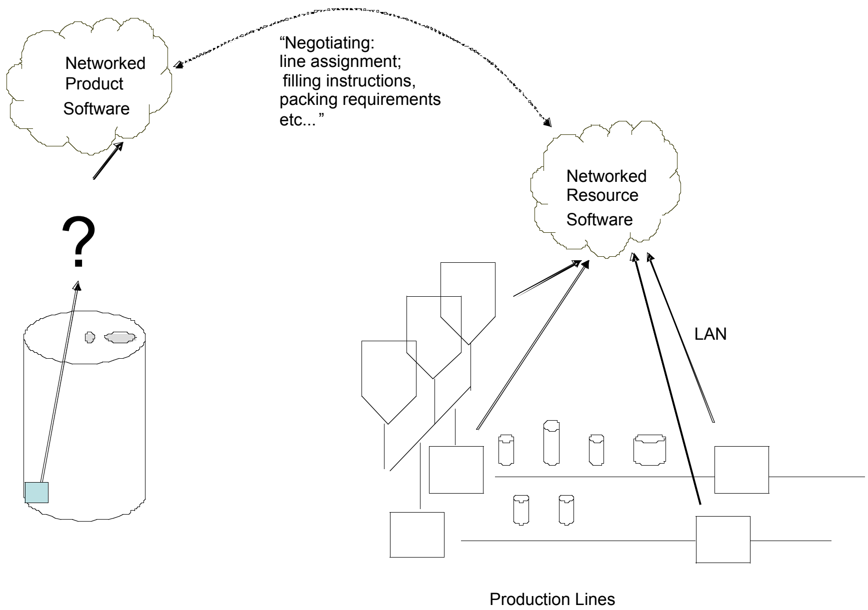

Figure 9 Incomplete Communication Between Product and Resource Holon

It is to address this decoupling that we now introduce the Auto ID developments into the context of manufacturing control and management and particularly with regard to distributed, intelligent manufacturing control.

4. AUTO ID IN MANUFACTURING CONTROL AND MANAGEMENT

The main aim of this section is to motivate the application of Auto ID technologies in manufacturing control and, in particular, motivate the intelligent product concept in this context. We will begin, however, by demonstrating that there are in fact significant advantages to be gained by deploying Auto ID data in a relatively conventional manufacturing control environment

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4.1 Auto ID Enhanced Manufacturing Control and Management

The approach to deploying Auto ID data in a relatively conventional manufacturing control environment is conceptually simple in that it predominantly involves the integration of Auto ID data with existing commercial information and control systems. It is likely that early inclusions of Auto ID data into manufacturing control and management systems will follow this approach.

Unique, item-level data in individual or aggregate form provides an automated means of determining product presence and movement. Auto ID data is therefore a supplement to existing sensed information provided directly from the operations. By way of illustration we next discuss the way in which Auto ID data can enhance manufacturing control operations.

Figure 10 illustrates the conventional hierarchy for decision making in a manufacturing control system as in Figure 5, but for which the sensing has been enhanced by the availability of product identity (Auto ID) data.

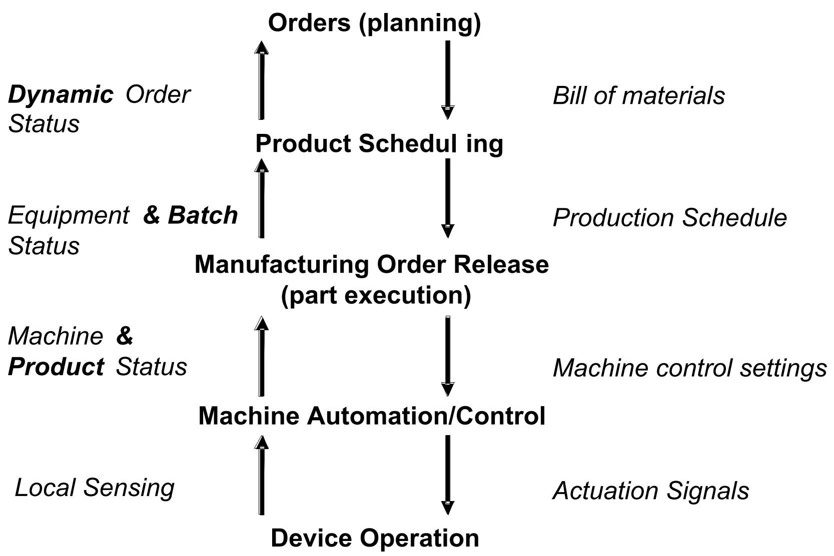

Figure 10 Conventional Manufacturing Control Hierarchy

We make the following observations about the impact of Auto ID data on each of these interacting loops:

- Conventionally, in the planning and scheduling loops, the sensing or status monitoring is primarily intended as a means of approximately determining the status of a particular batch of products and a customer order respectively. *Order status* information is typically collected intermittently by manual or indirect means, and this sensing operation might be entirely replaced by the collection and analysis of *Auto ID data from completed products.*
- *Equipment status* is only at best an indirect indicator of whether operations – and hence customer orders - are keeping to schedule or not, and such monitoring would be greatly improved by the availability of *product status information* which would unambiguously indicate successful completion of batches. The introduction of timely, accurate and unique item-level information into these loops would greatly enhance the effectiveness of the current planning and scheduling functions.

- Auto ID information on products and their constituent components would significantly impact on the order release stage, for example, reducing unexpected delays due to unavailable parts and minimising the risk of incorrect order processing.
- *Device control* loops – conventionally continuous or discrete time control systems – are less effect by the inclusion of Auto ID information because they represent actions taken by individual machines carrying out their prespecified instructions. By and large these actions are instigated simply on command from the machine controller and do not directly benefit from information about product status. The setpoints for these loops may indeed change dependent on the current product mix, but this is an issue for the execution loop.

The timely and accurate availability of product identity and specification information helps to reduce delays and to reduce the risk of errors occurring in raw materials stock holding, production operations and finished goods management.

We next consider the combination of Auto ID technology with distributed, intelligent control concepts.

4.2 The Intelligent Product Driven Manufacturing Control and Management

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. Here we require a new approach to information management and decision making in conjunction with the introduction of Auto ID data.

4.2.1 The Intelligent Product in Manufacturing Control

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 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 11 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.

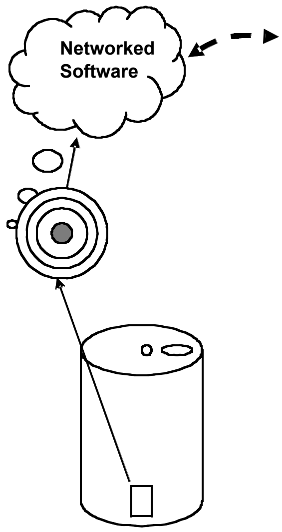

Figure 11 "Intelligent Soda Can"!

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[1]. 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 (refer to Figure 11).

[1] 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.

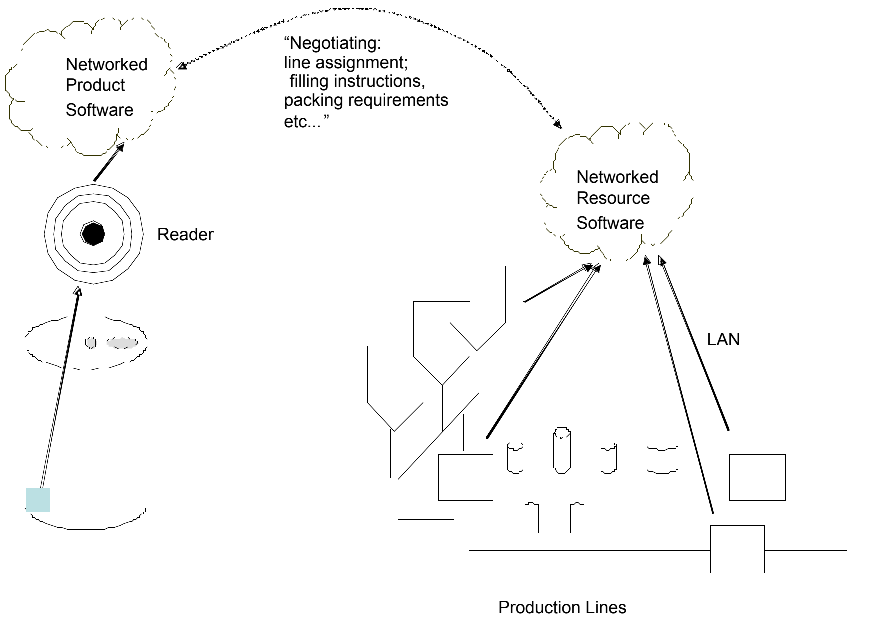

Figure 12 Intelligent Product Driven Manufacturing Control

5. EXAMPLE – AUTO ID ENHANCED ASSEMBLY CELL CONTROL

To illustrate the way in which an Auto ID based control systems might operate in a production environment, an assembly cell system illustrated in (see Chirn and McFarlane, 2000, 2001) has been adapted to reflect how Auto ID capabilities might be integrated. Both conventional and holonic control strategies are considered here.

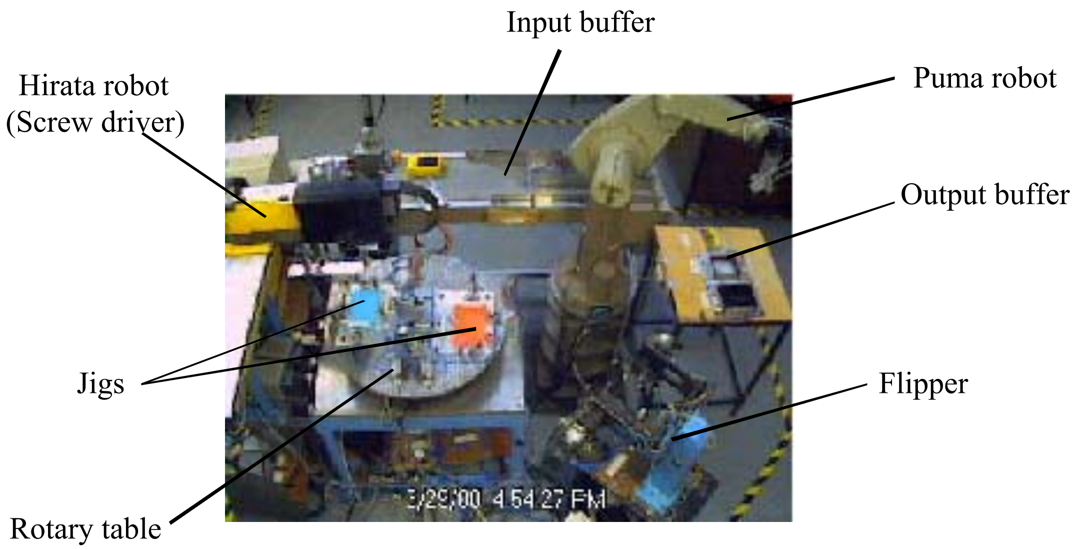

Figure 13 Robotic Assembly Cell

5.1 Assembly Cell Description

The task of the robot assembly is to complete the assembly of a simple electrical meter box. A layout of the cell operations is provided in Figure 14. 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.

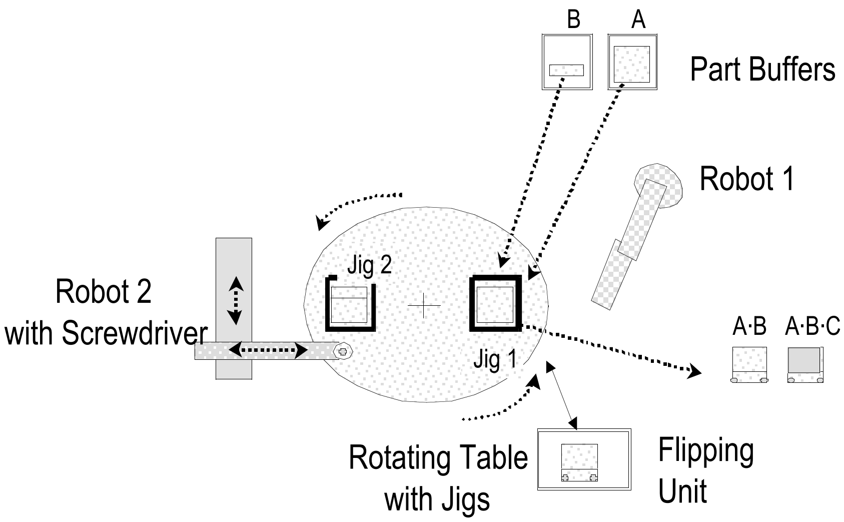

Figure 14 Layout of Simple Assembly Operation

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.

5.2 Auto ID in Conventional Assembly Cell Control

The conventional cell control system includes the execution, machine control and device operation layers in Figure 5 and Figure 10. A centralised Petri net based task execution system was implemented in which a set of predetermined operations were executed and monitored. The principle advantage of the introduction of product identity data into the conventional control system was to ensure the arrival of the correct items for assembly and to track the product (and its sub components) through the different stages of assembly. The addition of Auto ID data enables the system to handle the following scenarios:

- Item Identifiability – randomly arriving components can be sorted both in terms of product type and also item identifier so that specific items can be preassigned to particular orders
- Tracability and Quality Error Management – direct tracking of the items moving through assembly enables a accurate status of each item to be maintained in a suitable data store. This provides correlation information that can be used with any error – both product or process – that is detected, enabling simpler fault finding.

These, enhancements are essentially "information oriented" improvements to the operation of the assembly cell, reflecting the fact that the Auto ID data doesn't directly alter the control operations.

5.3 Auto ID in Holonic Assembly Cell Control

A holonic control environment has been developed in which orders for meter boxes are represented as product holons and machines and robots as resource holons. This holonic control environment (implemented using largely conventional computer control hardware) has been shown to be more readily reconfigurable than a conventional control system and capable of automatically dealing with frequently changing orders (Chirn, 2002). Being consistent with the holonic methodology, we emphasise that there is no predetermined schedule or control for this holonic cell as was the case for the conventional control system, where a preassigned production sequence was used.

In the holonic cell environment the customer order generates product specification/recipe software which is embedded in a product agent which negotiates on behalf of the order to have the product made on the resource holons that are available – namely two robot holons, a turntable holon and a flipping machine holon. In the Auto ID enhanced cell environment the customer order not only generates product specification/recipe software, 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 but – as was the case for the conventional control system - with the Auto ID system in place it is possible to track the product (and its sub components) through the different stages of assembly. However, in addition to enhanced tracking, in the holonic control context, this information also makes reorganisation of production simple both in terms of the information & control systems and also the physical operations. In trials (refer to Chirn, 2002), the system has been shown to readily handle the following scenarios (on top of those reported for the conventional control):

(1) *multiple simultaneous orders* – orders for two customers were produced 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 incomings 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 interruption 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 are not intended to be conclusive but rather to illustrate the potential benefits of combining Auto ID technology with advanced manufacturing control systems. More systematic developments to demonstrate the benefits of Auto ID based control are currently under development.

6. CONCLUDING REMARKS

The manufacturing deployment of Auto ID technology is unlikely to be its first industrial application as there are immediate benefits in warehouse and retail environments to be achieved in a relatively straightforward manner. However, this paper has indicated that many of the often cited long term challenges for manufacturing – customer responsiveness, ready mass customisability, and small volume/high variety order management – can be addressed by the combined application of Auto ID technology and distributed, intelligent control. The next steps in this work are twofold. To formalise successful approaches for combining Auto ID data with both conventional and distributed, intelligent manufacturing control methods such that consistent developments can take place with relatively low risk. The second key issue is the need for the development of measures and indicators which enable the manufacturing control system developer to be able to determine for a particular situation a) whether such a development would be beneficial and b) when implemented, how the performance of the system compares to its non Auto ID performance. A set of control theoretic measures are currently under development to address some of these issues.

Finally, we note that many of the potential applications for Auto ID in manufacturing control and management described in Sections 4.1 and 4.2 have direct analogues in the related areas of inventory management and distribution logistics and the role of the intelligent product in these situations is explored in some detail in Wong et al (2002), Bajic and Chaxel (2002).

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