LEGO FACTORY:
AN EDUCATIONAL CIM ENVIRONMENT FOR ASSEMBLY

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ABSTRACT

This paper describes a general concept for a computer integrated manufacturing (CIM) environment intended for the design and assembly of "products" built out of Lego blocks. These "products" are conceptualized and designed within a Lego CAD System from a small set of the most commonly used Lego building blocks. Process planning and trajectory planning software is used to determine the build sequence and robot program for assembling the model directly from the 3D CAD model. The robot program is fed into a cell controller to perform the physical build of the "product". This paper also describes student projects designed to explore the feasibility of the technical concepts necessary for such a system. These include a robot gripper, a block sorting mechanism, and an assembly planning system integrated with the Lego CAD system and the physical assembly cell.

INTRODUCTION AND MOTIVATION

Computer Integrated Manufacturing (CIM) is typically defined as the use of Computer and Automation Systems to operate and control production. This definition breaks the production activities into two major categories: the information processing performed by Computer-Aided Design and Planning systems and the physical activities performed by automation systems. Information processing tasks include: the design of components; planning the production of the components; controlling the operations in production and performing various business related functions necessary for running a manufacturing enterprise.

The physical activities are performed by a wide range of devices, often automatically controlled, including machine tools, assembly stations, robots, material handling and storage systems and quality inspection systems. These devices perform material transformations according to predefined process steps, move about a factory, take measurements, and ultimately feed back information to the human operators. They automate the physical activities.

In the same way that the devices on the shop floor automate the physical activities, the CAx (x = Design, Process Planning etc.) systems automate the information processing functions assuming that these different functions are closely integrated. To achieve CIM, all aspects of the manufacturing enterprise must be integrated so that they can share the same information, communicate with one another and provide a global picture as to the state of the entire manufacturing facility at any time.

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The primary challenges for academic institutions which wish to offer CIM courses are: (1) the cost of the appropriate equipment, and (2) the relative complexity of a functional and meaningful CIM environment. It is clear that creating educational systems that emulate the complexity of industrial systems for studying CIM concepts for assembly in particular is not a trivial task.

This paper describes a general CIM system concept which can be used to design and fabricate *products* built from Lego blocks. Such products are conceptualized and designed within a *Lego CAD System* from a subset of the available Lego building blocks. Assembly sequences for building these products are carried out by means of robotic devices. Process planning and trajectory planning software are used to determine the build sequence and programming the robots for assembling the model directly from the 3D CAD model. The robot program is fed into a cell controller to perform the physical build of the "product". The overall sequence of activities carried out by the system is shown in Fig. 1.

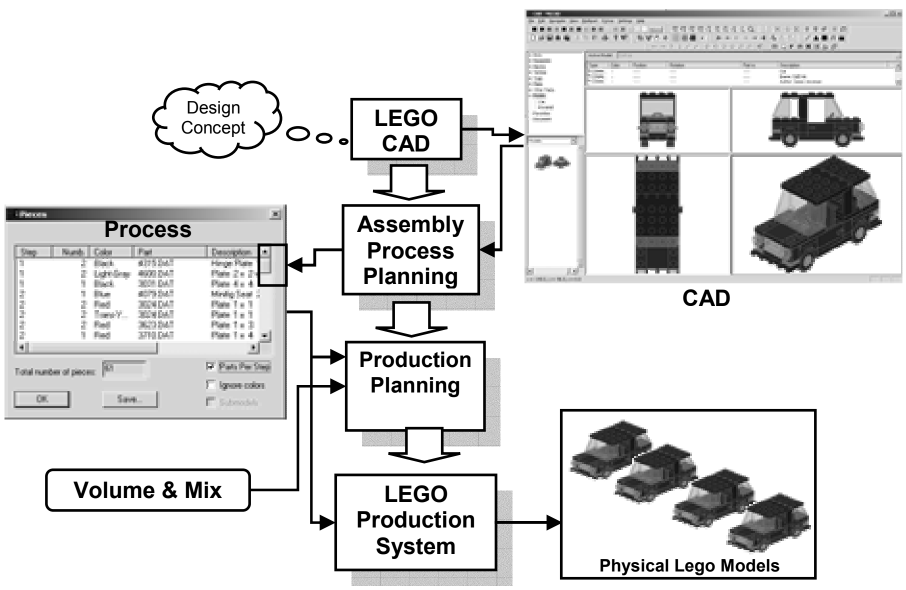

Figure 1 Lego production system activities

The long-term goal of this effort is to develop and implement such a concept by utilizing the assembly capabilities of Lego blocks. Lego blocks have the combined advantage of providing a richly diverse part family from an assembly perspective while at the same time simplifying fixturing and gripping issues through use of the blocks patented fastening mechanism.

EXISTING APPLICATIONS

Lego is a building system based on modular blocks (also called bricks), equipped with a functional binding mechanism. Two Lego parts can be connected to one another in a number of different ways and stay that way until they are separated. While the original Lego block concept was purely mechanical, most recent offerings also include embedded computational and sensing capabilities.

The idea of using Lego blocks for educational purposes is certainly not new, in particular that Lego is not just a toy (as it is typically perceived), but also a learning tool. Several examples exist of the use of the Lego concept in tertiary education and research for manufacturing systems simulation[1], mechanisms design[3], virtual prototyping[4] and as test components[2,6]. The pedagogical role of the Lego block concepts in teaching engineering and physical principles has also been documented[6,7]. These cases demonstrate that Lego Blocks play a role in teaching and research for higher education. At the same time, a study of the documented activities has not yielded an example that matches the concept described in this paper.

Numerous examples of systems exist in the area of CIM for education; such systems have been developed at universities for both the research and education purposes[8,9,10,11]. In addition, several commercial companies specialize in producing CIM environments for education[14,15,16].

CIM ENVIRONMENT FOR LEGO PRODUCTS

The challenges of developing CIM environments within an educational setting are not trivial in the assembly area. While several options exist for machining, the same is not true for assembly to the same extent. In particular, CIM for machining allows students to explore the physical hardware related technology integrated with 3D CAD/CAM systems and increasingly some form of Computer-Aided Process Planning capability. A wide range of machineable geometries can be created, tool paths generated and operation sequences planned within such CAD/CAM/CAPP systems.

The same is not true for an assembly. A CIM assembly cell that integrates CAD, requires generic fixturing and gripping concepts that can be used consistently across multiple part families. Lego models provide another option for assembly where fixturing, gripping and fastening are simplified through a generic stud pattern. Lego blocks are self-fixturing in that an exposed studded surface on any state of the assembly provides the necessary locating and fastening mechanisms to add new blocks. This same stud pattern can be exploited to design and build generic grippers. By removing the requirement of specialized external fixtures and grippers, it is possible to automatically build a wide range of Lego models using a robotic cell integrated with a 3D Lego CAD system (Figure 2).

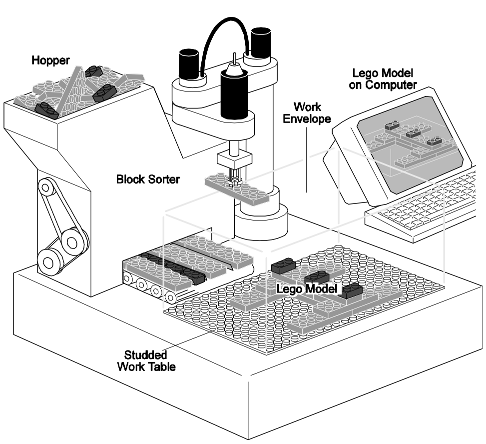

Figure 2 Concept of a robotic Lego assembly cell

Important concepts in CAD, CAPP, integration, virtual manufacturing, optimal path planning, force feedback and control, and material handling can be taught and researched using this environment. Further, by integrating several of these cells together with a material handling system into a production line (Figure 3), other areas such as task allocation and line balancing, production planning, throughput analysis, reconfigurability and mass customization can also be addressed.

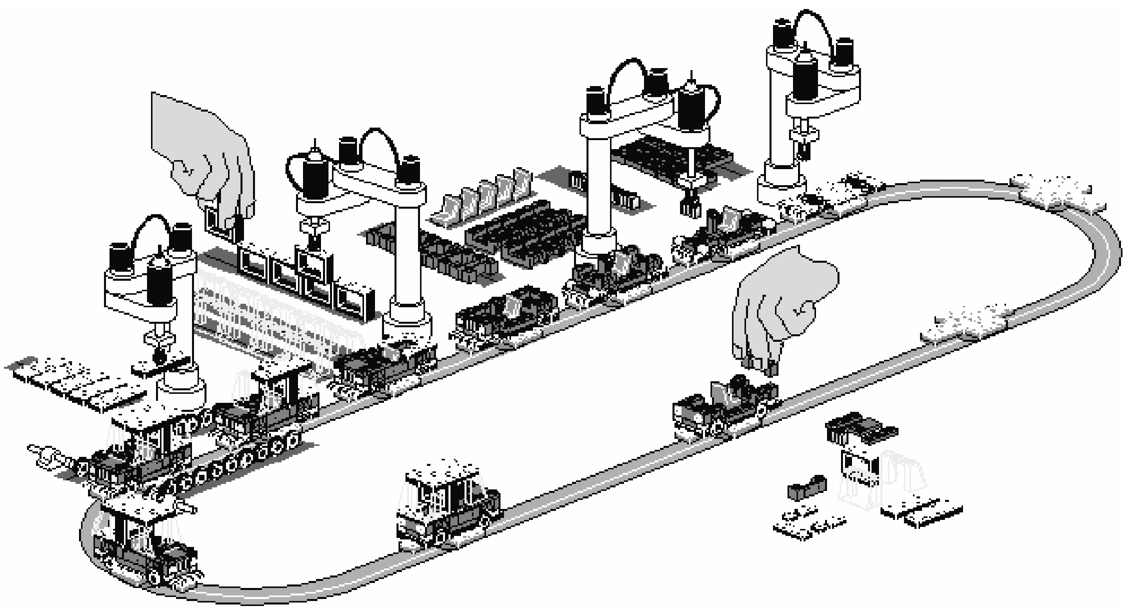

Figure 3. Lego Model Assembly Production Line Concept

NECESSARY ENABLERS

To reach the goal of a CIM environment for product assemblies made out of Lego blocks, it is first necessary to find feasible solutions to a number of technical issues.

One of these issues is the design of a mechanism for gripping Lego blocks. Such a mechanism mounted as the robot end-effector will act as an assembly gripper. One has to remember that the original Lego block assembly process is intended for manual assembly, which primarily relies on the dexterity of human hands. The assembly process for Lego blocks can be automated by means of robotic device(s), but only if they are equipped with a proper gripping mechanism that assures reliability and repeatability in achieving accurate block grasp.

If the block assembly is to be performed by a robotic device, then an associated problem of proper presentation of the blocks to the end effector must also be solved. This must account for the relative immobility of the robot, which usually has a stationary mount and limited reach within a predefined workspace. This constraint creates the need for the blocks to be presented to the robotic gripper in a consistent way and at a well defined location within the workspace. A solution to this issue is the design of an appropriate block-feeding system. If the input to the block-feeding system is assumed to be a random mix of a select set of Lego blocks, then these block must also be sorted and appropriately oriented before they can be added to an assembly by the cell robot.

To program and run the cell, methods need to be developed and implemented in the areas of Computer-Aided Process Planning (CAPP) for assembly and tool path planning. These will determine the optimal build sequence and generate collision free programs for assembling the physical Lego model directly from its 3D CAD model. These software tools have to be integrated with the hardware components described above in such a way that the CAD model of a Lego assembly can be realized as a physical assembly within a matter of minutes.

The long term goal of this effort is to integrate several of these cells with a material handling system into a production line. Important CIM and production concepts in areas such as Computer-Aided Process Planning (CAPP), production planning, customization, reliability and reconfigurability can be demonstrated with this system.

FEASIBILITY STUDY PROJECTS

The Lego factory development effort was initially set up as a senior level capstone design (ME450) project that consisted of two teams. One team worked on a design for sorting and delivery of the Legos and the other team worked with the robotic end effector and cell design for assembly of a finished product. Each team was able to generate several design concepts and eventually a final detailed design that was fabricated and integrated with a commercial educational 5 axis robot for a competent working design (Figure 4).

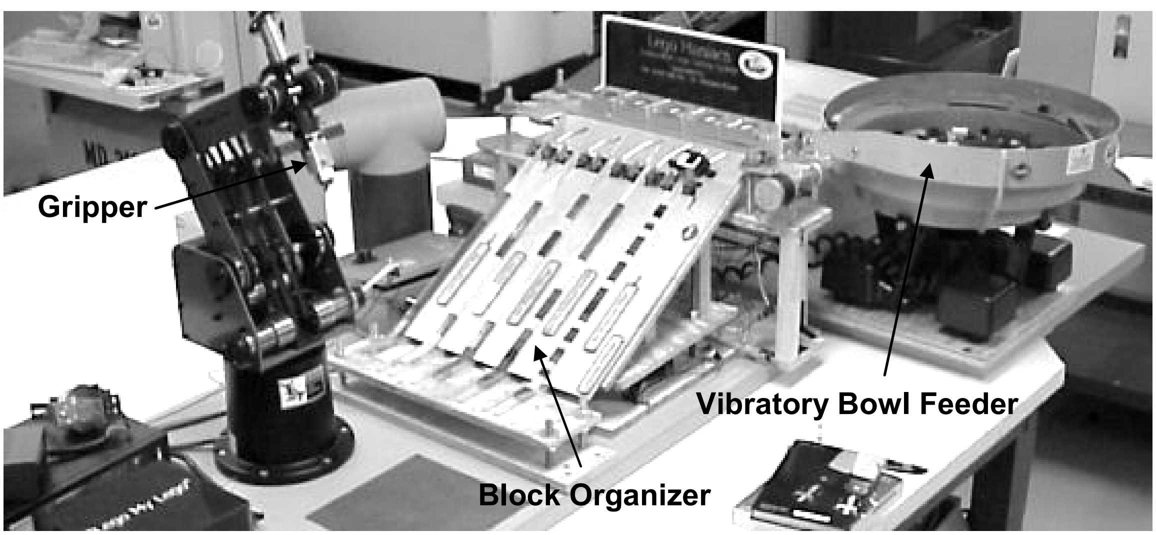

Figure 4 Implementation of the Lego Factory system

The task of the first group was to design, fabricate, analyze, and test an electromechanical gripper for grasping Lego building blocks and moving them from the cell input positions to their assembly location within the work envelope. The engineering specifications considered were (1) the gripper must be able to place blocks adjacent to other blocks without any interference, (2) it must be able to provide a force ranging from 20-50 N to lock the blocks securely into place, (3) it must be able to pick up 5 different Lego blocks, and (4) the gripper must be compliant to 0.5 mm to compensate for the inaccuracy of the robot. To exclude the potential robot interference with other blocks during assembly it was decided that the gripper must be no bigger than a 2x2 Lego block and must pick the Lego blocks up directly from above the block location. In the design process multiple concepts were explored (Figure 5). The selected end effector included a modified Lego block as a gripper, a digital linear actuator for the linear motion mechanism, and a spring for the release mechanism. The solution met all of the force and wiring specifications necessary to accomplish the prescribed tasks and interfaced well with the robot model used.

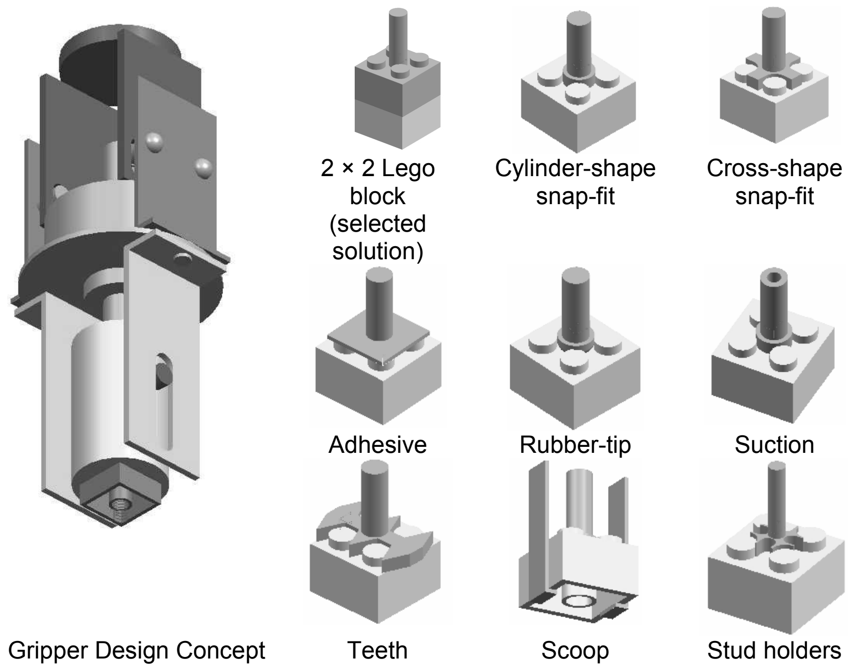

Figure 5 Alternatives for Lego block gripper solutions

The second project team developed a Lego block feeding and sorting system. The purpose of the system was to load a randomly mixed group of Legos (consisting from the five most popular block types) into the "factory," sort them into appropriate size groups and orient them for use by the factory robot. The feeding and sorting system of the Lego factory consists of two main components: a vibratory bowl feeder (VBF) and a gating mechanism that sorts the blocks according to their length. The feeder is a stand alone mechanism. The sorter consists of numerous sub-components that were ordered and installed for specific purposes tailored to the Lego project.

The design of the VBF (Figure 6) had to take into account the random orientation of the Lego blocks that were placed in the hopper. Blocks needed to be oriented stud side up for them to be properly presented to the gripper. This was accomplished by using special modifications to the path along the inside of the VBF that the blocks traveled along to exit the feeder. These modifications enabled blocks with the studs facing downwards to be ejected from the ramp back into the bowl to the back of the block queue. Upon reaching the top of the ramp in the VBF the blocks exited onto a moving conveyor system that was part of the sorting mechanism.

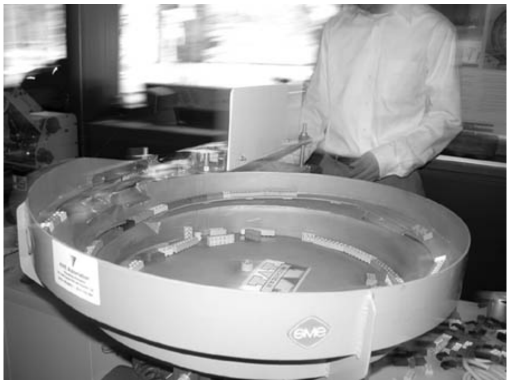

Figure 6 Vibratory bowl feeder

The Lego sorter (Figure 7) operates by taking the parts from the feeder and laying them on a conveyer. The parts then go through an LED – photo diode infrared remote sensing system. This measures the length of the part based on the length of time the sensor's output varies. This information is used to control a solenoid attached to one of a series of gates that would direct the Lego block into a machined slot on an inclined aluminum plate. Blocks of the same size would slide down the slot forming a stack the end of which is the pick-up location in the cell for that particular block.. Each slot is equipped with its own LED – photo diode pair which alerts the system if the lane is full. If this is the case, the corresponding solenoid would not open the gate and the block continues on the conveyer to be placed back in the hopper at the beginning of the process. The functions of these components are controlled by the operation and coding of a basic Stamp microprocessor[17].

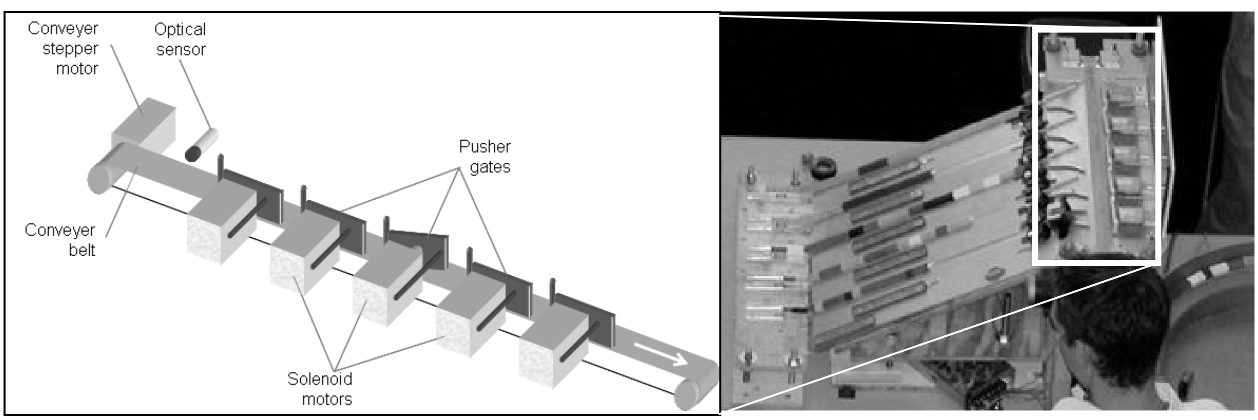

Figure 7 Block Sorting Mechanism

The third student team explored the issues related to Lego CAD software and its integration with the rest of the system. The computer aided design software used was the MLCad modeler[12,18], which facilitates user-interactive assembly of Lego models and provides graphical 3D displays of virtual Lego models and the blocks they consist of. The building of a model out of a library of Lego blocks is self-explanatory. MLCad has an intuitive interface (Figure 8). For the basic functionality, the user can just drag and drop the desired blocks onto the screen and align them properly using the 4 different views available. The sequence of steps or order of building the blocks is very important as (for now) it determines the model build sequence. The designer is constrained to add blocks to the model one level at a time. This is to ensure a collision free build sequence. Future enhancements will include assembly and trajectory planning modules that will create an optimal sequencing so as to minimize build time while automatically detecting and avoiding collisions.

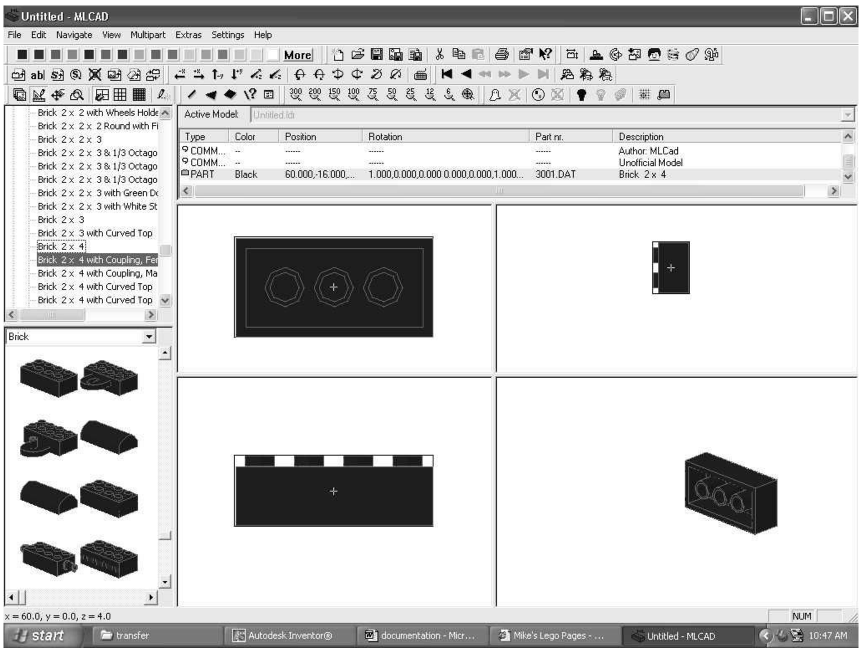

Figure 8 Example window of MLCAD

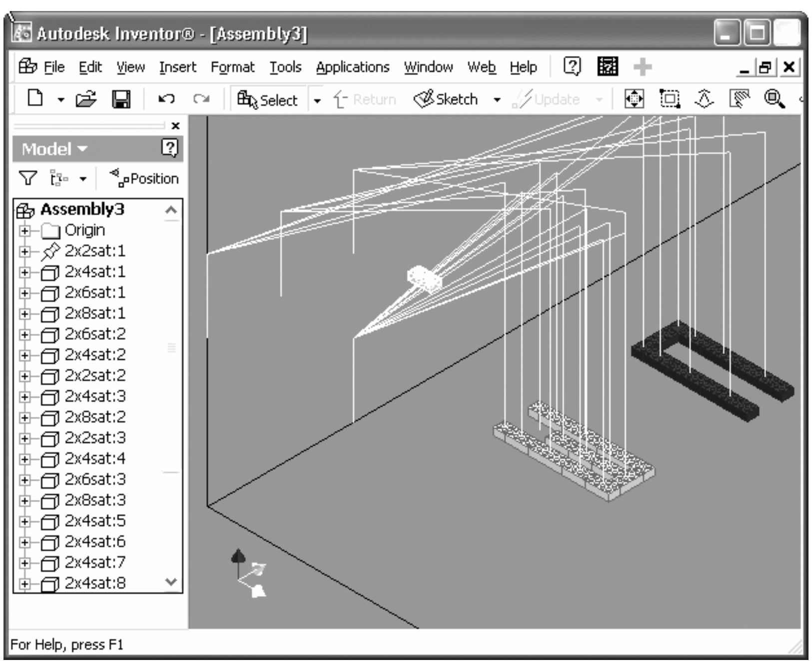

Figure 9 Example view of the assembly sequence in Inventor

The process of building a model can be simulated and verified using Autodesk Inventor. A custom-written Visual Basic (VB) plug-in to Inventor interprets the model component file from MLCad and converts it into a sequence of block motions for transfer of blocks between pickup locations to their final destinations within the assembly model (Figure 9). From the simulation the user can see if there are errors in the assembly sequence of the blocks as decided by the designer before they are physically put together.

The final step after the simulation is to download the assembly motion sequence to the robot for execution. This task can be carried out by means of a customized API provided by the robot manufacturer. This enables direct transfer of the verified motion control program from MLCad to the robot.

DISCUSSION

Completed prototypes from the student teams were integrated and the resulting Lego Assembly Cell demonstrated at the 2003 ME450 Student Design Expo (Figure 10).

Each component of the cell functioned successfully though not without reliability problems that need to be addressed if the concept is to be expanded. The VBF was the simplest and, not surprisingly, the most reliable of the components. The modifications to the generic VBF were highly effective in ensuring that the Lego blocks were correctly oriented before being presented to the sorter. One concern prior to testing was that the VBF would not be able to deliver the required throughput of blocks to keep the cell functioning continuously. It quickly became apparent that for the prototype set-up this would not be the bottleneck. However, for a system with multiple cells it may be necessary to have several of these feeders to ensure that the line would run continuously.

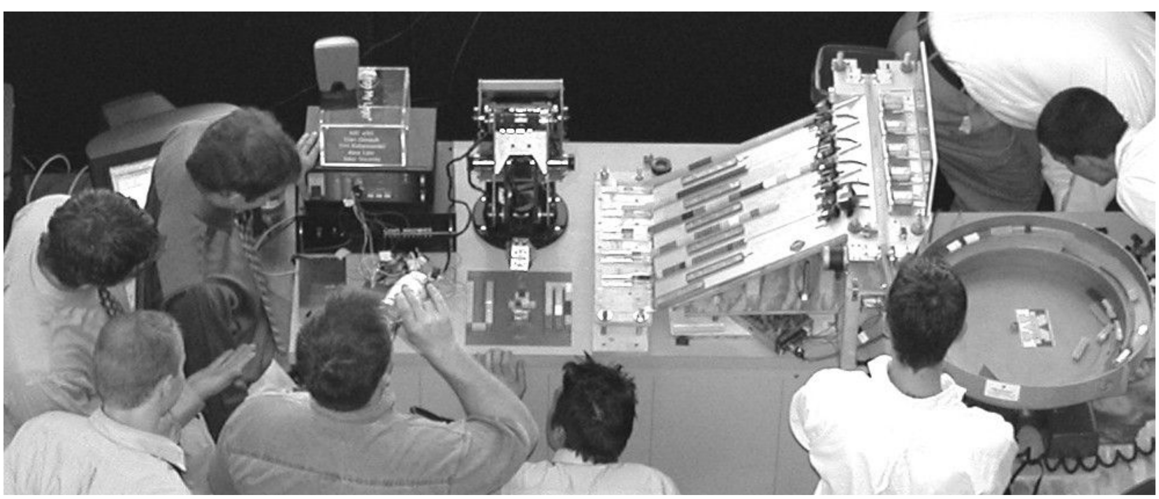

Figure 10. Complete Lego Assembly Cell at 2003 ME450 Design Expo

Reliability of the sorter was affected by sticking of the solenoid controlled gates. It was generally felt that this problem could be resolved by improving the design of the hinged gates and by choosing a better solenoid/spring combination. Proper deflection of the blocks by the gates from the conveyor into the inclined tracks was also unreliable for the smaller blocks. Square blocks in particular when oriented on the diagonal would get caught up at the entrance to the track. Again it was felt that this problem could be resolved easily by modifying the geometry of the track entrance for these block sizes.

The gripper turned out to be the least reliable component of the cell as well as the bottleneck. This was largely due to the type of robot used. Difficulties in orienting the wrist where the blocks where first grasped and added to the assembly together with compliance due to the belting used in the joint drives significantly affected the speed of the assembly process and the ability to fit blocks into corners without becoming dislodged. It was decided that SCARAB robot configuration with greater rigidity would be better suited to the pick and place operations required for assembly of Lego blocks rather than the articulated arm robot used.

In addition to the hardware modifications noted above, the biggest additions to enhance the CIM capabilities of the cell are to come from process planning software. This will include developing the following:

1. *Algorithms for creating assembly trees for Lego models:* This tree captures all possible assembly sequences for the model. This will be constructed using the solid modeling kernel, ACIS®. With ACIS, interference zones between blocks and obstructions can be identified utilizing intersection operators on bounding volumes and sweeps of blocks.
2. *Algorithms for identifying infeasible models:* Even with a limited set of building blocks, infeasible models are possible. This is the case when parts of the model are not properly supported. Again, ACIS will be used to identify these conditions.
3. *Algorithms for collision free trajectory planning:* Tool path planning and finding the optimal build sequence are coupled activities. To avoid collisions building at a constant z-depth is preferable. However, this may lead to a longer build time. Solid modeling tools will be used to generate tool paths.
4. *Algorithms for determining the optimal build sequence:* Optimization approaches such as Genetic Algorithms or the A* Algorithm will be investigated for this. Distances and times from block feeding locations to positions in the final model will be an input. These come from the trajectory planning algorithms.

Beyond a single cell, the production line concept requires consideration of a material handling system, and the introduction of controllers at the system level to coordinate activities amongst different cells. In addition process planning software for distributing tasks amongst cells in a balanced fashion will need to be included.

SUMMARY

The presented Lego CIM environment concept has a great potential for exposing university students to CIM concepts for assembly and general manufacturing automation concepts. Lego block system has a universal appeal (due to its intuitive understanding) also to K-12 students. Such CIM concept can leverage this appeal to educate and attract pre-college students to manufacturing, and engineering in general. The CAD front-end provides a level of interactivity that makes this concept appealing as a hands-on exhibit in a museum, theme-park or science and technology centers.

BIBLIOGRAPHY

1. Chandra, V., Mohanty, S.R., Kumar, R., "Automated control synthesis for an assembly line using discrete event system control theory", Proceedings of the 2001 American Control Conference, Arlington, VA, USA, Vol. 6, pp. 4956-4961.
2. Hiransoog, C., Malcolm, C.A., "Multi-sensor/knowledge fusion", Proceedings of the IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, Taipei, Tiawan, 1999, pp. 177-122.
3. Tsuboi, T., Hirai, S., "Reconfigurable mechanisms: An approach to the rapid prototyping of multi-link mechanisms", Advanced Robotics, Vol. 13, No. 3, 1999, pp. 255-256.
4. Young, P., Chen, T., Anderson, D., Yu, J., Nagata, S., "LEGOWORLD: A multi-sensory environment for virtual prototyping", Proceedings of SPIE - The International Society for Optical Engineering Vol. 3295, 1998, pp. 313-321.
5. Cyr, M., Miragila, V., Nocera, T., Rogers, C., "Low-cost innovative methodology for teaching engineering through experimentation", Journal of Engineering Education, Vol. 86, No. 2, 1997, pp. 167-171.
6. Langley, C.S., D'Eleuterio, G.M.T., "Pose Estimation for Fixtureless Assembly Using a Feature CMAC Neural Network" 31st International Symposium on Robotics (ISR 2000), Montreal, Canada, May 2000, pp. 356 – 361.
7. *Lego Robotics at UNM* homepage, http://wotan.me.unm.edu/~starr/lego/lego.html
8. Kitto, K.L., "Teaching Industrial Robotics Using Multidisciplinary Product Design Projects", Proceedings of the 26th Annual Conference on Frontiers in Education, Salt Lake City, UT, 1996, Vol. 2, pp. 699-702.
9. Erevelles, W.F., "Implementing a Flexible Assembly Cell", Proceedings of the ASEE Annual Conference, Washington, DC, 1995, Vol. 1, pp. 711-715.
10. King, L., Hoag, M., Li, T., "Students teach what they learn to learn better what they were taught", SME Technical Paper 1998, ER98-324.
11. Kubel, E., "Focus on integrated manufacturing", Manufacturing Engineering, Vol. 119, No. 4, Oct 1997, pp. 100 – 106.
12. *Mike's Lego CAD* homepage, http://www.lm-software.com/saver
13. *LegoCAD* homepage, http://www.lego.com/dacta/legocad/
14. *Intelitek* homepage, http://www.intelitek.com
15. *Emco-Maier* homepage, http://www.emco-maier.com
16. *Denford* homepage, http://www.denford.com
17. Williams, A. *Microcontrolled Projects Using the BASIC Stamp*, CMP Books, Lawrence, KS, 2002.
18. Clague, K., Agullo, M., Hassing, L. C., *LEGO software power tools*, Syngress Pub., Rockland, MA, 2002

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