The State of Auto-ID Technology in Manufacturing & Supply Chain Control

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1. Introduction

Modern day manufacturing and supply chains must function in harsh environments. They are often hindered by a lack of coherence between product and information flow.[1] The lack of information may come from within a single company's manufacturing plants which operate horizontally to provide a set of similar products or operate vertically to supply each other. Additionally, the lack of information may come from across an entire supply chain in which individual companies do not effectively share information and collaborate.[2] This lack of information causes uncertainty and variability in the form of the Bull-Whip effect[3] or the Forrester effect.[4] The result is three mutually coupled supply chain problems: 1.) high inventory levels to create buffers against the variability, 2.) long lead times to get through the supply chain and manufacturing operation, 3.) a lack of responsiveness to new product lines and demand fluctuation[*]. The inventory problem, in particular, causes a further lack of product visibility which re-amplifies the variability[2]. In this sense, inventory is both the cause and effect of a number of manufacturing and supply chain problems.

Inventory is further inflated by a number of managerial phenomena. In order to protect against missed orders, companies mitigate long lead times by accumulating safety-stock. Also, upstream suppliers must increase inventory levels due to inflated demand estimates made by downstream customer. These inflated estimates come from the need to create inventory to protect from further downstream disturbances as well as a "gaming" phenomena where a downstream customer will overestimate the order with the expectation that he will only receive a fraction. Additionally, supplies are purchased infrequently and in large batch sizes to minimize the cost associated with placing an individual order. Finally, forward buying strategies are used to take advantage of momentary low prices in an environment of high price fluctuation[2]. The result is elevated inventory levels throughout the supply chain, and particularly amplified as you head further upstream.

While these phenomena have always existed in production, they are further exacerbated by a number of new trends that demand increased responsiveness[†]. Of the more fundamental ones is a shift from functional products to innovative ones. This results in a single product

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[*] It is important to note that demand fluctuations are not just variations in quantity. They also represent variations in "quality"; the same product with perhaps a very different set of customisations. The latter can cause supply chain problems just as much as if not more than pure variations in demand quantity.

[†] This text defines responsiveness as the ability to return quickly to a desired performance crieterion in the event of an internal or external disturbance.

with many customizations, and a divided and unpredictable demand[5]. Additionally, companies have begun to outsource increasingly. This, in combination with globalization, creates longer and more complicated supply chains composed of a greater number of elements. Finally, product lifecycles are ever shorter causing a lack of demand history from which to forecast[6].

The crux of all of these manufacturing and supply chain problems is the need for timely, accurate and accessible information[7]. A set of technologies, collectively called Auto-ID, have been developed over the last decade to fulfil these information requirements[8]. While each type of technology provides its respective advantages, the Auto-ID[9] centre has developed a framework in which specifically RFID tags are used to link products to their information in a single networked-architecture[10]. This paradigm has the potential to provide "perfect supply-chain visibility" and effectively reduce many of today's problems in manufacturing and supply chains[11].

This paper will first survey these Auto ID technologies and briefly describe some of their industrial application. It will then highlight some of the faults of industrial technologies and show how they are resolved with the Auto ID centre's infrastructure. After describing some of the possible future benefits of this work, it will describe in detail how the Auto-ID based control has already been implemented to create a responsive manufacturing system. The paper will conclude by noting some of the unresolved issues involved with full industrial implementation.

2. Auto-ID in Industry

Prior to the founding of the Auto-ID Centre in 1999, the term Auto-ID technology was already prevalent within industry and the research literature. Unlike the Auto-ID centre's exclusive use of RFID tags, various companies and research work refer to Auto-ID as a collection of remote tagging methods. In all cases, these technologies emerged in the early nineties to replace paper-based methods[12] and keyboarded database-entry methods[13] to track product flow and inventory levels. Efforts to reduce cycle times and defect rates required the elimination of the bottleneck of information flow caused by frequent error and low speed data entry methods[14]. Congruently, the technologies were viewed as ways of enabling total quality management and continuous process improvement principles[15].

2.1. A Survey of Auto ID Technologies

Auto ID technologies are typically categorized (in order of prevalence) as Barcodes, RFID tags, 2D Barcodes/Portable Data Files, Magnetic Stripes, Optical Character Recognition, Automatic Speech Recognition[13,15], and Machine Vision[13]. The first five are surveyed here.

2.1.1. Bar Coding

The familiar set of uneven thickness black and white lines can now be found on nearly all retail goods. It has also been adopted effectively inside manufacturing plants between stations, and less frequently between supply chain partners[6]. These black and white lines provide a visual form of binary logic that can be interpreted by a line-of-sight optical device which is either manually operated or machine mounted[13]. Typically, the manufacturer and stock-keeping unit (SKU) is encoded but there is not sufficient space to encode the serial number[8]. It provides a fast and efficient technology with an error rate estimated as low as 0.5 ppm[16] and is the cheapest of Auto ID technologies. The system integrator often has a wealth of printing and scanning options from which to choose[13]. Finally, the functionality of barcodes has often complemented by Electronic Data Interchange (EDI): a proprietary based method of electronic data sharing between companies[13,14].

2.1.2. 2D Barcodes & Portable Data Files

Two dimensional Barcodes and Portable Data files grew out two separate requirements: 1.) the need for more data to describe the product 2.) the need for this data to follow the product[16]. The growth of product customization drove the first requirement, and it was realized that 1D barcodes provided an insufficiently small information density. Efforts were made to stack barcodes into what are sometimes called 1.5D barcodes[8]. However, the physical size of the product and scanning constraints often rendered this method impractical[14]. Instead, 2D barcodes were developed to hold as much as a megabyte with similar accuracy as their 1D counterparts[15]. The second requirement came about from the perceived logistical difficulty of accessing a database that used barcodes as keys to larger data files[16,17]. Two dimensional codes provided similar cost benefits with most of the excess costs coming from more expensive optical scanners[12]. A number of open and proprietary two dimensional codes were developed to meet space, information, and manufacturing process requirements. For example, Nokia moved to a 2D code to take full advantage of the space in its mobile phones. An engine manufacture began to use 2D codes when it needed to included the injector specific performance characteristics. Finally, Rolls-Royce created its code as physically marked onto its turbine blades to avoid the creation of stress accumulation points[18]. Figure 1. shows five examples of two dimensional Auto ID codes.

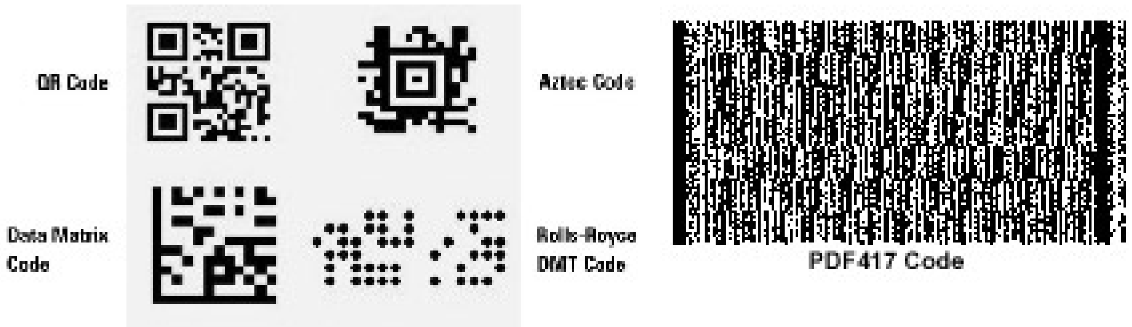

Figure 1. Five 2D Codes in Auto ID Technology[16,18].

2.1.3. Optical Character Recognition

Optical Character Recognition systems typically employ a set of numerical characters that are machine and human readable and are often considered as a bridge between manual data collection and the "cryptic" data acquisition with barcodes[13]. OCR systems, also, require require a high level of computing power in order to recognize their typically highly stylized characters[15].

2.1.4. Magnetic Stripe Systems

The familiar magnetic stripe is well standardized in financial and security applications. The technology has the ability to read and write unlike the previously mentioned technologies. Finally, it has a low implementation but suffers from a lack of robustness and information density[15].

2.1.5. RFID Tags

RFID tags offer a great deal of variability in characteristics, performance, and cost[15]. The common functionality requires a scanner or reader to broadcast a radio frequency to the tag which responds with coded data on a different frequency when within a typical range of a few centimetres to few meters[8]. The reader receives the signal and sends it to a networked computer system[13]. An RFID tag is composed of an integrated circuit, an antenna, a connection between the two and a silicon substrate on which all of them sit[19]. Their memory size greatly and come in read-only and read/write options[8]. One source states a maximal size of 32 Kb[13] while another says they are more typically 1Kb[12]. The Auto ID centre RFID tags hold either 64 or 96 bits[20] and still contain more information than a typical barcode[6]. The variability in memory is commensurate with its variability in size which varies from many centimetres to hundreds of microns[13]. RFID tags, also, come in passive and active power options. The former relies on the power of the inductive coupling of the carrier signal and the latter relies on an attached battery[8]. The greatest feature, however, over the previously mentioned technologies is their ability to be continually scanned as opposed to a discrete moment such as checkout and inventory checks[6,21]. This has caused one publication to ask "Will RFID Put the 'Auto' into Auto ID?"[22] Fundamentally, it is the only technology that is truly automatic. No human involvement is required, misreads are minimal and there is almost no additional reading cost once the system is setup. Additionally, the RFID tag does not require line of sight[6]. The tag can be in any orientation provided that it is within the range of the scanning signal[23]. This allows the Auto ID system to be able to acquire continuous location data, faster than other technologies, even when the product is obstructed from view (hidden in a plant, or packaged in box.)[6].

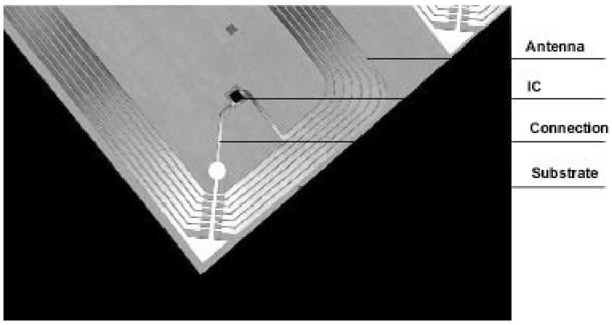

Figure 2A Magnified View of an RFID Tag[19]

2.2. Usage of Auto ID Technologies

Over the course of Auto ID development, each technology has developed to complement the usage of the others with each providing its own set of investment and maintenance costs, flexibility, and general performance[15]. Together, they have been implemented in as varied industries as the airline[24], recycling[25], defence[26], health care[27], and transportation[28] industries. Their main use has been in material handling, inventory control, batch traceability and tracking, production monitoring, data collection and management[29]. In fact, barcodes have been used as an electronic form of kanban[30]. Similarly, Udoka proposed a method of integrating Auto ID technology in three architectures * of Computer Integrated Manufacturing[31]. The results of the investment usually pay off but often times at different

* The three architectures mentioned are IBM's CIM architecture, Purdue University's CIM Reference Model, and the EC's CIM-OSA.

time scales. Cardinal IG, a glass maker in Minneapolis implemented an out-of-box barcode solution and reduced their packaging and shipping error rate from 3% to 0.3%[12] In the mid 1990's however, Tesco, one of England's largest supermarkets did not have as immediate of success. It implemented a barcode solution composed of outer case codes (OCC) for packages entering distribution centres. The codes were scanned using handheld scanners connected to a central EDI via a wireless RF network to diminish delays and difficulty in product identification at distribution centres. As a result, Tesco experienced initial coding problems, which were eventually prioritized and resolved[32].

The Tesco case also showed definitively that Auto ID technology would only be taken up when the value of the information acquired exceeded the cost of implementation[32]. For example, in the paper industry, paper may run as fast as 1,600 meters/min. At such speeds, the tagging process itself can become a bottleneck and special care must be taken in the Auto ID system design[33]. The construction industry provides even greater challenges that have historically impeded the industry from adopting Auto ID methods[14]. Specifically, the industry exhibits a standard T type assembly process[*]; a large number of products from a large number of suppliers must enter assembly simultaneously in order for assembly to proceed. As a result, downstream processes of distribution, storage, assembly, installation, commissioning and maintenance can only reap the benefits of Auto ID when it has been effectively implemented by upstream suppliers. This may be difficult when 1.) there is no clear benefit for the upstream supplier, 2.) the supply chain relationships are temporal 3.) there is no effective method of data transfer between supply chain partners. Furthermore, it has been noted that misunderstanding of the benefits of Auto ID, misunderstanding of the importance of implementation detail, reluctance by staff to embrace 'seemingly useless' new technology and concerns about reliability have all impeded adoption within the construction industry[14].

This section has surveyed the spectrum of Auto ID technologies and highlighted the strengths and weakness of each one. It has also shown some of the real world difficulties that face these technologies in practice. The following section will show how these technologies are a first generation technology, and how the Auto ID centre's response brings a fundamental next generation improvement.

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[*] T-type assembly processes are commonly found where the final product is too big to be moved i.e. ships, airplanes & buildings.

3. The Auto-ID Centre

The focus of the Auto ID centre was not to simply advocate one of the previously mentioned hardware options, but it was also to advocate an integrated and streamlined method of management of the collected data. Furthermore, research and development energies shifted from collecting product data to controlling those products and finally to creating intelligent products that are able to negotiate their production.

3.1. System Architecture

In the context of manufacturing and supply chain, the Auto ID centre system architecture may be viewed as a RFID tags that send a single product identifying code to a scanner which is connected to a LAN network which uses this product code to access a unique writable file on a remote database. This paradigm, however, would not truly encompass the scale and functionality of the Auto ID system architecture. The Auto ID centre paradigm is to tag every item such that it is networked to the rest of the "networked physical world"[23]. Each tag maybe queried, tracked, and managed in a remote, contactless manner. This newly formed network will allow for new dynamic relationships between objects, their manufacturers and users in ways never before perceived.

Perhaps the best way to understand the versatility of the Auto ID system architecture is to compare it and its components to the internet[10]. In fact, the Auto ID centre's process for developing standards is based upon the one used by the World Wide Web consortium[34]. The Auto ID system components are the 1.) RFID Tag, 2.) The Electronic Product Code (EPC) 3.) The Object Naming Service (ONS) 4.) The PML Server 5.) The Savant.

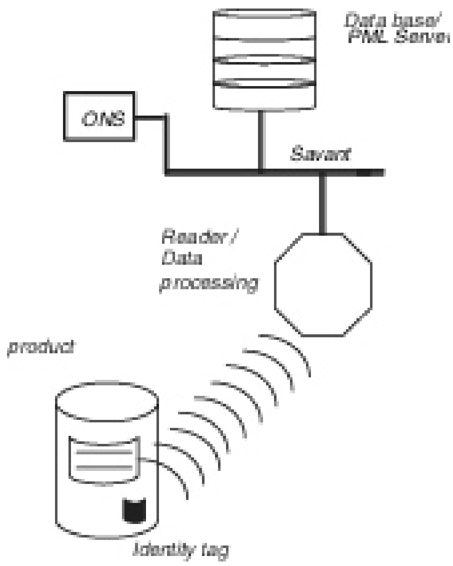

Figure 3. A Graphical Representation of Auto ID System Architecture[35].

3.1.1. The RFID Tag

The Auto ID uses the same technology as the previously mentioned RFID tags. However, they are specially optimized for cost[19]. Hence, they are fully passive, read-only, ideally 0.25mm square in size and carry the minimal amount of memory required to save the EPC. All other tag functionality is transferred to the rest of the Auto ID system architecture[23]. The RFID tag can be viewed as an individual computer or network card.

3.1.2. The EPC

The Electronic Product Code (EPC) is a 64 or 96 bit representation of the product. The 64 bit version is a fully compatible prototype version of the latter that will lower initial cost and aide in near term adoption. The 96 bit code consists of four parts: header, manufacturer, product, and serial number in 8, 28, 24 and 36 bits respectively[20]. The main advantage of the EPC is that it goes beyond the Uniform Product Codes found in barcodes by including the serial number for each uniquely defined product[6]. To explicate the efficiency of the EPC, it accounts 268 million manufacturers, each with 16.8 million products, and each with 68.7 million individual products. In the internet analogy, its analogue would be the IP address. It acts as a unique pointer to the tag/product and communicates directly with the system architecture[23].

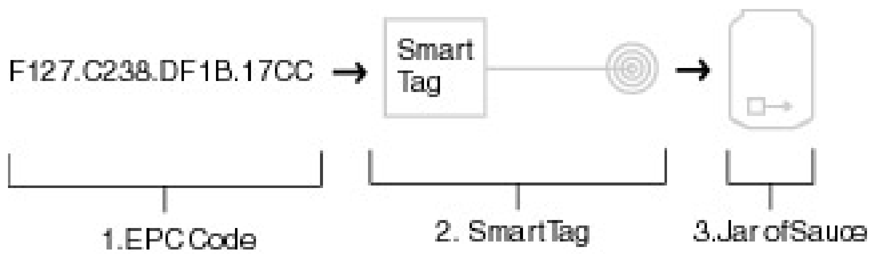

Figure 4. An Example EPC Code[1]

3.1.3. The Object Naming Service (ONS)

The ONS resembles in name and function to its internet analogue; the Dynamic Name Server (DNS). As the RFID tag only carries the EPC, the ONS must resolve this code and have it point accurately to the files that describe the product's details[23].

3.1.4. The Physical Markup Language (PML) Server

The Physical Markup Language is a variant of the well known XML language, and their PML servers cointain PML files much like HTML servers will store HTML files. These files will uniquely describe the details of each product. Of the advantages of PML files, are its ability to be read easily by people, and be queried easily by relational databases[23]. In this way, PML servers house can virtually house a great deal of product information without requiring that it be physically attached to the product.

3.1.5. The Savant Software System

The Savant System is a highly modular and parallel software application that will serve as the backbone upon which this extraordinary amount of network traffic can take place. It provides the primary interface between RFID scanners, the ONS, the PML servers[36].

3.2. Rationalization of System Architecture

By designing a system architecture that pays as much attention to how data is acquired as to how the information is managed, used & transferred, the Auto ID centre has developed an architecture that resolves most of the problems of first generation Auto ID technologies. It has chosen RFID tags as the only true automatic data acquisition method as it requires neither line of sight nor manual operation. In response, it has tried to aggressively limit the tag cost by transferring most of the functionality away from the tag and to the rest of the data management system. Because the combination of the Savant, ONS, and PML servers provide access to real time data in a simple, transparent and effective way, there is no need follow the trend of putting large amounts of data on tag, as is done on portable data files. Finally, the Savant, ONS and PML servers provide scalable solution for capturing events across supply chain partners.

The Auto ID centre provides further advantages from the nature of its integrated design. First, the system is platform independent. The reliance on a minimal tag with PML servers allows for all computer operating systems and most machine hardware to use the system. Secondly, the architecture is standard and open. According to the Metcalfe's Law, the value of a network depends directly on the square of the number of users. An fully standard open network allows for rapid adoption, disperses value to all, and is cheaper and more effective than a number of smaller scaled proprietary networks. Finally, the Auto ID system is fully flexible and can be modified readily in the future[23].

3.3. Applications and Business Cases

After the conception of the Auto ID system architecture, a wide variety of business cases and models have been proposed to take full advantage of its innovation. These include business information systems[37,38], retail[39,40,41,42,43,44], shrinkage[*45,46,47,48], distribution[49], food manufacture[50], consumer packaged goods[51,52], full product life cycle[53,54], defence[55], pharmaceutical[56,57,58], transportation[59], automotive[60] and materials handling[61] applications. In the interest of brevity, we proceed directly to Auto ID applications in Manufacturing Control.

3.4. Auto ID Based Manufacturing Control

As previously mentioned, the Auto ID centre shifted the focus of Auto ID technology from a data collection method to manufacturing and supply chain control method. This required a deep investigation in how control systems work in manufacturing operations and supply chains. A control system can be defined as a process comprised of sensing, decision and action elements that work together to improve the performance of an operation towards a target level[62]. In manufacturing control, sensing can be performed on the production resources (i.e. machines, people, transportation units) or on the products themselves[63]. In the case of the latter, sensing has almost always been indirect[64]. With directly sensed product information, one gains a further degree of system observability[†65] and hence may expect to approach the target performance more closely and rapidly. In order to see how to achieve this added controllability, the ideas of intelligent products and software agents must first be defined.

3.4.1. The Intelligent Product & Its Software Agent

An intelligent product has five characteristics that may be categorized into two levels of functionality. In Level 1, a product must 1.) have a unique identity, 2.) communicate effectively with its environment, 3.) store information about itself in relation to the environment[1]. One can note that these three functions are immediately satisfied by the Auto ID infrastructure. It will form the basis of manufacturing control enhanced by Auto ID data.

A Level 2 Intelligent Product forms the basic building block of Auto ID Driven control and requires two further functionalities: 1.) Usage of a language to display its features and production requirements. 2.) Ability to negotiate with manufacturing resources and other intelligent products, and make decisions with regard to its own production[1]. To gain this new functionality, a software agent is required. A software agent is a "distinct software process

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[*] Shrinkage is the combined term of normally unpredictable industrial losses such as product failure, theft, expiration and obsolescence.

[†] Improved observability can be defined as the ability to measure a greater number of transitions from one state to another[65].

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"[66]. Hence, a fully intelligent product should be viewed as product itself, its RFID tag, its connection to the PML server via ONS, and Savant and finally a software agent that governs the automated behaviour of the product as it approaches manufacturing resources and other intelligent products.

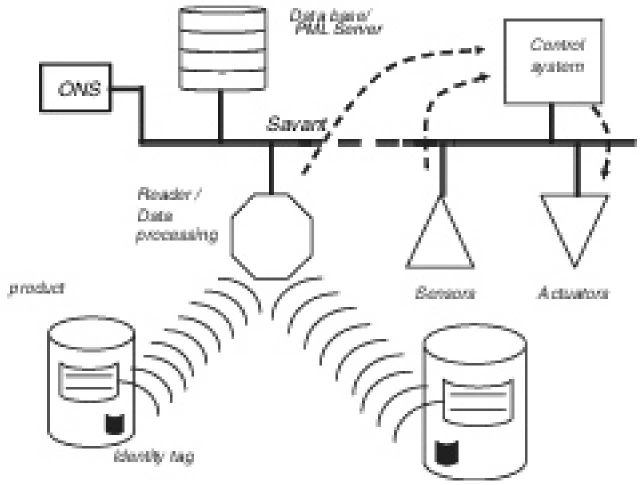

Figure 5. Two Intelligent Products Interacting via Auto ID Infrastructure[35].

3.4.2. Auto ID Enhanced Control

Once product specific data can be gathered effectively, modern manufacturing control systems can effectively use this data to improve operations[1]. Conventional manufacturing control uses hierarchical top down-structure of conveying operations. Orders are converted into a production schedule which creates a part execution which drives the machine automation which is controlled by machine/process specific automatic control systems[62]. Conventional control can not respond rapidly to product specific data, but it can take advantage of the improved visibility provided. For example, the management can effectively track products through their usage history and recalls, accurately measure lead times, and perhaps identify shop floor bottlenecks[1]. In short, the management can collect enough data about its products that at some later time it can change its planning, product scheduling and execution scheme to improve upon the deficiencies, it had previously observed.

3.4.3. Auto ID Driven Control

Auto ID Driven control can be categorized within the class of Distributed Intelligent Manufacturing Control. Multi-Agent-Based Manufacturing Control and Holonic Manufacturing Systems[35] are also very much closely related control schemes. . Prototype examples of all of these can be found in Section 3.4.4. These types of control systems have some critical features[62]. 1.) The system responds in real time to changes in low level product data such as a specific inventory as well as to high level information like change new orders and product recalls. 2.) No single product or resource has access to all of the available data. 3.) Each intelligent product must interact with other intelligent products and resources that operate upon them in order to move through production. In other words, each intelligent product has sort of real time "awareness" of the machines around it which updates as other products take up the machines' availability. This type of extremely flexible and responsive control can allow for a product to choose less congested traffic routes through a plant, avoid broken/unavailable machines, and allow for mass customization of final products[1].

3.4.4. An Auto ID Driven Control System Prototype.

To demonstrate the flexibility of such a control system, the Auto ID centre at the University of Cambridge developed a prototype composed of two robots[67,68,69]. A schematic of the production is shown below.

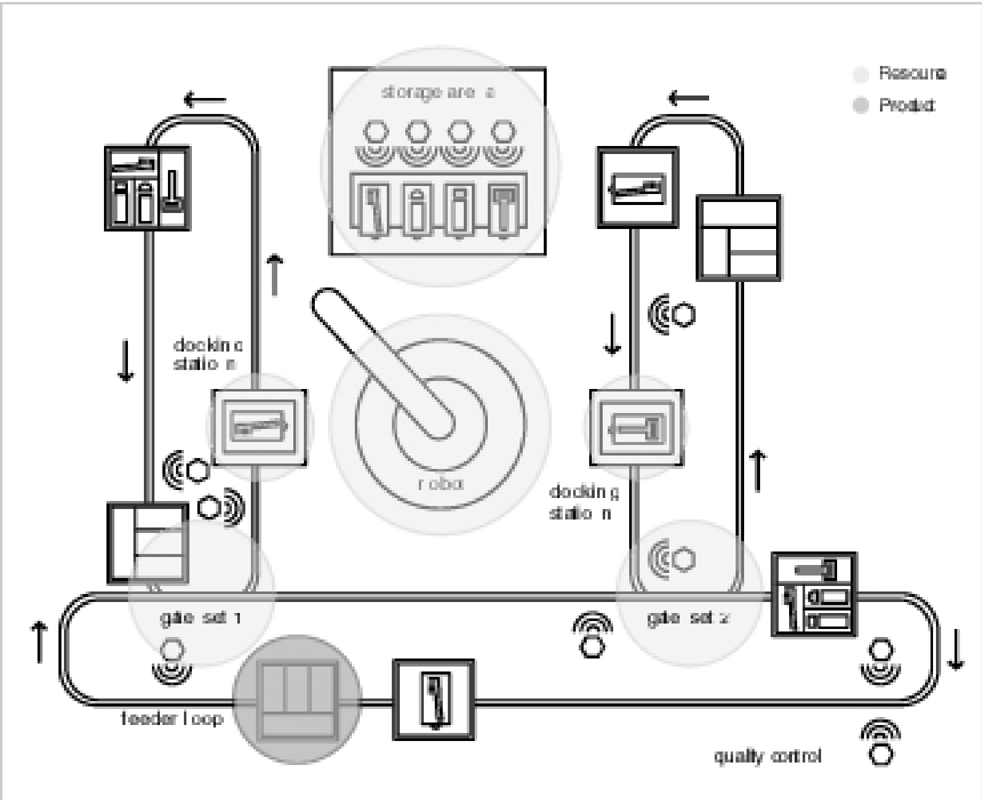

Figure 6.A Schematic of a Protoype Auto ID Driven Manufacturing Sytem[68].

The final product is a "Gillette Shaving Gift Pack". This is composed of a box that will include three items among them a shaver, shaving cream, and deodorant that can be placed by the centrally located robot into one of two possible configurations. The input goods[*] are stored in an area adjacent to the robot. The robot is then provided with an order of shaver gift packs. The number of packs, its contents and their orientation is chosen randomly and is not predefined in anyway. The demonstration is started and small carts make their way around the feeder loop (idly) until the first order is received. At which point, it enters the docking station for production. In the meantime, other orders can be placed and they will enter the secondary loop and stop at its docking station. Upon order completion, the cart (now with finished product) leaves the station, re-enters the feeder loop and is stored by a gantry robot overhead. The demonstration has the ability to recall any of the finished products or works in products and replace them with a cancelled or modified order. It is absolutely critical to note that the timing and execution of these events is not scheduled or known a priori. Instead, the products negotiate for availability of the two robots to proceed through production. As you can see, this is an entirely automated, flexible and distributed control scheme. It takes advantage of the ability of the software agents to make use of the specific real time product data, to negotiate with other software agents and determine the future path of production[68].

4. Conclusion

In this report, we have seen two distinct generations of Auto ID technologies. In the first, the primary goal was to collect more efficiently data about manufacturing operations and perhaps supply chains. A wide variety of technologies were used that provided varying levels of functionality depending upon the investment cost. In the second generation, a fully integrated RFID based technology was developed by the Auto ID centre. To take advantage of all possible functionality, and minimize an integrated open-architecture data management solution was proposed to create a "Networked Physical World". This led to dramatic improvements in manufacturing plan observability and led to Auto ID enhanced control methods and Auto ID driven control methods that required specifically the Auto ID open architecture to function. Finally, a prototype of the latter was demonstrated to show the dramatically improved responsiveness and flexibility of the control.

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[*] From this point forward, the shaver, shaving cream and deodorant will be referred to as the input goods.

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