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A Working Model of a Manufacturing Enterprise with Internet Control*

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This paper outlines the development of a working model of a manufacturing enterprise, consisting of a manufacturing system, a warehouse and a customer. A model train is used to ship the goods between the three stages. The model can be viewed and controlled interactively on the Internet. This means that the user can explore different operating strategies to optimise the performance of individual components or the manufacturing enterprise as a whole, in terms of delivery time and total cost. The manufacturing enterprise model is built using LEGO and controlled by LabVIEW. The complete model and its controlling software was developed by a group of engineering students as an undergraduate project. The paper also discusses the educational advantages of developing and using such a system.

INTRODUCTION

THIS PAPER outlines the development of a working model of a manufacturing enterprise, which can be viewed and controlled interactively on the Internet. The model was developed as part of the Undergraduate Research Opportunity Programme (UROP) which allows undergraduate Mechanical Engineering students to experience a research project in the vacation period between the first and second semester at Nanyang Technological University in Singapore. The project was specifically designed with these time constraints in mind and so it was important that the objectives could be met in the six-week project period.

The finished manufacturing enterprise model (Fig. 1), which is built using Lego Dacta consists of three components: a manufacturing system, a warehouse and a customer location (Fig. 2). The manufacturing system incorporating a feeding, production and inspection station 'makes' small components. At the inspection stage, a light sensor distinguishes between good and bad products; rejected parts are dumped in a bin and good parts are loaded onto a train, using a robot arm. The products are then shipped via the train to a warehouse. The warehouse consists of a racking system, which stores the components. The customer can order different quantities of parts depending on his requirements. If the warehouse has the required parts in stock, the goods will be sent to the customer using the train. If not the warehouse will send an order to the manufacturing system which will make the parts. The concept is loosely based on the Beer Game. [1, 2]

The model is controlled via a control panel developed using LabVIEW on which the user can select the number of parts to be ordered, and receive updates of the number of parts made, inventory levels and shipments. The control panel also displays a video image of the model, obtained from a camera mounted above the model. The user is able to remotely pan and zoom the camera through the computer. The control panel and camera can also be accessed through the Internet so that a user is able to take control of the model from anywhere in the world.

The user is thus able to explore alternative strategies for running the manufacturing enterprise by changing the configuration of the system through the virtual control panel. It is important, for example, to reduce inventory levels in the warehouse whilst responding to customer demand. In practice, this balance can be hard to achieve. The model therefore demonstrates the dynamics of a simple supply chain, which is particularly relevant to Singapore, where logistics management is recognised as a major area of growth in the next millennium. The model also illustrates the potential of the Internet as a major tool for developing a collaborative environment, where information is shared across different echelons of a supply chain.

Various elements of the development reported here have been used for education and widely reported in literature. However it is believed that this is the first time a working model of a manufacturing enterprise has been controlled over the Internet.

There are several examples of the remote operation of equipment across the Internet. For example Carnegie Mellon University in the United States [3] and the Federal University of Santa Catarina in Brazil [4] each have laboratories which allow the remote operation and control of equipment across the Internet. Taylor and Trevelyan [5] discuss the

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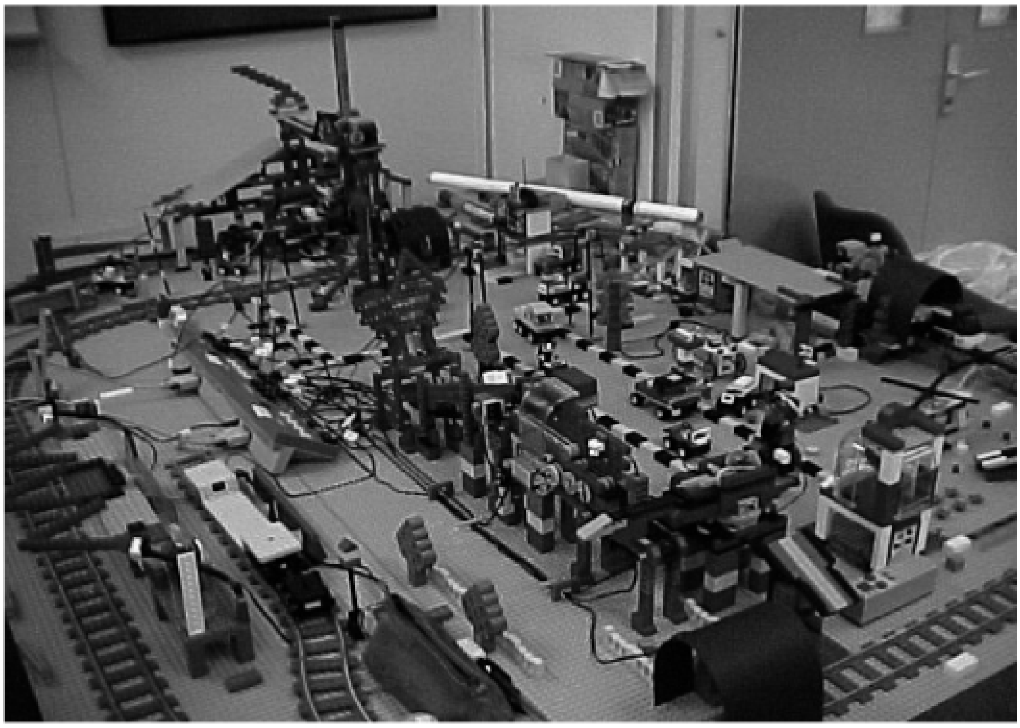

Fig. 1. Lego model of manufacturing enterprise.

remote operation and programming of an industrial robot across the Internet. Of particular interest is a model railway with Internet control developed by the University of Ulm in Germany [6, 7]. A feature of the system is that if several users access the site simultaneously, they can join a queue to take control of the train.

There are numerous examples of the use of LabVIEW in education. Its capacity for data acquisition and control, graphical programming and the creation of virtual instruments make it a natural teaching tool for laboratory projects. Examples include McStravick and Kelley [8], Sherry and Lord [9] and Stegawski and Schaumann [10]. Of particular relevance are projects by Palotai [13], who reports the development of a control system for a warehouse model and Park [14] who discusses the control of a miniature flexible manufacturing system using LabVIEW. Recent developments in Internet technology provide the user with even greater flexibility. ComponentWorks (a sister product of LabVIEW) provides ActiveX components so that the sliders and switches of a virtual instrument can be accessed by an interactive user interface on the Web. A Visual Basic platform can then be used to develop the user interface, by providing a container for the ActiveX components. These features limit the developers and users to Windows platforms and the users to MS Internet Explorer on Windows platforms. Examples of such experiments have been reported by Gilet and Salzmann [15], Pee [16], and Dutcher [17].

LEGO has been used increasingly in the educa-

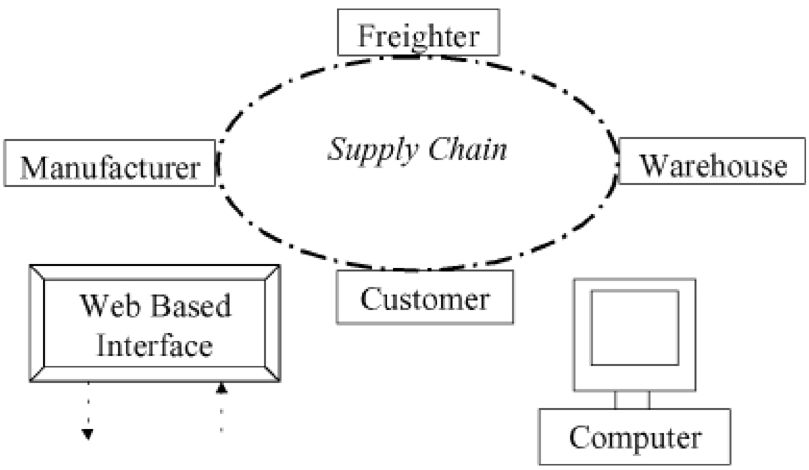

Fig. 2. Schematic of manufacturing enterprise model.

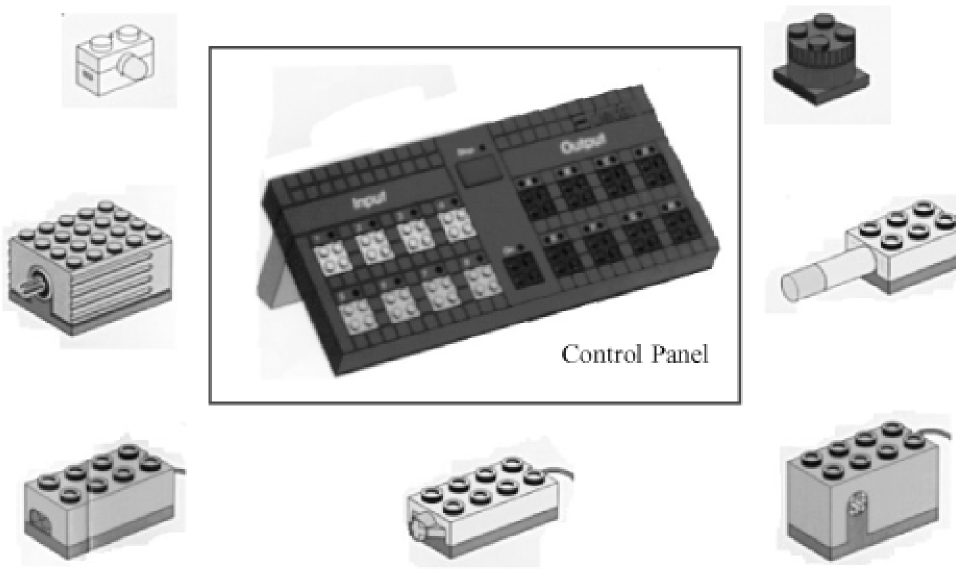

Fig. 3. Interface box and sensors.

tional environment (for example McKenna and Agogino 18]. Cyr [19] of Tufts University replace the standard Lego Dacta control lab software with a LabVIEW software interface. This seamless integration of LabVIEW and LEGO provides a versatile teaching environment which can be used at all educatonal levels [20]. Tufts University has developed a LabVIEW interface and a set of drivers (LegoEngineer) for the Lego Dacta serial interface box. (See the Data Acquisition and Prototyping System (LDAPS) web site—http:// ldaps.ivv.nasa.gov/index.html—for more details.)

The same team has also developed Robolab, a similar interface for the RCX, a programmable Lego brick that allows a program to be downloaded to the brick via an infrared interface, thus alleviating the need for PC control [21]. Although Robolab has significant educational potential, it is not as relevant for Internet control. The system developed in this paper, therefore, uses the LegoEngineer software. Osborne [22] demonstrates the potential of using this configuration for remotely controlling Lego products across the Internet by developing an interactive drop tower, which is controlled through the World Wide Web.

This paper is organised as follows. The following section presents a detailed description of the components of the model and its development. The

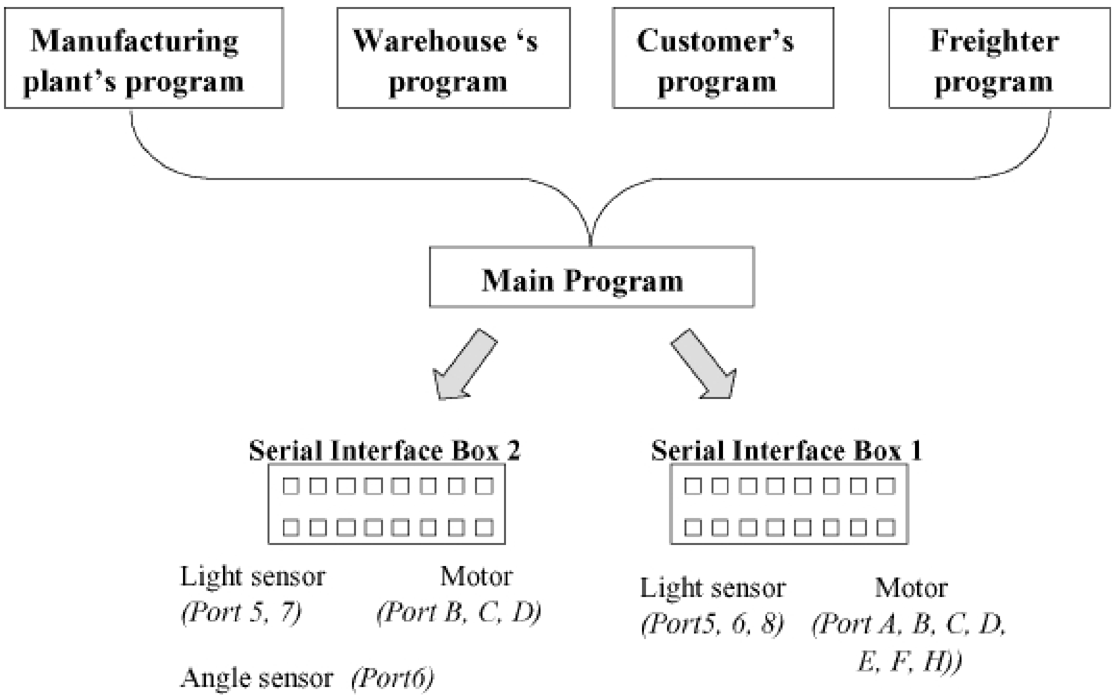

Fig. 4. Input and output connections for Lego model.

next section discusses the applications of the model and its integration with the interactive learning environment at NTU. This is followed by a discussion of the educational issues concerning the development and subsequent use of the model. The paper is summarised in the conclusions which end the paper.

THE MODEL

Software control

The model of the manufacturing enterprise is built using Lego Dacta which consists of standard Lego bricks, wheels, gears pulleys, beams axles, connectors and belts. The system also includes digital and analogue input devices such as touch, light, temperature and angle sensors and output devices such as DC motors and lamps. These can be interfaced to a computer by the Lego Dacta RS-232 interface box (Fig. 3). The interface box has eight digital output ports and eight input ports. Two such interface boxes are used in the model (Fig. 4). The interface box can be controlled by LabVIEW, a graphical programming environment for instrument control and data acquisition. LabVIEW also allows the development of a control panel so that the interface box can be fully controlled from the computer by clicking the relevant buttons, sliders, etc. on the display screen. LegoEngineer, developed by Tufts University provides a set of drivers for LabVIEW which interface to the control box and provides communication for the various sensors and motors.

LabVIEW is a program development environment that includes libraries for data acquisition, GPIB and serial instrument control, data analysis, data presentation and data storage [23]. LabVIEW programs are called Virtual Instruments (VIs) because their appearance and operation can simulate an actual instrument. A VI consists of an interactive user interface (a front panel containing knobs, switches, graphs and indicators), a dataflow diagram that serves as the source code (G Code) and icon connections that allow the VI to be called from higher levels.

An Internet developers' toolkit for G code provides access to the Internet from within the G environment using VIs [24]. This allows a VI front panel to be viewed from any Web browser. The built-in server can respond to multiple clients connected to the program and continuously update the displays of each remote user. ComponentWorks is a collection of ActiveX (or Object Linking and Embedding (OLE)) controls for acquiring, analysing, and presenting data within any compatible container (such as Visual Basic) [25]. Visual Basic (Control Creation Edition) is used here to create ActiveX controls, therefore providing an interface between the browser (Internet Explorer) and LabVIEW, through the ActiveX controls provided by ComponentWorks [26]. The configuration for controlling the Lego Model of the Manufacturing Enterprise is shown in Fig. 5.

The system also includes a Canon VC-C3

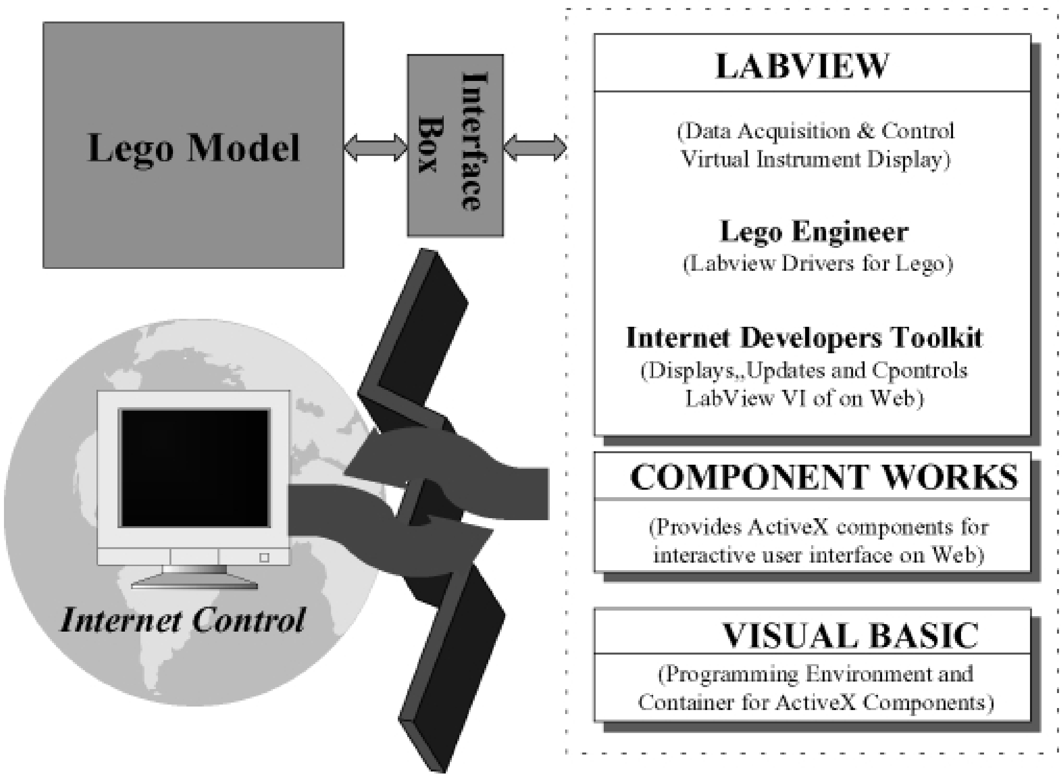

Fig. 5. Software configuration for controlling the enterprise model across the Internet.

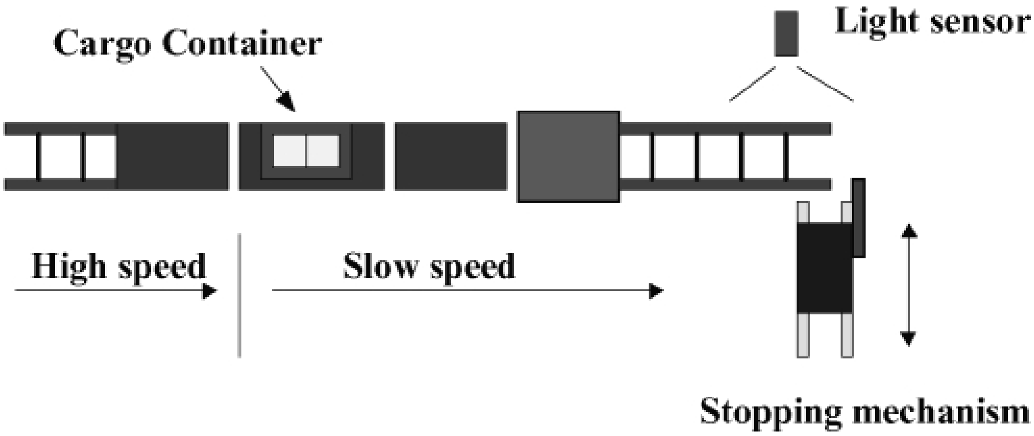

Fig. 6. Freighter docking procedure at the warehouse.

Camera. The camera is controlled by Canon's WebView/Livescope image transmission system that enables interactive viewing of real-time images, of the manufacturing enterprise model on the Internet by allowing users to control camera angles and the zoom magnification of the camera. The WebView system consists of two components: a camera server software which transmits live images input by the camera over the Internet and a viewer software which is used to view the transmitted images live. The live image of the manufacturing enterprise model is integrated into the control panel so that the user can immediately view the consequences of his interactive control decisions.

The train (freighter)

The model is built around a standard Lego electric train system. The train is connected to the serial control box so that its speed can be directly controlled from the computer. The manufacturing enterprise is built around the train layout. This consists of a manufacturer, a warehouse and a customer. Optical sensors are placed at each location so that the train can be programmed to stop at each part of the manufacturing enterprise. Because of the critical positioning of the freighter at the warehouse a stopping mechanism, was added to the design so that the train stops at the exact position (Fig. 6). The stopping mechanism automatically retracts when the loading or unloading is completed. Parts are placed on the pallet (container), which rests on the train. The pallet and its holder are designed to have two wings so that the forklift can lift it at the warehouse stage. One end of the pallet is open to facilitate the pouring motion at the customer stage. The velocity of the train is programmed so that it slows as it reaches each location. This ensures greater accuracy in the positioning of the train, which is critical for the effective operation of the model.

The manufacturer

The manufacturing facility consists of three components: feeding, production and inspection (Fig. 7). The products are 15-mm cubes that are not modified during the manufacturing operation. The feeding mechanism holds the raw materials needed for the production and feeds them via a conveyor belt to the production section, one part at a time. An optical sensor is used to control the feeding. The production section simulates the production of the parts, after which they pass through an inspection station consisting of another optical sensor, which differentiates between 'good' yellow (light) parts, and 'bad' blue (dark) parts. A robot arm is then used to load the good parts onto the freighter whilst the rejected parts are collected

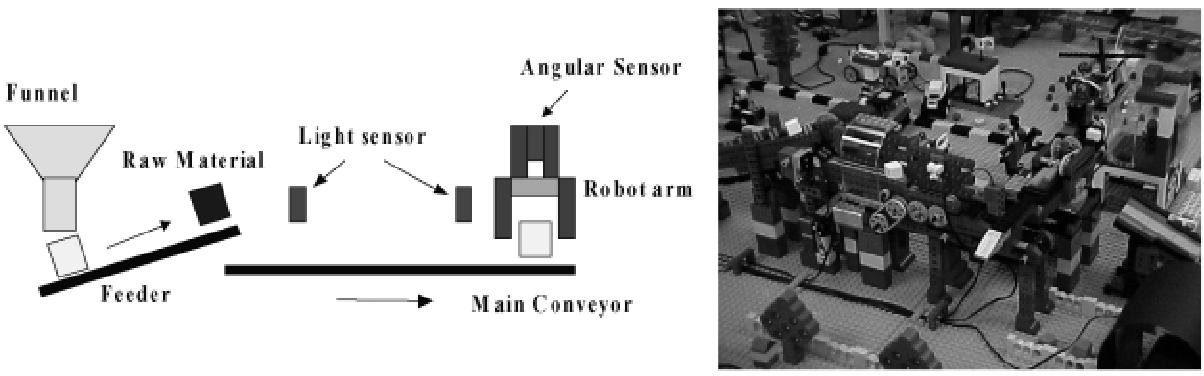

Fig. 7. The manufacturing system.

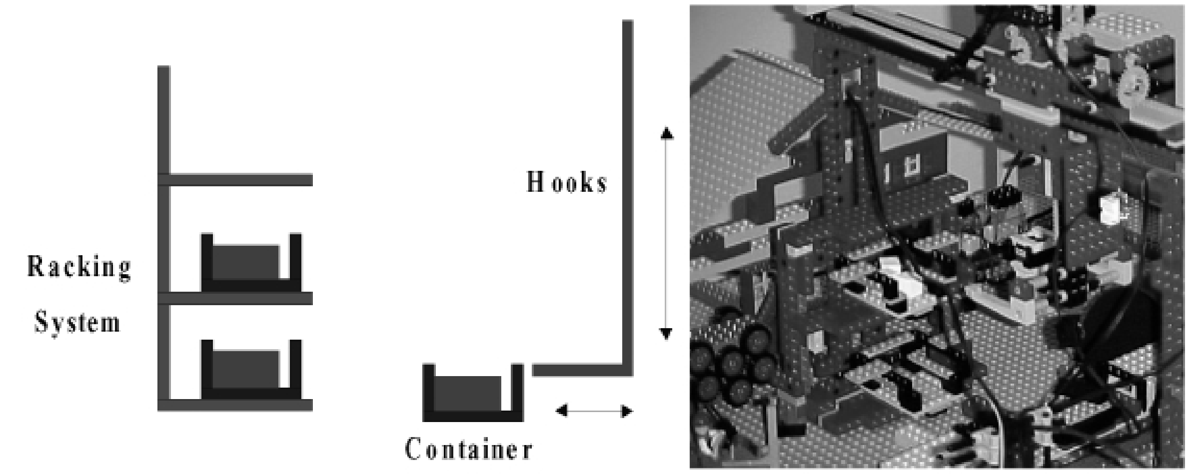

Fig. 8. The warehouse.

in a bin for rework. An angle sensor is used to control the required sweep of the robot arm.

The warehouse

The warehouse consists of a gantry built over the rail track (Fig. 8). Pallets are stored on a three level racking system, each level holding a predetermined number of parts. A forklift mechanism is used to move the pallets from the warehouse to the freighter and from the freighter to the warehouse. Two 9 V motors are used to control the horizontal and vertical movement of the forklift. Parts are stored in quantities of two, three or five. The parts are stored on the three-tier racking system depending on the number of parts on the pallet. The system can therefore keep track of the number of parts in each storage location. For simplicity, the customer is allowed to order any combination of these parts.

The customer

The customer stage consists of a mechanism that tilts the platform when the train comes to dock thus tipping the required parts into a container (Fig. 9). This is achieved by using a rack of linear gears, to rotate a lever, which then lifts the handle attached to the platform. The mechanism is mounted on a stand, which moves next to the train when it docks. An optical sensor indicates the presence of the train and initiates the procedure. The rotating lever then tilts the platform that pours out the goods, after which the mechanism returns to its original position.

The control screen

The control screen consists of a control panel for the manufacturing enterprise model and a live video image of the model itself (Fig. 10). The screen can be viewed and controlled on the Internet. Slider controls for the camera allows the user to pan, tilt and zoom the camera. The control panel displays and updates the current inventory at the warehouse and the number of goods received by the customer. The model can be run in either automatic or manual mode. Modes can be changed by clicking a toggle switch. In automatic mode the user can start the model which will then run for a default set of customer orders and inventory levels. In manual mode the user can choose the amount the customer orders and then select the inventory policy which suits his requirements. In this way it is possible to experiment with different inventory policies to optimise

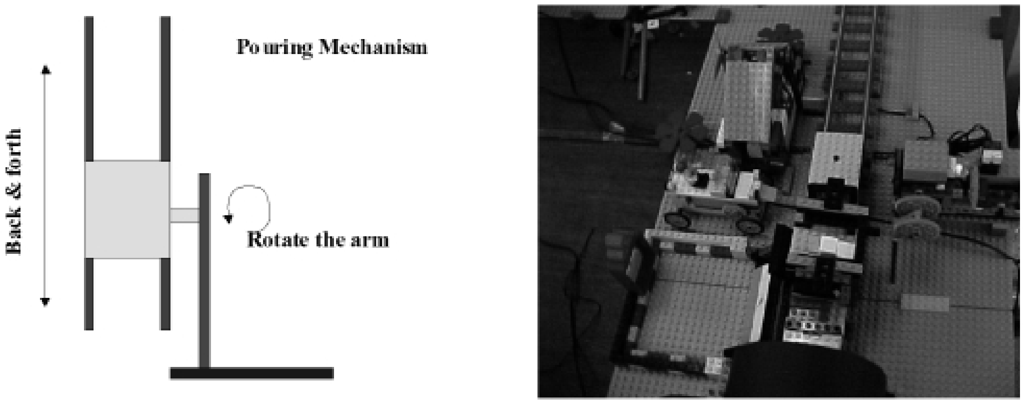

Fig. 9. The customer stage.

Fig. 10. The control screen.

the performance of the manufacturing enterprise in terms of cost, productivity and efficiency.

Simulation model

In addition to the development of the model, a Discrete Event Simulation Model was developed to represent the manufacturing enterprise depicted in the Lego model (Fig. 11). The model is built using Promodel Version 4.1 and runs in two modes: automatic or manual to simulate the environment of the Lego model. This demonstrates an important link between an actual system (in this case a working model) and a simulation model. By running the two systems concurrently it is possible to demonstrate the advantages of computer simulation in representing an actual system in terms of time compression (where a real time scenario of several hours, for example can be simulated in several seconds on the computer), scenario analysis, productivity analysis, etc.

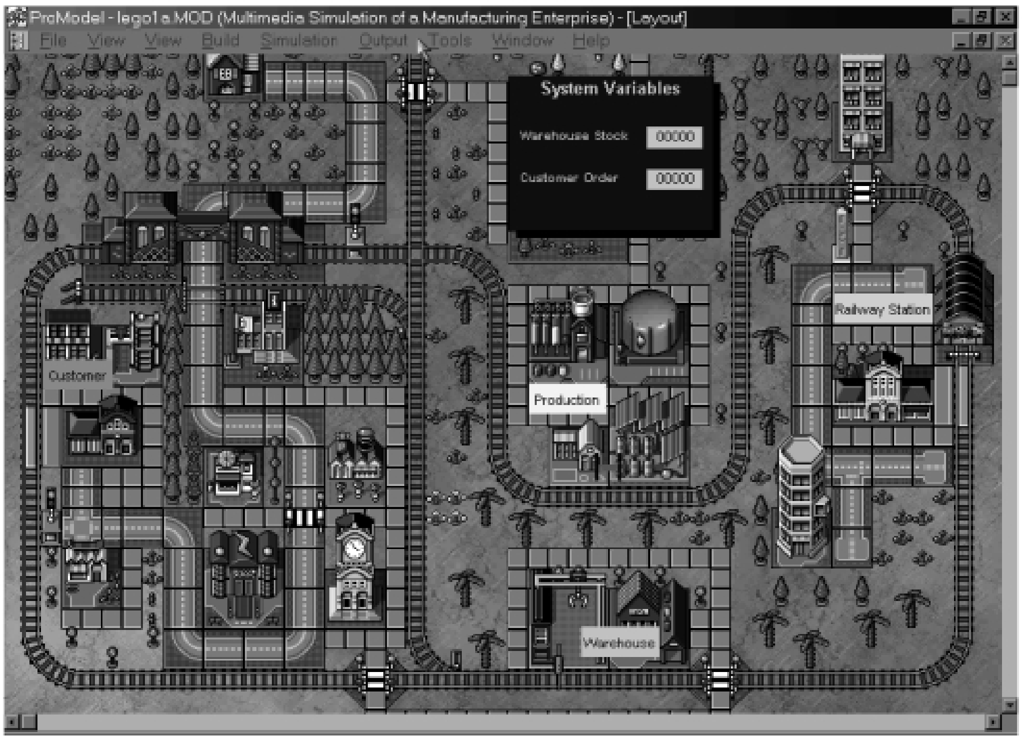

Fig. 11. Simulation model of manufacturing enterprise.

LEARNING ENVIRONMENT

The working model of the manufacturing enterprise was developed as part of the School of Mechanical and Production Engineering's Hypermedia Instruction and Teaching Environment (HITE). The Unit was set up to develop multimedia learning material and to provide facilities and technical support to lecturers and students for developing interactive courseware material within the School.

The project was initially targeted at the School's part-time courses which include Masters of Science degrees in Computer Integrated Manufacturing and Logistics. Students enrolled in these courses come from a diverse backgrounds and so to facilitate the learning process the multimedia courseware enhances the traditional learning environment by providing extra material and background information as well as up-to-date lecture components. The system is designed to correspond to different levels of ability and experience and so alleviate a classic problem of engineering education, which is difficult to approach using conventional mediums. Part-time students sometimes have problems attending classes if they are posted overseas. The multimedia environment enables them to keep up with course from their hotel room via the Internet.

A home page for each subject provides a week-by-week teaching schedule where students are able to download an interactive multimedia presentation for each lecture. The presentation includes text, diagrams, animation, videos and interactive simulations where the student can develop an in-depth understanding of a particular concept by experimenting with key variables and settings. For example the courseware for Systems Simulation and Modelling, a course offered as part of the Masters in Computer Integrated Manufacturing Programme, includes a complete simulation model of a semiconductor manufacturing system, typically found in Singapore [27, 28]. Students are able to interactively explore the design features of the system to optimise performance and to explore ways of improving the design of the system. Statistical analysis is also integrated into the simulation to enhance the analysis and provide a link between theory and practice. This simulation model represents a further development of the educational principles presented in the Lego model. Students are thus able to interactively explore an actual manufacturing enterprise, through the Lego model, a simulation model of a manufacturing system and finally the statistical analysis for improving the performance of such a system.

The model of the manufacturing enterprise is used in both the Masters in Computer Integrated Manufacturing and Masters in Logistics programmes. At present the model is demonstrated in the Lecture Theatre (through the Internet). The students are also given access during certain periods. Students are able to explore strategies for improving the operation of individual stages (such as the warehouse or manufacturing system) or the system as a whole. Thus it is possible to investigate how more efficient quality management of the manufacturing system, or an improved inventory policy at the warehouse, may impact on the performance of the manufacturing enterprise. The concept of optimising the system as a whole rather than each individual element is of fundamental importance at the manufacturing enterprise level.

EDUCATIONAL ISSUES

The finished model is useful as a demonstration of a manufacturing enterprise and illustrates the principles of manufacturing and inventory management, computer integrated manufacturing, supply chain management and the concept of a collaborative intelligent environment, where different echelons of a manufacturing enterprise or supply chain share information across the Internet to optimise management information integration.

The educational advantages of developing the physical model from a pedagogical perspective are also quite numerous:

- *Mechanical design and development*. The design and subsequent development of the physical model requires students to build several mechanisms. Operational aspects such as performance, accuracy, efficiency and stability need to be carefully considered.
- *Data acquisition and control.* Students need to understand the sensors and controls at their disposal. The selection of the most appropriate sensor for its intended application, its effective use and subsequent computer interface is critical to the success of the system. An appreciation of interface and control concepts such as analogue, digital, RS-232, etc. are important.
- *Computer control* The student needs to understand the principles of the LabVIEW programming language and develop procedures to run each element of the model effectively and then integrate each procedure into a program for running and controlling the entire model.
- *Web design and development.* This necessitates ensuring that the necessary controls are available across the Internet which requires a basic understanding of computer networking, Visual Basic, ActiveX, etc.
- *Management of a manufacturing enterprise and supply chain*. To build an accurate and realistic model the student needs a thorough understanding of a how a manufacturing enterprise operates so that the concepts are best illustrated.

A significant development was the teamwork that ensued from the project. Each member of the team worked on an individual element of the project, manufacturing, warehouse, customer, freighter, computer control, web design, etc.

However, it was not only necessary to ensure that each element was successfully developed but that each is finally integrated to form a unified model. This required a well-managed team effort. The team met once a week for brain storming sessions with the project supervisor (the author) and interested researchers so that the incremental design of the project could be steered to a successful conclusion. The group dynamics at this stage were particularly important. In this aspect, the project was a great success, even with the heavy workload of an engineering degree, students worked evenings, weekends and vacation periods to ensure the success of the project. Even months after the project was completed the sense of ownership was such that the students visited the model to make sure it was still operational.

Lego has certain advantages and disadvantages for a project of this nature. Firstly, the ease and speed at which mechanisms and structures can be built should not be understated. In addition, the ease at which Lego models can be disassembled makes incremental design and further development an attractive alternative. If a permanent model is not required, the modelling elements could be used for future projects without loss. A significant amount of effort has been taken to ensure a seamless integration with the control software LabVIEW. The fact that LabVIEW is an easy to use, flexible and powerful software is a great bonus. This is an important point. It is appreciated that LabVIEW was easily adapted for the task of building a project of this nature, but far from being just an educational software it is conceivable that the same software could be used to control an actual manufacturing enterprise in a similar manner.

As the model was intended to be a permanent display, perhaps the most significant disadvantage of using Lego was its reliability and repeatability. The initial idea of the project was to develop the model such that it could be controlled from anywhere in the world, twenty-four hours a day without human intervention. However, Lego components such as sensors, gears and pulleys are not designed for such a rigorous application. The repeatability and reliability of the model was not of a sufficiently high standard to allow remote operation without intervention for more than a few cycles. Such limitations have to be balanced with the advantages above.

CONCLUSION

This paper has outlined the development of a working model of a manufacturing enterprise with full Internet control. The potential of the model as a learning experience in the development stage as well as a teaching example when complete are discussed. The model utilises Lego Dacta products, LabVIEW to control the model and an interactive camera to view the model on the Internet. Users are able to explore best strategies of managing the manufacturing enterprise efficiently and economically. They are also able to optimise the operation of individual components of the manufacturing enterprise or take a more holistic approach and optimise the system as a whole. A fascinating aspect of the project is that similar technology is being applied to real-life manufacturing enterprises through intelligent collaborative environments such as the Internet and therefore this project ably demonstrates the potential of such technology.

The students were totally absorbed with the project and their great enthusiasm led to the successful completion of the model and computer interface within the 6–week time frame. The students particularly enjoyed the weekly brain storming sessions and continued developing the model in their own time long after the project had officially finished. The model will be featured in the School's part time MSc courses in Computer Integrated Manufacturing and Logistics. Several overseas universities also plan to access the model as part of their teaching activities.

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