Using radio frequency identification in agent-based control systems for industrial applications

Pavel Vrbaa,*, Filip Macúrek a, Vladimír Maříka

aRockwell Automation Research Center, Pekařská 695/10a, 15500 Prague 5, Czech Republic
bDepartment of Cybernetics, Czech Technical University in Prague, Technická 2, 166 27 Prague 6, Czech Republic

Received 15 January 2007; received in revised form 3 December 2007; accepted 7 January 2008
Available online 3 April 2008

Abstract

The radio frequency identification (RFID) is a technology for automatic identification of items, particularly in supply chain, but it is becoming increasingly important for industrial applications. Unlike barcode technology that detects the optical signals reflected from barcode labels, RFID uses radio waves to transmit the information from an RFID tag affixed to the physical object. In contrast to today most often use of this technology in warehouse inventory and supply chain, the focus of this paper is on the exploitation of RFID in industrial environments, particularly for the purposes of the real-time programmable logic controller (PLC)-based manufacturing control. The paper also presents a unique architecture integrating the RFID technology with the agent-based industrial control solutions by proposing special RFID agents as mediators between physical RFID readers and other agents. Integral part of this solution is the introduction of the work piece agents directly negotiating with the manufacturing resource agents about the details of production.

Keywords: RFID; EPC; Manufacturing; PLC; Multi-agent systems; Simulation

1. Introduction

Although barcodes are the most wide-spread technology for tagging and identification of physical objects used today, this technology suffers from several restrictions and drawbacks. One of the major issues is the need for manual positioning of the item in order to ensure line-of-sight between the reader device and the label. The other problem is that the barcode is not designed to allow distinguishing between individual instances of objects (all objects of the same type have the same ID) and, especially for manufacturing purposes, as the tag is placed on the surface of the physical object to be visible to scanner, it has a low resistance against dirty environments containing for example dust or oil.

The radio frequency identification (RFID) technology allows remote identification of objects using radio signal, thus without the need for line-of-sight or manual positioning of each item. The RFID tags comprised of a small chip and antenna are attached to the physical objects. When the tag enters the range of the RFID reader, it absorbs the energy from the radio field and the microchip, which bears the unique identity code, returns this information back to the reader via modulation of the radio waves. The transmission distances range of passive tags, which do not have their own power supply, vary from centimeters to meters. Active RFID tags with built-in batteries are able to transmit their data over distances up to 100 m; however, they suffer from larger size and higher price. The major advantage of RFID technology over the barcodes is that the RFID system allows detection of multiple items simultaneously as they pass through a reader field (for example the presence of all the items in a closed box can be checked without opening it). Additionally, each physical object has its unique ID (even two products of the same type have two different IDs) enabling to precisely track and monitor the position of each individually labeled product piece.

The RFID tags and readers themselves are only a part of the overall RFID solution. Recently, the so called
EPCGlobal Architecture Framework (EPC Global, 2007) has been developed as a global standard for automatic and unique identification of objects in the physical world and their linkage to the virtual representation in networked databases (Harrison et al., 2004). EPCGlobal Architecture Framework provides a collection of hardware, software and data standards aimed at facilitating the exchange of information about physical objects between trading partners. A crucial component is the introduction of the Electronic Product Code (EPC), which is basically unique code number embedded into RFID tag’s memory. The EPC coding scheme (with different lengths, like 96, 128 or 256 bits) is designed to contain the information about the manufacturer of the product, type of the product and, as a major advantage over bar codes, a unique serial number of the particular product piece. For instance, 96-bits EPC allows distinguishing of 268 million of different manufacturers, 16 million of different product types for a single manufacturer and 68 billion of different serial numbers of products of the same type.

The EPC Information Service is a network infrastructure that enables trading partners to share different subsets of their live EPC data through standard interface, thus without any need to access the underlying databases directly. The supporting technology is the Object Name Service (ONS) used to translate an EPC into one or more Internet addresses (URLs), where further information about the object can be found. Typically, these URLs identify an EPC Information Service, although ONS may also be used to associate EPCs with manufacturer’s web sites relevant to the objects.

Filtering & Collection layer, commonly referred to as middleware (Lee and Kim, 2006) is placed between the physical reader infrastructure and higher-level information systems (EPC Information services). Its role is to collect, filter and aggregate raw EPC data coming from one or more RFID readers and convert them into a meaningful form for higher-level applications and information systems. This layer reduces the volume of information sent to applications—only significant data events and summary data packets are propagated to applications and information servers, rather than every individual tag read (Chokshi et al., 2003). Examples of EPC data processing performed in this layer include filtering (eliminating some EPCs according to different criteria such as discarding all EPCs of particular product type), aggregation over time intervals (eliminating duplicate reads within that interval), grouping (for instance summarizing EPCs within a specific object class), etc.

All the major players in the RFID business, including IBM, Sun, SAP, OAT, Oracle or Microsoft have introduced their RFID frameworks. However, in the majority of cases the aim is on integration with enterprise business applications. Rockwell Automation, as a major provider of industrial automation solutions with the ControlLogix™ programmable logic controllers (PLCs) as its flagship product, realized that there is a need for specialized RFID middleware solution tailored toward the specific aspects of industrial environments. Additionally, with a long history of researching into the agent-based manufacturing control solutions (Mafik et al., 2005), the major topics discussed in this paper, which are quite unique and rarely addressed in the literature, are:

- Exploitation of the RFID technology in the industrial control environments. The objective is to implement a lightweight middleware application that enables to collect, filter and aggregate EPC data from variety of RFID readers and provide them in appropriate form directly to real-time control applications running in industrial controllers (PLCs).
- Proposal of an original architecture enabling the integration of RFID technology with the agent-based manufacturing control systems. Special RFID agents (that internally embed the middleware) are introduced to serve as mediators between the physical readers and other control agents that are interested in the RFID data. Work piece agents are additionally proposed as intelligent and active representatives of particular product pieces that, with the help of RFID, directly negotiate with resource agents (machines, transport system components, etc.) about the details of production and transportation.

The paper is organized as follows. Section 2 discusses major differences in requirements on the RFID infrastructure for common warehouse inventory and shipment tracking systems and manufacturing applications. Section 3 reports on the development of the RFID middleware infrastructure dedicated to the industrial controllers and discusses some useful filtration methods. Section 4 then introduces special RFID agents to be used in agent-based control applications as RFID data providers to other agents. Section 5 then gives some conclusion remarks.

2. Manufacturing-oriented RFID framework requirements

The recent upspring of RFID technology has been motivated by mandates imposed by major retailers on their suppliers, requiring them to tag deliveries with RFID tags. To remain in business, all suppliers have to comply and thus have been looking for solutions and the RFID industry has boomed. Tagging deliveries with RFID tags represent an added cost for the supplier, with no compensation from the retailer. It is understandable that suppliers are looking for ways to get some return on their investment in RFID technology. This attempt has initiated the idea to take advantage of the presence of RFID tags already in the production phase of the product lifecycle. Such possibilities increase especially with the introduction of item-level tagging—while at this moment most RFID tagging is done at the level of pallets or cases, it is quite probable that as soon as tag prices decrease, each individual item will be tagged. The focus on item-level
tagging has been initiated by growing number of regulations intended to secure the flow of prescription drugs from manufacturers to distributors and on to pharmacies (Collins, 2004), requiring the use of an effective system for electronic tracking and tracing of individual packages of medicine (e-pedigree systems). RFID tags are used as a relatively secure carrier of unique identification of individual packages of prescription drugs.

It is quite understandable that most RFID equipment manufacturers focus on the largest share of the RFID market and try to satisfy needs specific to warehousing and shipment tracking business. Looking for ways of benefiting from the presence of RFID tags on items in the production phase of product lifecycle, we quickly found that there are many specifics of the usage of RFID tags in the manufacturing process that need to be catered for if the use of RFID technology should bring any benefit. Item-level tagging seems to be the main enabling factor of the usage of RFID tags in the manufacturing phase. The presence of RFID tags on individual items (parts) allows for effective tracking of items in the production process. Tagging at the level of stock keeping units (SKU—e.g. case or pallet) seems to bring very limited benefits in the production phase. In this study, it is assumed that the price of RFID tags will drop quickly and that item-level tagging will become a standard practice in the foreseeable future. Another assumption is that manufacturers may get return on their investment in RFID (mandated by retailers) by tagging items early in the production process and take advantage of their presence to improve the manufacturing process.

Listed below are main differences in requirements on the RFID infrastructure specific to warehouse inventory and shipment tracking and manufacturing usage.

2.1. Amount of items to be read at the same time

A typical warehousing and shipment tracking application uses RFID tags on the level of pallets or cases. RFID readers are typically located at gates of the warehouse (portal readers). When the shipment is received, the RFID tags of the goods in the shipment are read and the information about the goods received is stored in a database. Most of these applications can be characterized by a large amount of tags appearing in the read range of the RFID reader at the same time. All of the tags need to be read and the information contained in those tags must be processed. Other typical operation is the use of handheld RFID readers to search for specific case or pallet in shelves of the warehouse, or the use of handheld readers at the time of customer checkout at the retail store (in case of item-level tagging). In some cases, RFID-enabled forklifts help to keep track of the movement of goods in the warehouse. If handheld RFID readers are used, it may be desirable that only a single RFID tag is read at the time (the reader operator only wants to get information about a single item of interest, but not about all the other items in the same storage shelf).

Although it is difficult to estimate all the possible ways of using RFID tags in the manufacturing process, it is probable that the predominant usage will be in identification of individual product parts on the production line. It can be assumed that individual tagged parts enter the production process. These parts typically enter the process sequentially (one at a time). In the course of the process, individual parts of different type, each tagged with an RFID tag, are grouped together as the final product is being gradually assembled from those parts. Individual tagged items cease to act as individual parts and new items composed of those parts are conceived, each of them tagged with multiple RFID tags formerly belonging to individual parts. Thus, the important characteristic of RFID usage in manufacturing seems to be gradual grouping of tagged items into new entities.

2.2. Time criticality

Although the shipment entering the warehouse portal usually contains a large number of tagged items and all of them need to be read, time performance does not seem to be of high criticality. Even if the shipment is scanned on the run (loaded on a forklift moving through the portal), the speed of movement is relatively slow. The reader performs a large amount of read cycles to make sure that all tags in the shipment are read. The use of handheld readers imposes no requirements on the speed of tag information reading. The speed of relative movement of the scanned item and the reader is negligible.

In manufacturing applications, it has to be assumed that the items move through the production line at high speeds, and it is very important to be able to read tag info even at high speeds.

2.3. Processing of tag information

The architecture of systems used in warehousing and shipment tracking applications usually deploys edge controllers (IBM, 2007) as interfaces between RFID readers and the enterprise-level system. The edge controller connects to one or more RFID readers using the reader protocol, typically does some basic tag data filtering, and then uses one of the standard communication protocols used by the enterprise-level system to communicate relevant data to a database. One of the EPCglobal standards deals with sharing of information about tagged products among different parties involved in the supply chain. The EPC Object Naming Service allows the interested party to locate the source of information about an item based on the EPC tag data. Enterprise-level systems used in these applications are capable of working with different data types and performing large numbers of database transactions with the data. That is why filtering of tag data at the level of the edge controller is not so critical.
It can be assumed that the primary means of processing of tag data in most manufacturing applications are PLCs. Such devices are not designed to perform large numbers of transactions with tag data (especially in string format). That is why it is very important to limit the amount of data reaching the PLC as much as possible with advanced filtering either at the level of the reader or at an intermediate level (RFID Manager).

2.4. Summary of manufacturing process requirements

Previous sections attempted to point out differences between mainstream RFID applications and applications of RFID technology in manufacturing. The specifics of RFID technology applications in manufacturing environment can be summarized as follows:

- The number of tagged items usually entering the reader’s vicinity at the same time is small.
- As the final product is assembled, individual tagged parts cease to act as individuals and the new item tagged with multiple RFID tags formerly belonging to parts the item is assembled from are conceived.
- The speed of movement of tagged items may be relatively high and read reliability is critical.
- RFID tag data are processed by relatively simple devices, such as PLCs, not designed to handle large amounts of string data.

It is obvious that the manufacturing-oriented RFID architecture should provide some additional features not common with current RFID systems oriented towards warehousing and shipment tracking. These features should (i) overcome the inherent limitations in data processing of industrial controllers (PLCs) and (ii) improve performance of RFID readers in aspects critical to manufacturing applications. As a result of these considerations, Rockwell Automation decided to implement specialized lightweight middleware application that gathers RFID data from variety of readers, applies different filtration methods and subsequently provides the data to PLC programs using standardized industrial communication infrastructures (allowing for instance to map the RFID middleware as a standard I/O module of the PLC accessible over Ethernet/IP).

3. RFID middleware designed for industrial applications

3.1. The RFID manager

The core of our RFID middleware architecture is a compact Java application called RFID Manager, which task is to collect the EPC data from RFID readers, apply basic filters and temporarily store the data in its internal memory. The RFID Manager has a set of well-defined interfaces through which the internally stored EPC data can be provided to various external applications like for example the PLC control programs, RFID agents, remote GUI, higher-level information systems such as MES or ERP systems, etc. As shown in Fig. 1, the RFID Manager consists of four main parts: (i) the drivers interface module, (ii) the filtration and processing module, (iii) the EPC data storage and (iv) the application interface.

The first module manages the drivers by which the RFID Manager communicates with physical RFID readers and receives the data. Today, mostly preferred and almost always sufficient type of connection is via Ethernet. However, when required, for instance in real-time applications, there is also a serial connection available on most readers. Although the EPCGlobal has ratified a standard for interacting with a reader (EPCGlobal Reader Protocol), each manufacturer still uses its own specific communication protocol. The RFID Manager thus contains a library of drivers for major reader manufacturers that can be additionally simply extended by adding new reader-specific drivers without a need for modifying the rest of the application. The architecture provides the dynamic capabilities of connecting to newly installed readers at runtime or disconnecting from readers that are not needed any more.

The filtration and processing module handles all incoming EPC data in terms of applying different filtration and preprocessing techniques on raw data retrieved from readers prior they are stored to the internal memory. The basic data processing technique is for instance the determination of the logical reader entities, duplicity reads filtering, etc. (see below). Original solution is that the filters can be arranged into different groups to allow applying different sequences of filters on data received from different readers. Also filters can be dynamically added or removed at runtime (or just temporarily deactivated) and new application-specific filters can be introduced later on to extend the capabilities of the RFID Manager application.

The third module is the EPC Storage where the processed data are temporarily stored. Each record contains not only the EPC number, but also additional information like the physical reader and antenna number identification, logical reader recognition (see later), time stamps, etc.

The application interface then provides stored EPC records to external applications. It has been primarily designed with aim to provide the data to control applications running on the industrial controllers. Two different methods are supported (Macírek et al., 2004):

1. Transferring the EPC data to the PLC by direct writing into tags (not to be confused with EPC tags) with predefined structure in PLC’s memory. These PLC tags are commonly accessed by the control programs, for instance by the ladder logic code. This is Rockwell’s proprietary solution working only with the family of Logix™ controllers.
2. Providing the EPC data via the Ethernet/IP network. This solution is based on the Common Industrial
Protocol (CIP)—an open standard managed by ODVA (2007), which provides the users with a unified communication architecture throughout the manufacturing enterprise and which is supported by hundreds of vendors. In this case, the RFID Manager looks like a CIP device that can be accessed over the Ethernet/IP network from the PLC like a standard device or I/O module. The proposed RFID CIP object specification includes the support for receiving filtered EPC data, writing EPCs (most RFID readers have the writing capabilities) and provides some basic control commands for controlling the readers, like for instance setting the parameters, turning on/off the RF field, etc.

Currently, there is an effort of Rockwell Automation to convince the reader manufacturers to directly implement the RFID CIP object specification in their readers to enable an easy connection of their RFID readers into the Ethernet/IP networks (IP here stands for the Industrial Protocol).

The application interface additionally provides a server–client architecture for accessing the RFID Manager over the Ethernet. An example of the client is the graphical user interface (GUI) that is used for remote monitoring, control and configuration of the RFID Manager. As can be seen in detail in Fig. 2, it displays the list of all connected physical readers and their status, the list of installed filters and defined filter groups as well as the table of the latest received and stored EPCs. Through the GUI, the user can also fully control the RFID Manager—he/she can for example switch on/off the particular readers, activate or deactivate filters, change the mapping between physical and logical readers, connect new readers, etc. Any control action done by a particular client is then propagated through the server to all other clients. Apparently, any other non-GUI client (the RFID agent for example as described later on) can also monitor and control the RFID Manager in the same way. Moreover, the client can subscribe to the server to be informed just about particular EPC events, like for instance “report only records that correspond to a particular reading zone”, etc.

3.2. Filtration methods

The very basic and most commonly required type of data filtering technique is the duplicity read filtering. As the tag enters the RF field of the reader, its EPC is polled by the reader continually as long as the tag resides in the field and is thus reported repeatedly by the RFID reader (for example at 1 s period based on the reader settings). However, from the application point of view, it should be rather interpreted as a single EPC read event. Our duplicity filter implementation is based on marking the EPC reads with time stamps. In case that the time difference between the two reads of the same EPC exceeds given timeout, it is interpreted as a new occurrence of the same EPC in the observed zone (corresponding to a situation when the tag left and then entered the reading zone again). Similarly, the readings of the same EPC that fall into a specified time interval (for example 5 s) are interpreted as a single occurrence of the EPC (corresponds to a situation when the tag still resides in the reading zone). Some more
advanced methods of filtering tag reads over time were
described for example in (Brusey et al., 2003).

Second, even more important processing technique
proposed is the Logical Mapping engine (Macuřek et al.,
2004). It enables to specify the reading locations of interest
hiding the application from details which reader(s) and
which antenna(s) did actually a reading at a particular
location. Usually, there can be up to four antennas
connected to a single RFID reader device, where
each antenna can be used to read tags at different location.
However, to ensure the high probability of a successful
reading, especially in the case of a large number of
tags moving through a particular zone, it is beneficial to
cover that zone by more than one antenna. Sometimes,
it is necessary to use more than four antennas to cover
a particular zone, for instance a dock door, and thus
to use also more physical readers (see Fig. 4). However,
from the control application point of view it might
be annoying or even impossible to process all the data
coming from all readers and sort out what reading
zone they belong to. Logical Mapping mechanism imple-
mented in RFID Manager allows defining separated
reading zones called Logical Readers and associate
the information about the Physical Reader(s) and Anten-
nas(s) that belong to a particular logical reader. The notion
of logical readers can also be found in EPCGlobal
Application Level Events specification (EPC Global,
2005), others use a term symbolic location (Römer et al.,
2003).

In the example depicted in Fig. 3, there is a conveyor belt
with two separated reading zones—the antennas A1 and A2
cover the beginning of the conveyor and the antennas A3
and A4 its end. Although all four antennas are connected to
a single physical reader R1, this can be viewed as two
independent logical readers—LR1 associated with the
antennas A1 and A2 and LR2 associated with A3 and A4.

Any readings from the antenna A1 or A2 are then
interpreted by the Logical Mapping engine as readings
from the logical reader LR1, and respectively, readings
from antenna A3 or A4 are interpreted as readings from the
logical reader LR2.

Another example, depicted in Fig. 4, demonstrates a
different use of the Logical Mapping mechanism. In this
case, eight antennas connected to two physical readers are
used to ensure that all tags going through the dock door
(for example on pallets on a forklift) will be successfully
read. Thus, the logical reader LR1, representing the dock
door reading zone, is associated with all eight antennas.
Readings from any antenna of the physical reader R1 (i.e.,
A11–A14) or from any antenna of the physical reader R2
(A21–A24) are interpreted as readings from the logical
reader LR1.
Another interesting feature of the RFID Manager is that it allows to dynamically change the logical mapping definition to reflect the physical changes to the antennas layout. When, for example, it is recognized that more antennas are needed to empower the reading capability in a particular zone, a particular antenna can be physically removed from its current location in another zone and placed to a new location in the zone where it is needed. At same time, such a change is reflected in the definition of the Logical Mapping engine in the RFID Manager.

The raw EPC data received from readers are processed and filtered in the following way. First, the Logical Mapping engine determines the logical reader entity on the basis of the physical reader and antenna attributes of the EPC record. Second, the filtration module executes sequentially all filters defined in a particular filter group associated with the logical reader entity. Any of the filters applied on currently processed EPC record can decide to discard it, what causes that it is subsequently not stored in the EPC storage. The duplicity filter determines if the same EPC number has already been detected by the same logical reader. If so, and the difference between the time stamps exceeds a given interval, the new EPC record is stored in the EPC storage. Otherwise, the record is discarded. In the system in Fig. 3 for instance, as the two tags are moving through the reading zone at the beginning of the conveyor, the reader can for example report the following sequence of readings (antenna, tag): \((A_1, \text{tag}_1), (A_2, \text{tag}_1), (A_2, \text{tag}_2), (A_1, \text{tag}_1), (A_2, \text{tag}_2), \ldots\). The fact, that the antenna \(A_1\) was not able to read the \(\text{tag}_2\) can be caused, for example, by absorption of the RF waves by the object tagged by \(\text{tag}_1\) (usually in the case when the object contains metal or water). However, such a sequence, when processed by both the logical mapping engine and the duplicity filter, is interpreted as the single reading of \(\text{tag}_1\) by the logical reader \(LR_1\) and the single reading of \(\text{tag}_2\) also by the logical reader \(LR_1\).

4. Integration of the agent-based control with RFID

Multi-agent and holonic systems have been commonly recognized as enabling technologies for designing and implementing next generation industrial control systems featuring such properties like increased robustness, dynamic reconfiguration capabilities, scalability, enhanced adaptability to significant degrees of uncertainty and disturbances, etc. (Jennings, Bussman, 2003). The agent technology is being deployed at all levels of industrial control systems from real-time shop floor control (Mafík et al., 2005), through production planning and scheduling (Pechouček et al., 2007) up to virtual enterprises (Camarinha-Matos, Afsarmanesh, 2001). The common principles in industrial deployment of the agent technology are the distribution of decision-making and control processes among a community of autonomously acting and mutually cooperating units—agents. The agents are autonomous in that sense that under normal conditions they are capable of autonomous control of assigned part or component of the manufacturing process without any central supervision. However, to efficiently contribute to solving the overall goals or to appropriately react to abnormal conditions, like breakdowns, the agents collaborate with each other via message sending. The interactions vary from simple information exchanges to complex negotiations and auctions.

We expect that there is a great potential in the synergy of RFID technology with the agent-based manufacturing control systems. The association of work piece agents, as proposed in this paper, with the physical objects carrying the RFID tags, enables even more efficient distributed control of manufacturing processes. Along with the introduction of RFID agents providing the EPC data to other agents, the new features of such integrated architecture include: (i) enhanced material/product tracking—the work piece agent knows where the associated physical object (product) is currently located and what parts exactly the product is assembled from, (ii) direct negotiation between work piece agents and transportation agents about product routing, (iii) negotiation between product agents and resource agents (machines) about the details of production and (iv) negotiation between the RFID agents themselves and between the RFID agents and work piece agents for example to clarify situations where the work piece has been detected in two separate reading zones at the same time, etc.
There are very few theoretical studies on application of RFID in agent-based industrial control solutions in literature. Bratukhin and Treytl (2006) discuss different criteria for RFID deployment like passive versus active tags, frequency, size of the memory on a tag, etc. Three different categories of product tags are proposed: (i) product identification tag (PIT)—passive tags carrying only the product ID, (ii) product data tag (PDT)—tags carrying all necessary data for production (order specification, activities already performed, etc.) and (iii) product agent tag (PAT)—active tags carrying product identification data and additionally the product agent code. In (García et al., 2006) the proposal of the PROHA methodology as an heterarchical extension of the PROSA methodology (Van Brussel et al., 1998) is presented. It is argued that the multi-agent system model for controlling machining cells can benefit from the integration of RFID technology, although no closer details are given. Another rather general view on how emergent technologies like RFID and agents can positively impact the efficiency of manufacturing operations is described in Holmström, Främling (2006).

Evidently, most of the studies remain on a theoretical level with lack of focus on particular details of the RFID technology integration in agent-based manufacturing control systems. The key characteristics of any multi-agent system are the interactions between agents and, in case of RFID integration, obviously the interactions about the RFID data. Simply, the RFID data must be propagated towards interested agents without requiring the particular agent (controlling for instance operations of a CNC machine) to be able to connect to RFID readers, obtain and filter the data. The original and straightforward solution that is proposed in this paper is based on introducing special RFID agents that, with the help of presented RFID middleware, provide already filtered and processed data to other agents using standard agent communication mechanisms. The RFID agent is suggested to represent particular location of interest, i.e. a logical reader, while the other agents, that want to be informed about what RFID tags passed through that location, can subscribe to the RFID agent to receive this information. Additionally, the work piece agents representing the physical work pieces with attached RFID tags are proposed to enable direct interactions and negotiations between these intelligent entities representing products and other agents controlling the production process.

The proposed integration of RFID technology with agents has been implemented as a part of a pilot Rockwell Automation application called MAST—Manufacturing Agent Simulation Tool (Vrba and Mafič, 2005), providing agent-based simulation and control platform aimed mainly at material-handling tasks. The maturity of the solution has been verified on a real manufacturing scenario—the MAST system has been successfully used for simulating the Packing and Assembly environment at Cambridge University’s Institute for Manufacturing (Fletcher et al., 2003).

4.1. MAST system overview

The initial intention of developing MAST was to have a demonstration tool presenting clearly the major benefits of the distributed, agent-based control on some exemplary manufacturing application. The tasks of material handling and transportation management have been selected because the most common approach used in today’s factories or warehouses is the global routing—the centralized controller maintains the overall state of the manufacturing system and globally controls all particular transportation components, especially switches, to optimally route the products to requested processing stations. This requires, however, to determine all useful paths within the system in advance. Moreover, it is also necessary to take into account possible failures or breakdowns of particular equipment and find out the alternative routing paths for these situations. Obviously, for very complex systems with hundreds of conveyors, switches and stations it might require a tremendous effort for system designers to cover all the possibilities, probably still leaving some situations unaddressed.

The MAST system has been developed by Rockwell Automation to provide more flexible and fault-tolerant material-handling control solution based on the agent technology. The main characteristics is that there is no central controller with all the possible routes precomputed—the decision-making processes are distributed as much as possible over the agents and dynamically adjusted via the inter-agent interactions to react to the actual conditions.

The MAST system is aimed particularly at the transportation of discrete work pieces (products) among the manufacturing cells (machines) on the factory shop floor using a conveyor-based transportation. We have designed and implemented the following basic set of agents for elementary material-handling components (for more details see Vrba and Mafič, 2005):

- The work cell agent that represents a general manufacturing cell, for instance a drilling/milling machine, storage area, assembly machine, docking station, etc. From the transportation task point of view, the work cells are considered as places on a factory floor between which the work piece are transported using a network of conveyors. It is suggested that the work cell has one or more input conveyors through which the products can enter the work cell and one output conveyor used to send products out.
- The conveyor belt agent represents a conveyor belt that transports work pieces between two other components that it is connected to. As the conveyor agent is being instantiated, it informs its neighboring components that it provides the transporting capabilities between them. Thus, as a result of the initialization phase, each agent knows the identity of its topologically immediate neighbors, however, without any one having
the overall view of how all the components/agents are arranged.

- The diverter agent represents a crossing point of several conveyors—it routes work pieces coming from connected input conveyors to different output conveyors in order to navigate them to desired destination work cells. For these purposes the diverter agent holds an up-to-date routing table containing the information of what all destination work cells can be reached from the diverter's location by each of its output conveyors and at what cost.

The routing tables are determined by mutual cooperation of diverter, conveyor and work cell agents that exchange information on reachable destinations along with costs of the delivery in a back-propagation manner (cost of the delivery is specified for each conveyor, expressing for example a time-period needed to pass through the whole conveyor). This dynamic algorithm is carried out during the start-up phase of the system as the conveyors inform their neighbors about established connection as well as during the system reconfiguration, for instance in the case of failures and breakdowns or during the rearrangement of the structural layout of the factory floor (adding new components and/or removing existing components) (Vrba and Mafič, 2005).

4.2. Integration of MAST with RFID technology

To properly route a work piece that has just entered the diverter from some of its input conveyors, the diverter agent has to know the work piece’s identity and especially its desired destination work cell. In the original non-RFID scenario, the MAST system uses a simple mechanism of handing over this information via messages sent between neighboring agents as the work pieces move from one component to the other one. Apparently, such a solution would not be reliable for real systems—when there are no checkpoints in the transportation system where the identity of carried work pieces could be verified, the knowledge held by agents about the work pieces could easily get out of sync with reality. If a work piece is manually removed from or put on the conveyor, the successive diverter's knowledge about awaiting work pieces and their destinations is not updated accordingly and as a result the work pieces will be routed to other destinations than required. This is a point where the RFID can be advantageously utilized. Placing the RFID antenna on each conveyor directly in front of the diverter will ensure that the diverter agent has the exact information about the IDs of entering work pieces.

The RFID-related extensions of the MAST system include the introduction of the RFID agents and the modification of the diverter agent behavior so that it can optionally receive the information about IDs of incoming work pieces from the RFID agents. A schematic overview of a general layout of components that take part in the RFID-based work piece routing is shown in Fig. 5. In this case work pieces come to the diverter from two input conveyors leading from the work cells W₁ and W₂ and can be routed to two different output conveyors to finally reach the destination work cells W₃ and W₄, respectively. There are two reading zones in front of the diverter, LR₁ and LR₂, where the IDs are read. Obviously, these reading zones correspond to the logical reader entities from the view point of the RFID

![Fig. 5. Layout of the components in the RFID-based product routing in MAST system.](image-url)
middleware architecture so each reading zone can be, in the physical system simulated in MAST, covered by one or more antennas or even more readers. In the proposed solution there is an RFID agent associated with each logical reader. The RFID agent registers its capability of reading IDs in a particular zone in the Directory Facilitator (common component of the multi-agent system providing yellow-pages services). The diverter agent, provided by the names of the reading zones, then simply finds the corresponding RFID agents in the Directory Facilitator and subscribes to them.

As the work piece moves through a reading zone, a special component in MAST simulating the physical reader and its antennas emits work piece’s ID in the EPC format that is picked up by the RFID Manager middleware configured such as it recognizes the proper logical reader instance (LR1 or LR2 in the example in Fig. 5). Subsequently, the filtered EPC is propagated to corresponding RFID agent through the RFID Manager’s application interface described in Section 2.1. The RFID agent then sends a message to the diverter agent that a work piece with particular EPC has been detected in particular reading zone, which name is equal to the name of the logical reader.

It cannot be generally assumed that the EPC will contain also the information about the work piece’s destination (for instance when read-only tags are deployed). So, there must be a way how the diverter, having just the ID of the incoming work piece, finds out its destination to be able to route it properly. The original solution implemented in MAST is based on the consideration that each individual work piece is represented by an agent. Such an agent is usually designed as a smart entity that proactively fulfills its own objectives. Basically, it negotiates with the machine agents to perform specific set of operations as well as ensures the transportation of the physical work piece between these machines. Thus, while the work piece is being transported, the associated work piece agent knows exactly what is its current destination, i.e., the name of the next work cell where the work piece will be processed. So it can be queried for its destination directly by the diverter agent. To make this process as simple as possible, it is suggested that the name, at which the work piece agent can be contacted in the multi-agent system, is the same as the EPC number of the physical product (for example a5a5800546728232 in hexadecimal). When the product approaches the diverter and the RFID agent informs the diverter agent about its EPC, the diverter agent sends a query for destination directly to the work piece agent using the EPC as the name of the message receiver. Using this approach the diverter always has the most accurate information on the identity and destination of the passing work pieces. We have successfully tested this solution with both simulated and physical RFID readers involved. In the latter case, two antennas of the Samsys MP9320 reader formed the logical reader LR1 and other two antennas of the Alien 8780 reader formed the second reading zone LR2. Additionally, a passive Alien tag with the fixed EPC number mentioned above was used while all other components, like conveyors and diverter, were simulated in MAST.

4.3. Application of MAST on University of Cambridge’s Packing and Assembly environment

The Packing and Assembly environment at Cambridge University’s Institute for Manufacturing provides a physical testing platform for experimenting with the cutting-edge technologies like distributed industrial control and the RFID. Commercial-of-the-shelf manufacturing equipment such as Montech track conveyor system, Fanuc M6i robots, CheckPoint RFID readers, etc., is put together into a prototype production line, as shown in Fig. 6. Its operations involve packing and unpacking of customized gift boxes filled with different kinds of grooming items like gels, razors, shaving foams and deodorants. There are two different types of boxes, each with three diversely aligned slots that can be filled, according to user order, by any combination of four different grooming items.

The original high-level control system was implemented as a monolithic Java program processing all the sensor values and making overall control decision in a centralized way. Another purpose of that tool was to provide a simulation of the lab’s hardware and processes for testing the control algorithms. Being aware of weaknesses of the original centralized control, Rockwell Automation was asked to use MAST system for developing the decentralized, agent-based simulation of the Cambridge’s packing line.

Besides the implementation of the RFID agent and the modification of the diverter agent so that it is able to interact with the RFID agents, following set of new agents has been implemented in MAST to represent and control

![Fig. 6. The Packing and Assembly environment at Cambridge University's Institute for Manufacturing.](image)
particular components of the lab’s equipment (see more in Fletcher and Vrba, 2006):

- *FANUC M6i robots* that pack the boxes by the items picked up from the storage units.
- *Storage units* (shown in Fig. 6) for temporary holding of the items in four vertical slots (each for a particular type of the Gillette item).
- *Rack storage* that hold shuttle trays with both the empty and packed boxes as well as with the raw items that can be used to feed the temporary storage areas.
- *Gantry robot* that picks the box out of the rack storage and drops it to the shuttle and vice versa.

As proposed, each product (box in this case) is represented by the agent. The product agent plays an active role in coordinating the packing operations by negotiation with the other agents. It includes negotiation with shuttle agents that provide transportation capabilities, interactions with the gantry robot agent to pick up the box from the rack storage and drop it onto a shuttle, negotiation with storage units to select the one that holds the requested items, interaction with a robot agent to pack the items into box, etc.

5. Conclusions

In contrast to the typical utilization of RFID technology today in warehouse management and supply chain applications, the paper presents an architecture for RFID integration at the factory floor level for manufacturing control purposes. Additionally, the first attempt to make the RFID technology available for agent-based industrial control solutions is discussed. The summary of contributions of the papers is following:

- design and working implementation of a lightweight middleware application collecting and filtering EPC data from physical readers and providing them to control applications running on the industrial controller;
- proposal of a logical mapping mechanism enabling to define logical readers representing separated reading zones of interest, that can be physically covered by one or more antennas or even more physical RFID readers;
- design and implementation of the RFID reader agents gathering the RFID data from physical readers infrastructure and providing them to other agents using common agent communication mechanisms;
- introduction of the work piece agents representing physical products that are able—with the help of RFID—to negotiate with transportation agents and other resource agents about the details of production.

One of the main features of the proposed architecture is a high degree of flexibility and dynamic re-configurability. Firstly, new RFID readers can be easily integrated to the system at runtime as there are, for instance, new transportation paths or new machines added to the shop floor. In such a case, a new RFID agent can be created and associated with new reading zones or the existing RFID agent(s) can take the responsibility for these zones by extending its/their information registered in the Directory Facilitator.

Secondly, the functionality of RFID middleware can be dynamically changed by the agents. For instance, when an RFID agent detects a failure of a particular antenna that is used alone to cover a specific reading zone, it can inform the subscribed agents about the temporary inaccessibility of the EPC data from this zone. Concurrently, the agent proposes to the operator to physically move a redundant antenna from another zone and use it instead of the failed one (without the need to reconnect the antenna from the current reader). When it is done, the agent just changes the logical mapping definition in the RFID Manager to reflect such a change. All subscribed agents are then informed by the RFID agent that the reading zone is up again.

The proposed concept has been successfully verified in the lab environment using the MAST system. Two physical RFID readers were used to emulate reading zones located in front of the simulated diverters. The diverter agents were able to receive the EPC data of the moving products from the RFID agents through the RFID Manager middleware and subsequently navigate it properly by querying the product agents for their destination. In the fully agent-based manufacturing control architecture, all the agents are expected to run directly on PLCs. In such a case, it is highly recommended to run also the work piece agents on the PLCs (instead of placing them on a single/centralized computer). The mobility feature of the agent runtime environment enables that the work piece agent can move itself (including its program code and state) among the PLCs to be physically as close as possible to the product as well as to the machine agent(s) that control(s) the actual manufacturing operations.

References


