

WHITE PAPER

The Auto-ID Automation Laboratory: Building Tomorrow's Systems Today

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ABSTRACT

There is no better way to show the benefits of the deployment of Auto-ID systems than through a physical, industrial strength demonstration. This paper overviews the facilities that have been assembled in the Auto-ID Automation Laboratory in Cambridge, UK over the past two years as a means of supporting both research and implementation testing of Auto-ID systems within a manufacturing supply chain environment. The aim of the paper is enable future users of the laboratory (industrial and academic) to fully understand the facility that the Auto-ID Center has developed and the ways in which it might be usefully exploited.

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Biographies



Alan Thorne
Laboratory Manager

Alan Thorne is the Program Manager for the Auto-ID Centre Lab at Cambridge University. Mr. Thorne graduated from Anglia Polytechnic University in Electronics and Control Systems and has a varied background in the field of Automation and Control. He has been involved in British Aerospace/IBM research projects as a systems engineer investigating flexible manufacturing systems on civil and military aircraft production. He has most recently been involved in projects relating to the development of novel AI-based control strategies.



Duncan McFarlane
Research Director Europe

Duncan McFarlane is a Senior Lecturer in Manufacturing Engineering in the Cambridge University Engineering Department. He has been involved in the design and operation of manufacturing and control systems for over fifteen years. He completed a Bachelor of Engineering degree at Melbourne University in 1984, a PhD in the control system design at Cambridge in 1988, and worked industrially with BHP Australia in engineering and research positions between 1980 and 1994. Dr McFarlane joined the Department of Engineering at Cambridge in 1995 where his work is focused in the areas of response and agility strategies for manufacturing businesses, distributed (holonic) factory automation and control, and integration of manufacturing information systems. He is particularly interested in the interface between production automation systems and manufacturing business processes.



Steve Hodges
Associate Director, Auto-ID Centre Europe

Steve Hodges is an Associate Director at the Auto-ID Centre Lab at Cambridge University. Steve received his first degree in Computer Science with Electronic Engineering, from University College London, and received his Ph.D. from Cambridge University Engineering Department in the area of Robotics and Computer Vision. His interests include embedded sensor systems, intelligent devices, computer augmented environments, mobile robotics, image processing, low-power radio communication, mass customization of consumer products and RF tagging technologies.

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Simon Smith
Senior Electronics Technician

Simon studied and qualified as an Electronics Technician obtaining his "Higher National Certificate" while working within the University of Cambridge Engineering Department, gaining a wide variety of skills within the field of Electronics & Electro Mechanical Engineering. Over the last ten years he has been involved in many diverse research projects within the Engineering department, from active suspension control systems, through to quality inspection of railway track finishes after grinding. Simon has joined the Institute for Manufacturing in 2002 as a senior electronics technician, Working within the Auto-ID Centre to help develop current and future phases of the Laboratory environment for both research and demonstration activities.



Mark Harrison
Senior Research Associate

Mark Harrison is a Senior Research Associate at the Auto-ID Centre lab in Cambridge working on the development of a PML server, web-based graphical control interfaces and manufacturing recipe transformation ideas. In 1995, after completing his PhD research at the Cavendish Laboratory, University of Cambridge on the spectroscopy of semiconducting polymers, Mark continued to study these materials further while a Research Fellow at St. John's College, Cambridge and during 18 months at the Philipps University, Marburg, Germany. In April 1999, he returned to Cambridge, where he has worked for three years as a software engineer for Cambridge Advanced Electronics/ Internet-Extra, developing internet applications for collaborative working, infrastructure for a data synchronisation service and various automated web navigation/capture tools. He has also developed intranet applications for his former research group in the Physics department and for an EU R&D network on flat panel displays.

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James Brusey
Senior Research Associate

James Brusey previously worked (for about 13 years) in computer system administration, specialising in IBM mainframe assembler. He received a B.Ap.Sci in Computer Science from RMIT University (Melbourne, Australia) in 1996. He began studying autonomous robot control in 1998 and was a team member and the main software developer for RMIT University's Formula 2000 RoboCup team, which made the finals in the 2000 games.

James' Ph.D. is entitled "Reinforcement Learning for Robot Soccer". It developed a novel approach to bootstrapping reinforcement learning and also examined simulation-based reinforcement learning for a real robot.



Andy Garcia
Senior Research Associate

Andy H. Garcia received his Ph.D. from the Polytechnic Univ. of Madrid as well as an MSc in Electronics and Automation Engineering. He also has an MSc in Mechanical Engineering from Cordoba Univ. (Spain). He has been an Assistant Professor at the Polytechnic Univ. of Madrid, where he also worked in close collaboration with companies such as: Dragados y Construcciones (one year based at one of their sites), Iberdrola, Menasa and more. He continued these collaborations while an Assistant Professor at Carlos III Univ., also in Madrid. After that he became a Projects Engineer at Thyssen Automation, setting up automated warehouses in Spain, South America and the UK, until he joined Castilla La Mancha Univ. (Spain) as Lecturer-Senior Lecturer in Industrial Engineering.

WHITE PAPER

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Contents

1. The Rationale for an Auto-ID Automation Laboratory	5
2. Overview of the Laboratory.....	5
2.1. Conceptual Level Functionality.....	6
2.2. Systems Level Functionality.....	7
2.3. Component Level Hardware.....	8
3. Uses of the Auto-ID Automation Laboratory	9
3.1. Integration, Testing and Demonstrator Development.....	9
3.2. Trialling of Novel, Intelligent Software and Internet Based Ordering.....	10
3.3. Multi Operation Integration, Information Systems Management	11
4. Potential Users of the Auto-ID Automation Laboratory.....	13
4.1. Industrial End Users.....	14
4.2. Hardware Vendor Involvement.....	14
4.3. Software Vendor Involvement.....	14
4.4. Academic Collaboration.....	15
5. Summary.....	15
Appendix I.....	16

1. THE RATIONALE FOR AN AUTO-ID AUTOMATION LABORATORY

The Automation Laboratory at the Cambridge Auto-ID Centre in the UK has been set up to address the challenging task of supporting the research and development of Auto-ID as a global technology. It provides a world class test bed facility for research scientists and engineers investigating various topics from tag reader deployment through to the development of Auto-ID enabled manufacturing control systems of the future.

It is essential that the research work be undertaken in realistic and accurate conditions, so that the subsequent benefits found can be reproduced in real life scenarios. The Automation Laboratory provides these conditions within a controllable and realistic environment, using the latest manufacturing equipment that can be found in production lines today. It is also important to provide conditions that can enable innovative, long term, radical and ground breaking research that is very different from the norm, so the laboratory has been designed to be flexible and re-configurable so that these non-traditional ideas can be easily implemented and investigated.

The Automation Laboratory provides a controlled test environment that can be used for the testing and evaluation of industrial Auto-ID systems in objective settings. Test conditions can be varied in a controlled manner, allowing both equipment and systems to be stressed, thus enabling their operational limits and possible failure characteristics to be explored. This is an essential tool in system development and its subsequent certification before wide spread industrial deployment.

Over the last eighteen months the Automation Laboratory has provided a valuable demonstration facility, with over two hundred guests from a wide variety of disciplines coming and learning about the building blocks of Auto-ID as well as seeing live demonstrations showing the future of manufacturing in an Auto-ID world.

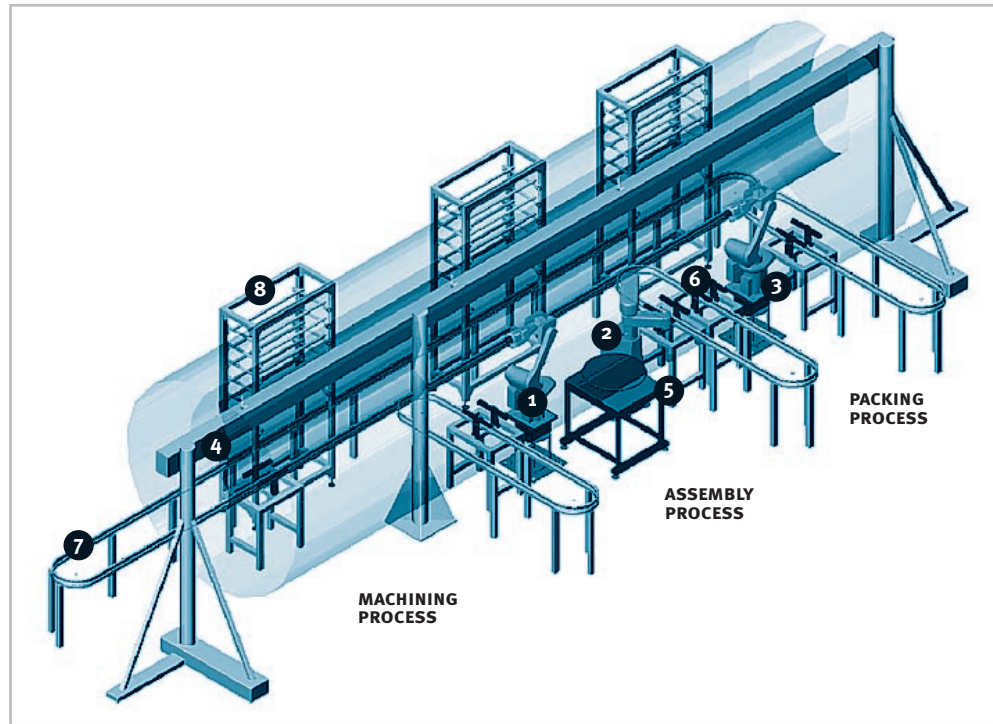
2. OVERVIEW OF THE LABORATORY

The Automation Laboratory is located within the Institute for Manufacturing at the University of Cambridge and covers an area of over 200 square meters. It consists of three flexible manufacturing systems with interchangeable capabilities, allowing them to adopt many different functionalities. A warehouse facility has been distributed between each of these manufacturing systems, providing goods in/out and work in progress capabilities. A monorail style conveyor is used to integrate the three production systems together, providing a dynamic and flexible routing system for the transportation of materials around the facility.

In each of the three production systems an integration area has been provided to allow specialised equipment to be easily integrated into the research work taking place within different production processes. An overview of the facility is given in Figure 1

Figure 1: Overview of the Auto-ID Automation Laboratory

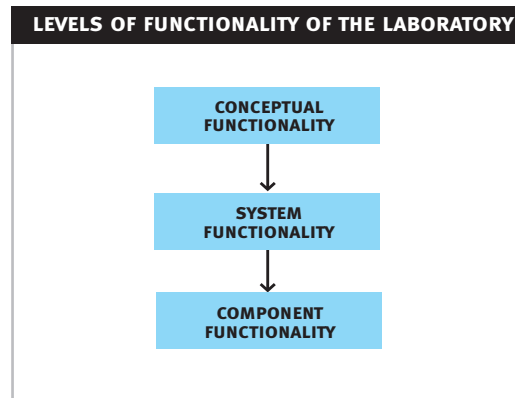
- 1 Anthropomorphic Robot
- 2 Scara Robot
- 3 Anthropomorphic Robot
- 4 Gantry Robot & (Work space)
- 5 Turn table
- 6 Docking Station
- 7 Monorail Conveyor System
- 8 Warehouse Facilities



The laboratory environment is supported with state of the art IT infrastructure, for both commercial and manufacturing environments. This ensures that the latest technologies and systems can be easily integrated into the laboratory research work.

In order to better understand the role and potential of the facility we consider three different levels of functionality, each with increasing levels of focus as in Figure 2.

Figure 2



2.1. Conceptual Level Functionality

The laboratory is intended to be a flexible and adaptable automated systems resource, enabling the replication of many different industrial environments in a realistic but controllable way. It can replicate multiple operational environments and the way in which they interact, effectively reproducing segments

of a manufacturing supply chain. Due to the nature of Auto-ID and the benefits that can be gained at different stages of the supply chain, this controllable “Mini Supply Chain” capability provides a very important facility for testing the interoperation of Auto-ID driven material handling systems which can coexist across a supply chain.

The core supply chain capabilities that are currently being developed are predominantly manufacturing oriented focusing on production, assembly, packing / palletising, distribution and storage. In the near future it is hoped to include some retail capabilities, allowing the interactions between manufacturers’ business systems and retail business systems to be researched and evaluated more closely.

The Automation Laboratory is a very powerful tool, enabling the development of new systems and providing an understanding of how new technologies in different environments will change the way we do business. By recognising and taking advantage of these changes it allows the new systems to be designed, tested and evaluated. This has recently been demonstrated with the integration of Auto-ID technologies into a flexible packaging environment within the laboratory, allowing researchers to understand the capabilities this new technology provides and therefore allowing them to develop new manufacturing control systems that best make use of these capabilities.

Test data generated in the realistic, but controlled environment of the laboratory is essential. It can be integrated back into our simulation tools allowing “Virtual Factory Scenarios”, where a real production process within the laboratory can interact with a simulated production process. This means hardware configurations do not need to be reproduced to test competitive control and scheduling strategies between duplicate systems. Hardware can be focused on providing different but realistic environments within the supply chain.

2.2. Systems Level Functionality

In the laboratory, different pieces of automation equipment can interact with each other, thus performing a variety of industrial tasks or providing different systems capabilities. For example, a robot and a conveyor docking station can interact together as an automated packing station, unpacking station or carry out rework operations on previously packed goods. All of these different system capabilities are available from these two pieces of equipment causing them to interact in different ways.

Currently the development of the system capabilities within the laboratory has focused on processes within the manufacturing supply chain, but we have built in flexibility in the way equipment interacts and is physically configured so that new, unthought-of capabilities can be achieved in the future.

Current system capabilities that exist within the Laboratory;

Localised flexible work in progress buffers are used for the storage of standardised item carriers. These work in progress buffers can be located within the production operations and interact directly the production equipment in their vicinity.

Flexible storage retrieval warehouse system is distributed throughout the laboratory, with each of the three production areas co-located with storage units. The storage system is used to store shuttle tops that are transported throughout the facility by the conveyor system. This provides each of the production areas with goods in/out and a work in progress area. The storage capability is handled by the interaction of both the conveyor system and the gantry robot.

Flexible packaging system; area one within the laboratory provides the functionality of a flexible packing facility. This packaging capability is provided by the interaction of the conveyor system, dual docking stations, anthropomorphic robot and a localised work in progress buffer.

Flexible assembly system; area two within the laboratory provides the functionality of a flexible assembly facility. This assembly capability is provided by the interaction of the conveyor system, dual docking stations, anthropomorphic robot, scara robot, turntable and a localised work in progress buffer.

Flexible machining system; area three within the laboratory is going to provide the functionality of a flexible machining facility. This machining capability will be provided by the interaction of the conveyor system, docking station, gantry robot and a CNC machine tool.

Palletising system; area three within the laboratory will have some free capability allowing for further development. Palletising and de-palletising are key operations that occur between organisations within the supply chain and it is intended to develop these capabilities. A floor mounted docking station and the gantry robot will provide this palletising capability.

Product identity and recognition systems; the laboratory environment has been instrumented with RFID tag readers. The tag readers have been located at key decision points around the production process and integrated with the Auto-ID infrastructure allowing the identity and status of products to be determined.

Real time, LAN based industrial control facility; the control systems used for production operations are divided into two parts, the low level real time control and a higher-level control strategy. The real time control is performed using several Programmable Logic Controllers (PLCs), sequencing their operations over a deterministic network. One of the PLCs has a secondary function, acting as a bridge between the deterministic manufacturing network and standard Ethernet running TCP-IP, thus providing communications with the higher level control system. Some of the production equipment such as the robots, tag readers and network direct devices can be integrated directly into the higher-level control systems over Ethernet.

2.3. Component level hardware

As previously discussed the laboratory has a number of capabilities that are determined by different pieces of equipment and interact in different ways. To ensure the capabilities of the laboratory can meet future demands it is essential that the equipment is as flexible as possible and can support future communication standards allowing easy integration. Although we do not discuss these in great detail at this point, the key categories of equipment available in the laboratory are:

- Material Handling Hardware
- Communications Hardware
- Sensing Hardware
- Controls Hardware
- Control & Information Interface Software

Further technical details on the equipment are given in the Appendix.

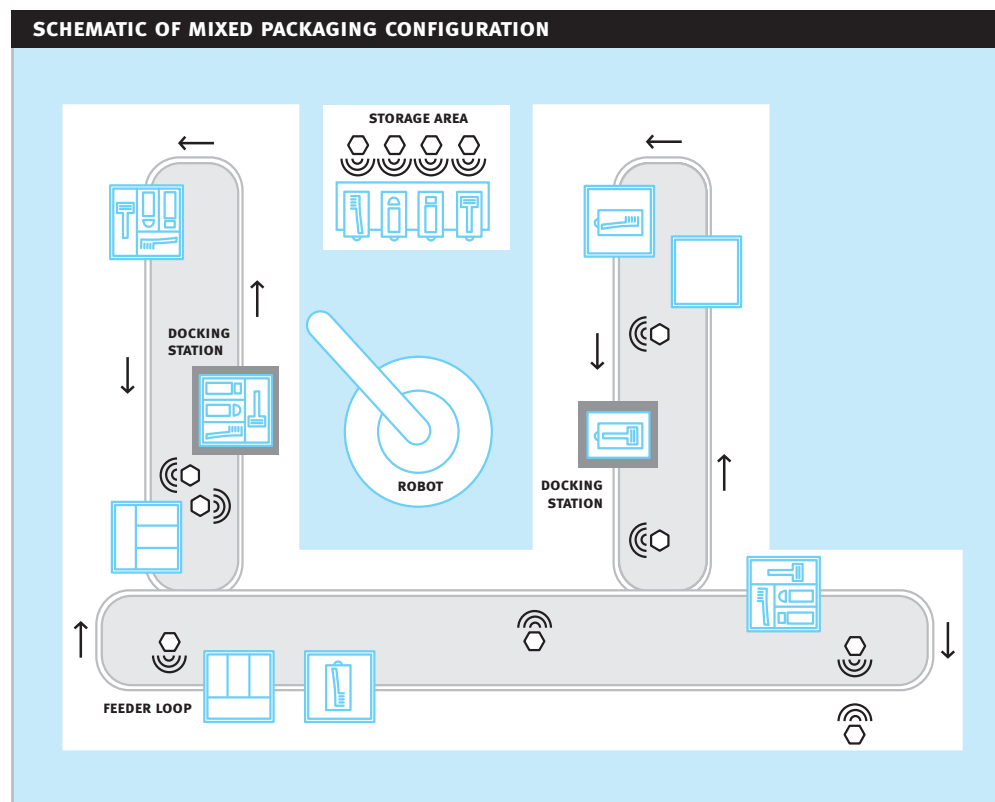
3. USES OF THE AUTO-ID AUTOMATION LABORATORY

In order to illustrate the different ways in which the Auto-ID Automation Laboratory can be used, the following section will look at some of the research work carried out within the laboratory over the last eighteen months.

3.1. Integration, Testing and Demonstrator Development

As part of the **first phase** of the laboratory development existing Auto-ID infrastructure was integrated after development with a conventional industrial control system to provide a simple and clear illustration of the way in which Auto-ID can enhance existing industrial operations. A prototype mixed retail packing configuration was developed for this purpose (see Figure 3).

Figure 3



The objectives of this work were to provide the Cambridge Auto-ID Centre with an environment that could be used for both research and demonstrations. The research work was to show the benefits Auto-ID could provide in the manufacturing sector and the demonstrations were to publicise Auto-ID to the general public and potential new sponsors. It was essential to get the initial building blocks of Auto-ID up and running within the laboratory, installing RFID Tags and Readers, implementing the EPC™ and setting up the Savant server. This was to allow the Cambridge Group to build on these developments in future research.

Through discussions with various Auto-ID sponsors we found that the majority of immediate benefits were in being able to trace packages, such as pallets and cases through the supply chain. As the focus

of the Cambridge Centre was manufacturing, we decided that a packaging system would be a good compromise. This has a number of characteristics that are similar to the palletising of mixed pallets as well as a traditional assembly operation within the manufacturing sector.

The packaging process was designed for one-off customised gift boxes. The system was developed in the laboratory, making use of one of the production areas and then developing a number of the laboratory capabilities, such as the conveyor system, work in progress buffers and the Auto-ID infrastructure.

To help with the adoption of Auto-ID in the short term, the system showed people the benefits that could be achieved by adding Auto-ID to their existing manufacturing systems. The control system implemented for the packing process was of a centralised nature, typical of manufacturing plants today. The Auto-ID infrastructure using current 'off the shelf' RFID technology was then effectively "bolted on to" the centralised control system. This provided a number of demonstrations, showing the benefits that could be achieved by simply integrating Auto-ID with existing manufacturing control systems. It was also a very successful public demonstrator, explaining the building blocks of Auto-ID and providing live demonstrations of Auto-ID in manufacturing to over two hundred guests.

This development phase was a major learning experience, indicating what Auto-ID could do with existing systems, but most important of all, pointing to even greater benefits that could be achieved by developing control systems that can work hand in hand with Auto-ID. References to technical white papers generated from this phase of the Auto-ID research work can be found in Appendix 2.

3.2. Trialling of Novel, Intelligent Software and Internet Based Ordering

In the second phase of the demonstration development knowledge gained from phase 1 was combined within a highly distributed control system environment (based on so called **intelligent agent** software) and with internet based customer interfaces to show further benefits that could be achieved by closely integrating Auto-ID data with systems directly compatible with product-oriented data.

Historically the Cambridge Research Group developed agent based manufacturing systems of the future, providing many of the benefits required in manufacturing today. For example providing machines (elements of a manufacturing plant) with a plug and play capability allows them to be easily swapped during hardware failure modes or to be replaced by newer models. In the future, this enables reuse of expensive equipment within modified or new plants, by providing a "plug in and go", reconfiguration capability. It is also essential that production systems become more flexible. Manufacturers are continuously developing and extending product ranges, where small changes to the design of an existing product have to be catered for. Customers are becoming more demanding and this requires customisation of products to meet their specific needs.

To implement this type of control system, the different physical elements that perform the operations of the manufacturing plant are broken down into resources. Each of the separate resources is controlled by self-contained pieces of software called "resource agents". Each of the agents has its own identity, behaviour, communications and functional capabilities.

Auto-ID is a real enabling technology for these types of control systems, as it allows the unique identification of different products and their status to be determined at decision points around the production system. It allows an associated software agent called a "product agent" to escort the physical product around the production system. The product agent makes use of PML (Physical Mark-up Language) as a "recipe" for the process steps that must occur in the production of the product. To ensure that the production process occurs in "best manner", the product agent negotiates with the different resource agents to get itself

manufactured and therefore by changing the PML “recipe” the production process of the product can be changed, allowing for easy customisation of products. In the unfortunate situation that a piece of production equipment fails, the associated resource agent goes off-line and the product agent will have to ascertain the capabilities of other resources to get itself manufactured. This means that the production line degrades in a graceful manner, allowing limited production rather than a catastrophic failure and an expensive stop in production.

Auto-ID provides global standards that can be adopted throughout the supply chain. Within the research work at Cambridge we have endeavoured to demonstrate how these standards can be applied within the manufacturing sector. This was effectively demonstrated, in a limited fashion during the Atlanta board meeting in February 2003. An implementation of an ordering system was used to generate PML data representing a production order that need to be completed. The order was submitted via the internet to the remote production facility in Cambridge UK. The PML data representing the order was interpreted by manufacturing control systems to allow the production of the customised gift boxes. At the same time a graphical user interface being updated with Auto-ID data was used in Atlanta US to provide real-time remote monitoring of the production facility in the UK, and showing the status and location of completed products and work in progress. This is important functionality and will allow future developments where factories around the world will be connected together across the Intranet, allowing them to advertise their capabilities and work loads, bidding and co-ordinating with other production facilities on a global level to obtain future production contracts.

The successful completion of phase two really demonstrated the benefits that Auto-ID could provide if the supporting systems are designed correctly and the power PML brings to this global technology. The controlled environment of the laboratory was essential in developing and debugging this system, as it allowed duplicate repetitive production runs to be performed and provided the tools to understand exactly what conditions were occurring at different levels within the control systems.

References to technical white papers generated from this phase of the Auto-ID research work can be found in section 4.2.

3.3. Multi Operation Integration, Information Systems Management

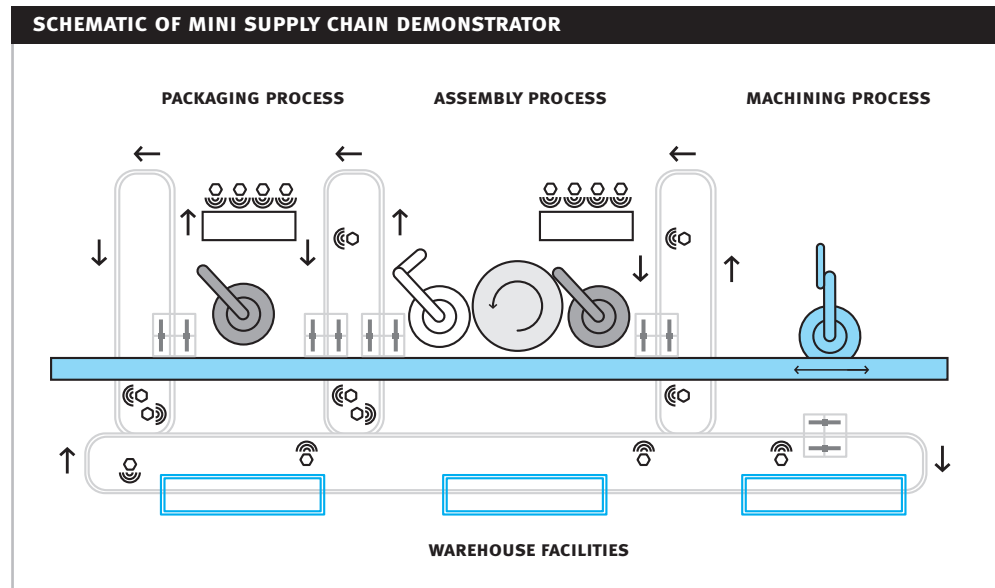
The great gains from deploying Auto-ID systems will come from the ability to integrate product information across different elements in the supply chain. Currently the Center is installing hardware in preparation for the phase 3 developments of the automation laboratory which will support the understanding and development of such capabilities. From the previous phases we have managed to implement many of the building blocks that are required to demonstrate concepts of Auto-ID.

The long-term goal is to demonstrate how Auto-ID can be implemented throughout the three main stages of a manufacturing supply chain, namely:

- 1) machining of the raw material into parts
- 2) assembly of the parts into a product
- 3) final packaging of the product (at multiple packing stations)

This is illustrated in Figure 4. In order to understand the range of features being developed in the laboratory to support the multiorganisational issues for Auto-ID we now take a detailed look at the type of operations that can be performed.

Figure 4



The scenario for Phase 3, involving a mini supply chain extends the previous work and will look at communicating Auto-ID data between different organisations, using the ONS, distributed PML services and the integration with other business information systems.

The first two phases developed the packaging stage of the supply chain demonstrator. Phase 3 will add the second organisation to this supply chain, the assembly operation (which is also capable of packing if needed). Due to the limited time available and the requirements to focus on Auto-ID issues, the assembly operation will be very basic, allowing easy integrating into the existing packaging process of the Gillette gift boxes.

Assembly: The assembly operations that Gillette performs in the manufacture of the products used in the packing cell are very complicated and outside the bounds of this project. Currently the Gillette parts are supplied to the packing process in easy to handle tagged plastic carriers. This “assembly” or pre-packing of the Gillette products into the different types of plastic carriers is a fairly simple assembly operation to automate and can provide the operational requirements of a second organisation. As can be seen in fig. 1, the assembly cell consists of two different types of robot on either side of a shared turntable. The configuration of the anthropomorphic robot has been set-up to duplicate that of the original packing cell. This will allow the interaction of a second organisation to be set-up quickly, allowing research to be carried out and investigating how the packing operation can be split between two separate organisations.

The second robot uses a very different joint configuration from the anthropomorphic type robot. This different style of machine is very useful, as it will enable us to test some of the recipe research work that will be linked to PML. This is investigating the conversion of generic high level recipes into instructions for specific machines. By describing machine operations using high level recipes, true flexibility can be obtained, as different types of robots with overlapping physical capabilities can perform the same operation.

PML can be used to help with these types of problems, capturing real position and dimension data about products being handled at a particular moment in time. Up until this point all the material

handling operations that the packing cell has performed has used pre-programmed pick and place locations stored within the robot controller. The requested sequence of operations to be performed has been captured in a “recipe” within PML; future research work should be able to link this sequence of operations with real position information.

Warehouse: Until now, goods inbound or outbound from the packing cell were left to circulate on a main conveyor loop, dramatically limiting the scale of the scenarios that could be handled within the laboratory. With the phase three developments to include multiple organisations, each of these organisations will be serviced with warehouse facilities. This will enable materials to travel in a traditional fashion between the two “separate” organisations within the laboratory, but has additional benefits as it allows us to research some of the interesting applications that can be achieved by integrating Auto-ID into warehouse environments and hand-over operations.

Materials Handling: In manufacturing, the reusable item carrier assumes the role of the simple pallet within the supply chain. Auto-ID can bring some immediate benefits to the use of these items, such as location, identity and time. The phase 3 developments will allow reusable item carriers to deliver multiple parts to the assembly cell. This will allow research to investigate the benefits that can be gained by adding additional instrumentation to the carrier, such as tag readers, for determining the identification of parts located on the carrier, as well as extra sensory information required. The carrier would have some built-in intelligence capability, allowing firmware to self-generate PML and transponder technologies to share this information with other business systems.

With the extra elements that are being integrated into phase three of the Auto-ID demonstrator, as listed above, many new research topics will be possible in the future, some of which are listed below.

- Demonstrate a product recall and its subsequent rework.
- Development and testing of a PML server.
- Providing PML from different manufacturers using ONS.
- The recycling or disassembly of an Auto-ID enabled product.
- Interpreting high level recipes to specific machine instructions.
- Integration of Auto-ID systems with network direct devices.
- E-Manufacturing/co-ordinated manufacturing of remote facilities.
- Examining RFID tag reader research and subsequent deployment strategies.

4. POTENTIAL USERS OF THE AUTO-ID AUTOMATION LABORATORY

The previous section was intended to provide an overview of some of the capabilities available within the Auto-ID Automation Laboratory. As discussed earlier, one of the aims of this paper was to clarify the way in which the laboratory might be able to support future developments in Auto-ID based systems – both in terms of industrial and academic activities. In this final section we simply summarise the type of development that different players in the Auto-ID area might consider undertaking. We have dividing the activities under the categories of

1. industrial end users (retail, distribution, manufacturing)
2. hardware vendors
3. software vendors
4. academic collaborators

We address each of these separately below:

4.1. Industrial End Users

End user organisers often perceive a test facility to be the domain of the equipment and software vendor but there are in fact a number of key instances where it is advantageous for an end user to be involved in and possibly drive a test environment. Particularly, in situations such as the Auto-ID project where global standards plays such an important role it is often highly desirable that end users direct any evaluations and developments to ensure the needs of the ultimate users are taken into account. Additionally, a test facility can provide a location for a prototypical development which may then be transferred to an end user site at a later stage. Activities that might be performed for an end user in the Auto-ID Automation Laboratory include

- evaluating different hardware components (e.g. readers).
- evaluating different system configurations.
- developing demonstrations for in-house awareness.
- developing prototypical systems for transfer to own facilities.
- collaborating on a focus issue with several other end users.

4.2. Hardware Vendor Involvement

The automation laboratory provides an environment where hardware vendors can readily install a variety of equipment for testing and evaluation. All aspects of the deployment should be straightforward, such as physically installing apparatus, providing a communications mechanism, and interfacing with the appropriate software system. This standard environment not only eases deployment of vendor hardware, but also provides a common baseline for comparison of the differing features and performance of different products (from the same and from different vendors)

The key opportunities for a hardware vendor include:

- Testing equipment in a standard environment with standard performance targets
- Examining integration implications for their equipment
- Demonstrating equipment capabilities to potential customers.

4.3. Software Vendor Involvement

Software vendors can install their software products onto the computer systems in the laboratory in order to experiment with how their software products will function with leading-edge manufacturing hardware. State of the art PC hardware platforms and operating systems are supported within the laboratory, together with modern networking facilities, to aid the coupling of the vendors' software with the laboratory's industrial equipment. This forward-looking environment provides an excellent opportunity to explore the spectrum of possibilities associated with connecting and experimenting with the interfaces between software and industrial-strength hardware. Software that can interface with automation and robotic equipment in a standard manner has an increased commercial value because it can be readily sold to a range of industrial customers who use that equipment. The fact that the equipment in the laboratory conforms to international industrial standards means that vendors need only develop a few (if not a single) interface in order for their software product to interact with and control the equipment in question.

The laboratory provides an excellent non-competitive facility to explore the potential for linking a vendor's software products with software from other companies. On a technical level, this aids building software systems that are interoperable, and whose combination can support a wider range of functionality or handle greater complexity than could be accomplished by any single piece of software. The laboratory environment also helps the vendors come together to create joint prototypes and illustrate how their combined software can work for existing and new customers. On a commercial level, the laboratory creates an atmosphere whereby vendors are able to come together to make strategic alliances concerning their future software development and create policies that do not interfere with each other. The laboratory also provides a means to exchange 'non-confidential' know-how concerning common technical issues.

In summary, key options for the software vendor include:

- Testing and Evaluating software on a standardised, industrial strength system.
- Demonstrating vendors' systems to potential customers.
- Integrating own software with 3rd party or research prototype software

4.4. Academic Collaboration

The academic research literature in industrial automation tends to be dominated by approaches and methodologies that, where they are tested at all, are generally tested under simulation. It is our contention that critical lessons about the nature of industrial automation cannot be derived from simulation alone. We feel that it is essential that, for research results to be well grounded, that they must be tested on physical robots, not just simulated ones. In addition, data from the real system can be fed back into the simulation, thus making the simulation more realistic.

The simulation tools developed so far allow remote researchers to develop control systems and to trial different implementation methodologies, without having to have access to the physical hardware. In addition, since the simulation test harness provides the same interfaces as the physical hardware control system, once these control systems have been developed, they can also be tested on the physical hardware.

This facility has the potential to allow remote researchers to test their ideas and obtain performance measurements from a real industrial automation laboratory, thus helping to bridge the gap between theory and practice in industrial automation, and specifically in the application of Auto-ID to industrial control.

5. SUMMARY

This brief report has introduced the state of the art Auto-ID automation Laboratory based in Cambridge, UK. Through careful planning, a highly flexible facility has been developed which is relevant to all stages of supply chain operations. Key features of the facility have been described in some detail and its role in supporting both industrial demonstration and academic research outlined. The facility is expected to be completed in its final phase in August 2003 and will be available for academic & commercial developments in the Auto-ID and industrial automation areas.

APPENDIX I: DETAILS OF AUTO-ID AUTOMATION LABORATORY EQUIPMENT

For completeness, this appendix outlines the details of the different facilities available in the laboratory.

A.1. Material Handling Hardware

2 Anthropomorphic Robots

The Fanuc M6i is a newly developed industrial robot that is very agile. It is ideally suited to arc welding and material handling applications. It has six degrees of freedom and is capable of handling a 6Kg load within a radial arc of 1.3 meters. The robot is controlled by a J3 controller allowing communication interfaces via Ethernet or Profibus or standard I/O.

1 Scara Robot

The Fanuc A520 is capable of handling heavy wrist loads, making it ideally suited to assembly operations requiring high Z loads and material handling applications. It has four degrees of freedom and is capable of handling a 30 Kg load within in a radial arc of 0.9 meters. The robot is controlled by a Fanuc J2 controller allowing communication interfaces via Ethernet or standard I/O.

1 Gantry Robot

The Fanuc M16i T Bar robot is an anthropomorphic robot that is inverted and suspended from a 12M beam. It is ideally suited for part picking, palletisation, multi-equipment applications and material handling applications. It has six degrees of freedom, one of which is the 12M beam and is capable of handling a 16Kg load. The robot is controlled by a J3 controller allowing communication interfaces via Ethernet or Profibus or standard I/O.

1 Conveyor Transport System

A Montech monorail transport system is used to transport materials around the laboratory using self-propelled shuttles. It consists of a main supply loop running the length of the laboratory, with three offshoot feeder loops supplying materials into the production processes. This system is ideal for the laboratory environment, as it can be quickly adapted to fit new scenarios. The control of the gates for routing materials and the stop/start functions of the shuttles are controlled by various PLCs within the laboratory.

5 Docking stations

The conveyor system is fitted with Montech docking stations at various locations within the three production areas. The docking stations can accurately locate one shuttle top at any time allowing a material handling or assembly operation to be performed. The mechanism for locating and releasing shuttles within the docking stations is controlled by the PLCs within the laboratory.

2 Work in progress buffers

General purpose buffer units have been manufactured in house and can be integrated into different production processes. The units consist of four first in/first out buffers, each able to handle up to eight universal item carriers.

3 Warehouse/Storage facility

A flexible storage facility has been developed using Montech Quick Set, enabling a wide variety of different size storage zones to be configured. The storage facility uses Montech shuttle tops as a standard storage medium and holds up to 18 shuttle tops on six levels. Shuttle tops can be automatically placed and removed from the storage system by the gantry robot.

8 Shuttles

The Montech shuttles are used to transport materials around the conveyor system at 30m/min, on 300mm x 400mm shuttle plates and with a payload of 17Kg. Built into the front of the shuttle is a sensor, automatically controlling the distance between itself and the shuttle in front. Start /Stop control signals are picked up from the track.

A.2. Communications Hardware

1 Deterministic Network

The lab supports a deterministic network, the Omron SYSMAC-LINK. This runs at 2Mbps over a length of co-axial cable that runs the length of the automation laboratory. This network is bridged to the Ethernet network using an Omron CV500 PLC with both a SYSMAC-LINK module and an Ethernet module installed.

30 Structured Wiring

In addition to the deterministic industrial network for traditional networked sensing and control of equipment, extensive structured wiring is also installed. This takes the form of 30 Category 5 UTP cable runs between outlet plates throughout the lab and a central patch panel. The Cat 5 cable, which contains 4 twisted pairs of conductors, is suitable for several different types of existing networking equipment and is also likely to be suitable for future networking technologies.

Ethernet

Currently the structured wiring is used to carry ethernet traffic throughout the lab, enabling easy (re-)deployment of network-direct devices (see below), computing resources and networked automation equipment. The ethernet infrastructure takes the form of a number of hubs and switches, and a single Cisco router, which interconnect the equipment connected to structured wiring outlets in the lab with each other and with other computing resources in the building. All the ethernet equipment concerned runs IP (the internet protocol), in most cases supporting both TCP/IP and UDP/IP traffic.

1 Internet

In addition to network connectivity within the automation lab and the building as a whole, there is also connectivity through to the Internet itself. This takes two forms; we have access to the Internet through JANET, the high-speed Joint Academic NETWORK used by UK universities and we also have a 2Mbps commercial Internet connection (supplied by British Telecom). This enables us to genuinely demonstrate operation of connectivity across the Internet, and also provides us with a mechanism to prove operation under two very different networking setups and policies.

A.3. Sensing Hardware

8 Tag Readers

A number of Checkpoint 13.56MHz readers are installed in the lab. Eight readers are situated near to the conveyor transport system (at various points along its length) so that they can detect any tagged items that move along the conveyor. In addition, four readers (with a more tightly defined read range) are used to monitor the identity (and location) of items in the work-in-progress buffer. All of these readers interface through to the lab Ethernet for easy integration. The capability to read UHF tags as well will hopefully be added in the future.

2 Network Direct Devices

In addition to the hard-wired sensors and actuators that are deployed as part of the automation hardware in the lab, there are also a number of ethernet driven networked devices. These 'network-direct'

device, which include sensors and actuators, offer a number of advantages over their more traditional counterparts: they are easily re-deployed to different physical locations for experimentation and re-configuration of the lab; they are easy to configure and monitor, by virtue of a built-in web interface; they are able to monitor and log their performance to aid with maintenance and production monitoring.

A.4. Control Hardware

3 Omron PLC's

The Omron Programmable Logic Controllers that have been deployed in the Laboratory to support a wide scope of applications. They are used for real-time control of production resources.

2 of C200H Alpha, Supporting (1184 I/O Points, 5/8/12/16/32/64 bit I/O Modules, 64K of Program capacity, 0.1uS instruction times, 102K of data memory)

1 of CV500 Supports (2048 I/O Points, 8/16/32/64 bit I/O Modules, 62K of Program capacity, 0.125uS instruction times, 24K data memory) The modularity of these PLCs is essential as it allows integration of many different features, such as communications and I/O standards.

4 Ethernet Based Robot Controllers

The robot controllers used within the laboratory support a high variety of communications and I/O capabilities. (Ethernet, Profibus, DeviceNet etc.) This is important, because the robots' controllers have to be closely interfaced with the manufacturing control systems at high level. Fanuc provide a number of tools to interface with their robots from different platforms and environments.

3 Rockwell Logix Controllers

A new addition to the Laboratory (Mid 2003) will be the Rockwell Logix PLCs. These support a Java environment and will allow the resource software agent to be run at a very low level, in effect on the production equipment.

A.5. Control Software

HCBA Software Architecture

The Holonic Component Based Architecture (HCBA) attempts to resolve the problem of migrating to a holonic architecture by making use of intelligent building blocks focused around resources and products. The building block approach is derived from the Component Based Development methodology and is intended to allow a holonic system to be built up by plugging reusable components together. A key characteristic of the HCBA architecture was the use of a Blackboard System (BBS) to communicate with hardware controllers such as Programmable Logic Controllers (PLCs). The main characteristic of the BBS is that it provides a flexible, unstructured way to communicate with the PLC.

JACK Agent-based Programming Language

This system is comprised of a development environment, a compiler and a run-time environment. JACK produces an output Java source code, which is then compiled and executed in the usual way. The agent system is roughly based on the Belief Desire Intention (BDI) model. Apart from being object-oriented (as it is built on Java), JACK also has "agents", "plans", "beliefs" and "events" as first class entities of the Programming environment.

Savant Auto-ID Systems Interface

A key part of any robotic system involves sensing the state of the environment. The JACK control system uses Auto-ID information to identify the position of parts in the manufacturing system. However, raw information from the tag readers is noisy and needs to be filtered. Savant(tm) from Oat Systems provides a mechanism for pooling and filtering tag reads.

GRASP Robotic Simulation Environment

Alongside other work on the phase 2 robotic packing cell, a GRASP(tm) simulation was built. This simulation demonstrated how the final cell would operate in three dimensions. In addition, it is a portable tool for exploring the characteristics of the Cambridge Packing Cell and the use, more generally, of Auto-ID for control.

A second, less graphical, simulation has also been built to allow the JACK control code to be extensively tested without making use of Hardware. This “test harness” is not specific to the JACK system and could be used to test other forms of control software. Although this second simulation lacks 3D graphics, it can support fast cycle times to allow learning all or part of the control system using a learning method such as Genetic Programming, Neural Networks, or Reinforcement Learning.

Wonderware Scada Database Tools

A new addition to the Laboratory (Mid 2003) will be Wonderware’s ArchestrA package thus allowing the three Laboratory production environments to be linked to the different modules that Wonderware support, such as Historian, Visualisation, InControl etc. This will also enable links into business information systems, allowing interactions between the three production processes at a business level.

APPENDIX II: AUTO-ID AUTOMATION LABORATORY RESEARCH OUTPUTS (2001-2003)

Table 1

RESEARCH GENERATED IN PHASE 1		
PML Server	Apache webserver and server-side scripts (CGI/ModPerl) with specific methods dedicated to the automation lab	“Auto ID Based Control – An Overview”, D McFarlane, 2002, www.autoidcenter.org/research/cam-autoid-who04.pdf
Orders	Only 1 box per order	
User Interface	Web interface for order placement and basic quality control Single customer placing orders	“Auto-ID Based Control Demonstration Phase 1: Pick and Place Packing with Conventional Control “, S. Hodges, A. Thorne, A. Garcia, J. Chirn, M. Harrison, D. McFarlane, 2002, www.autoidcenter.org/research/cam-autoid-who06.pdf .
Recipes	Specify for each box a sequence of three items to be packed in the box (bill of materials only) Only performed by one robot. Sequence of items interpreted by conventional top-down control system.	
Control	Simple monolithic control (Visual Basic)	“Development of a Prototype PML Server for an Auto-ID Enabled Robotic Manufacturing Environment”, Mark Harrison, Duncan McFarlane, www.autoidcenter.org/research/cam-autoid-who10.pdf

Table 2

RESEARCH GENERATED IN PHASE 2		
PML Server	SOAP service written in Perl with three generic methods – getpml(epc) – read(epc, path) – write(epc, path, value) Allow direct read/write access to fragments of the PML data at any hierarchical position in the PML data as specified by the XPath expression.	“Development of a Prototype PML Server for an Auto-ID Enabled Robotic Manufacturing Environment”, Mark Harrison, Duncan McFarlane, www.autoidcenter.org/research/cam-autoid-who10.pdf “Auto-ID Based Control Demonstration Phase 2: Pick and Place Packing with Holonic Control”, James Brusey, Martyn Fletcher, Mark Harrison, Alan Thorne, Steve Hodges, Duncan McFarlane www.autoidcenter.org/research/cam-autoid-who11.pdf
Orders	Batch orders consisting of multiple elements, each element specifying a quantity of a particular box configuration, as well as a priority for each element of the order	

Continuation of Table 2

User Interface	<p>Web interface for order placement and more sophisticated quality control – indicates serial-level swapping of contents</p> <p>Supports orders from multiple customers</p> <p>New web interface for remote control of cell (disabling/enabling of docking stations) and remote visualisation of location and contents of shuttles, inventory in work-in-progress storage chutes, quality control</p>	<p>“Auto-ID’s Three R’s: Rules and Recipes for Product Requirements”, Duncan McFarlane, James Carr, Mark Harrison, Andrew McDonald, www.autoidcenter.org/research/cam-autoid-who08.pdf</p> <p>“The Story of the Holonic Packing Cell” M. Fletcher, J.P. Brusey, 2nd International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS’03), Melbourne, Australia, published by the ACM, July 2003.</p>
Recipes	<p>Specify for each order element a quantity of boxes and sequence of three items to be packed in each box (bill of materials only)</p> <p>Only performed by one robot</p>	<p>“Evaluating the Holonic Packing Cell” M. Fletcher, D. McFarlane, A. Thorne, D. Jarvis, A. Lucas, 1st International Conference on Applications of Holonic & Multi-Agent Systems (HoloMAS’03), Prague, Czech Republic, published by Springer Verlag, September 2003</p>
Control	<p>Agent-based Holonic Control using JACK’ Agents (a Java language extension)</p>	<p>“The Cambridge Packing Cell – A Holonic Enterprise Demonstrator” M. Fletcher, D. McFarlane, A. Lucas, J. Brusey, D. Jarvis, International/Central and Eastern European conference on Multi-Agent Systems, Prague, Czech Republic, June 2003</p> <p>“The Diverge of Theoretical and Actual Designs in a Holonic Packing Cell,” M. Fletcher, D. McFarlane, A. Lucas, J. Brusey, A. Thorne, at the 7th IFAC conference of Intelligent Manufacturing Systems, Budapest, Hungary, April 2003</p> <p>“The Impact of Auto-ID Technology in Material Handling Systems”, A. Garcia, D. McFarlane, A. Thorne, M. Fletcher, at the 7th IFAC conference of Intelligent Manufacturing Systems, Budapest, Hungary, April 2003.</p>

