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Robotic Workcell Design Toolkit for Automated System Integration Education*

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Engineers constantly design and reconfigure automated systems to accommodate shifts in product design or manufacturing priorities. Often engineers require years of experience to become expert in this area. This paper addresses the motive, contents, and evaluation of a web-based robotic workcell design tool kit created to help students learn the design process systematically. The motive is based on interviews with application engineers at system integration companies. Components include problem, design and analysis. In addition, the toolkit allows the instructor to add new design problems that can capture users' mouse movements and key selections for research and teaching purposes.

Keywords: Robotic workcell; engineering design; automated manufacturing systems; system integration

INTRODUCTION

FROM THE ASSEMBLY and welding of automobiles to mixing and packaging pharmaceuticals, automated manufacturing systems, such as robotic workcells, play an essential role in the manufacturing industry. In addition, these systems play a significant role in increasing productivity and competence of manufacturing industries in this global economy. Hsieh [1] noted that there is a need to better understand how engineers develop expertise in automated system integration and to design a high quality comprehensive curriculum for automated system integration education in areas such as robotic system design.

Education in system integration and robotic workcell design is typically accomplished via a capstone course or senior design project [2]. In this type of instruction, students are expected to learn by doing, and learning outcomes may vary depending on the type and difficulty of the selected projects. Another approach is to create an interdisciplinary course, such as Industrial Automation [3], that allows students from different disciplines—such as mechanical and electrical engineering—to enroll. This approach can bridge the gap and create a common language across disciplines.

Reported robotic workcell system applications include automobile body welding [4], hydraulic cement mortar mixing [5], and transplanting of seedlings [6]. However, these reports focus on describing the design of entire systems with an emphasis on hardware design for a specific process and application; they are not explicitly designed for educational use. Similarly, in the area of software design, there have been numerous published efforts that describe the design of applications using software such as Delmia *IGRIP* [7, 8], Adept Digital Workcell Design (formerly *SILMA*) [9], and FESTO *Cosimir* [10, 11]. Baldini [12] describes the design of tool sets for simulation of robotic workcell design using a Petri-Net modeling approach. This modeling approach can detect potential interference among operations in a dynamic environment. However, these efforts primarily focus on applications such as off-line simulation, programming, and interference checking; they are not explicitly designed for instructional purposes. In addition, none of the described hardware and software applications are accessible to learners via the web.

Reported robotics education efforts have focused on topics such as economical ways to provide hands-on exposure to robotics technology [13], development of remote or virtual laboratories that allow robot operation or control [14–16] and, recently, on use of mobile robots for education [17–23]. In the case of mobile robots, the emphasis has often been on increasing popular awareness of robot technology via museum exhibits [16] or introducing robotics concepts in K-12 educational environments via classes and competitions [17–23].

There have been relatively few efforts to develop educational systems specifically to teach robotics in the context of manufacturing. Eydgahi [24] describes a system called ROBOTSIM, which has an educational focus. This system is designed to assist students in understanding and visualizing fundamental concepts of robot kinematics. But it does not address the topic of robotic workcell design.

McKee [25] has noted that a robotics curriculum should address the following questions:

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1. What is a robot system?
2. What use are robot systems?
3. What are the components of a robot system?
4. How does one build a robot system?

Regarding the fourth question, he notes that building a robot system involves integrating sensor, actuator and control devices, programming skills, and integration skills (e.g., the ability to translate a robot architecture into a real implementation). Many robotics education efforts have focused on the one or more of McKee's first three questions. Relatively few have focused on the design of robot systems, which involves higher level skills such as system design and integration.

This paper describes the design and evaluation of a robotic workcell design toolkit. The system allows learners to systematically design and evaluate different robotic workcell system design alternatives with an emphasis on teaching how to design a robotic workcell given a known request such as from a customer with constraints and budget limit. Hopefully this tool can help bridge the gap between practical needs and current methods of automated system design education.

The design of the toolkit is based on interviews with engineers about typical application engineer job tasks at system integration companies. The toolkit was developed in-house using Adobe (formerly Macromedia) Flash and includes three main components: Problem, Design, and Analysis. In addition, the toolkit can capture users' mouse movements and key presses for research and teaching purposes.

The Problem component includes a set of problems with written descriptions and pictures of a process to be automated. The user can use the mouse to select a problem of interest. The user interface is very flexible, allowing instructors to post new problems by changing the problem descriptions and image files.

The Design component includes two main steps: Process and Critical Path Method (CPM). This component facilitates activities related to conceptual design of a workcell. In the Process step, the user identifies and selects symbols corresponding to desired functions, then enters estimated costs and duration of each activity in a network. In the CPM step, the user can construct a CPM matrix of columns and rows to describe precedence relationships among activities. The system will automatically calculate cycle time for robotic workcell design activities.

The Analysis component includes three main parts: Layout, Simulation, and Show Designs. Layout shows the recommended layout for user's final design in terms of the number of robot and conveyer systems. Simulation allows the analysis of part flow performance to facilitate assessment of the properties of the user's conceptual design. In addition, the user can see calculated values for cycle time, critical path, and total cost. In Show Designs, the user can review different layouts in terms of operation time and cost of each step, overall cycle time and total cost.

The toolkit was evaluated by 27 undergraduate students who took a manufacturing automation and robotics course in Fall 2005. Students' comments and opinions were mostly positive and included suggestions for further improvement. Future directions include;

- adding an interactive tutorial component including a case study of designing an automated system;
- testing the prototype with a larger student population;
- soliciting input from industry experts;
- comparing and contrasting how similar problems are solved by experts and novices.

ROBOTIC WORKCELL DESIGN TOOLKIT

The Robotic Workcell Design Toolkit consists of the following components: problem, process, critical path method (CPM), layout, simulation, and design alternatives.

- *Problem.* The Problem component describes the problem to be solved using graphics and text. An administrator can add new problems by importing new picture and text description files. Figure 1 shows a sample screen for the Problem component.
- *Process.* The Process component allows the user to document the automated assembly process for the product. Primary categories of operations include *Feeding*, *Handling*, *Composing*, *Checking*, and *Adjusting*. Each operation has associated *time* and *cost* elements depending on the complexity of the operation. In general, as equipment cost increases, the corresponding cost element value also increases. The *time* element allows the user to enter an estimate of the time required for each operation. To provide increased flexibility for instructors, the cost elements for the process are stored in a text file. Cost elements can be easily modified by changing the text file. Figure 2 shows a sample Process screen.
- *Critical Path Method.* In this stage, users can specify the relationships among operations and which operations have precedence over others. This allows users to identify the critical path and cycle time for the entire assembly process. They can then further determine the number of workstations needed for the automated system, manipulate the combination of operations, or rearrange the precedence relationships among operations in order to reduce cycle time and/or number of workstations. This is a very essential step during system design; engineers must make sure their system meets customers' requirements in terms of cycle time and production rate.
- *Layout.* The toolkit currently provides four different layouts: workcell with one robot, workcell

Problem 1. Customers often ask engineers to come up with a proposal for automating a process within a reasonable budget and time for delivery. This prototype allows users to document the conceptual design of a proposal.

This page(1.Problem) will initialize your design for the next problem.

Fig. 1. Example of problem screen.

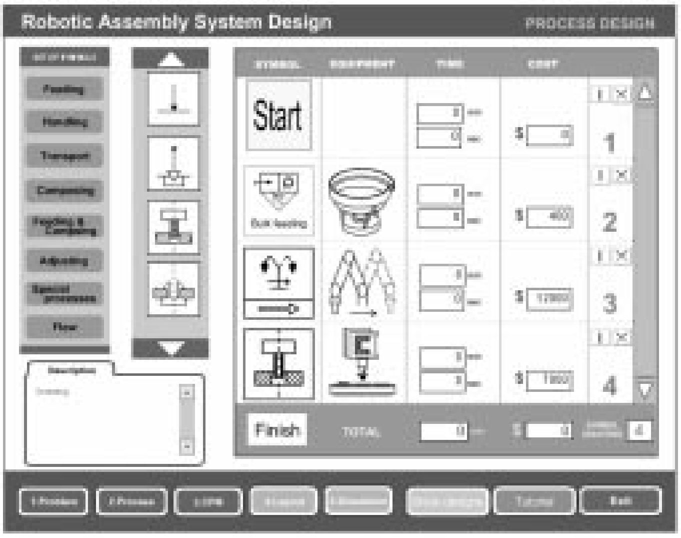


Fig. 2. Example of process screen.

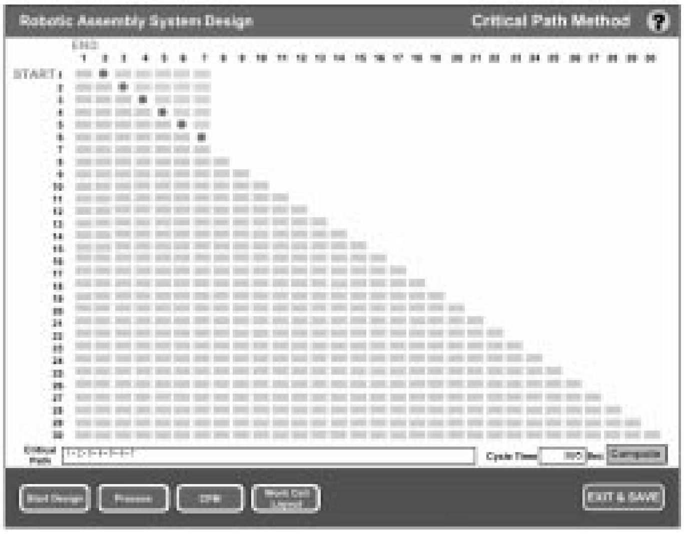


Fig. 3. Example of critical path method (CPM) screen.

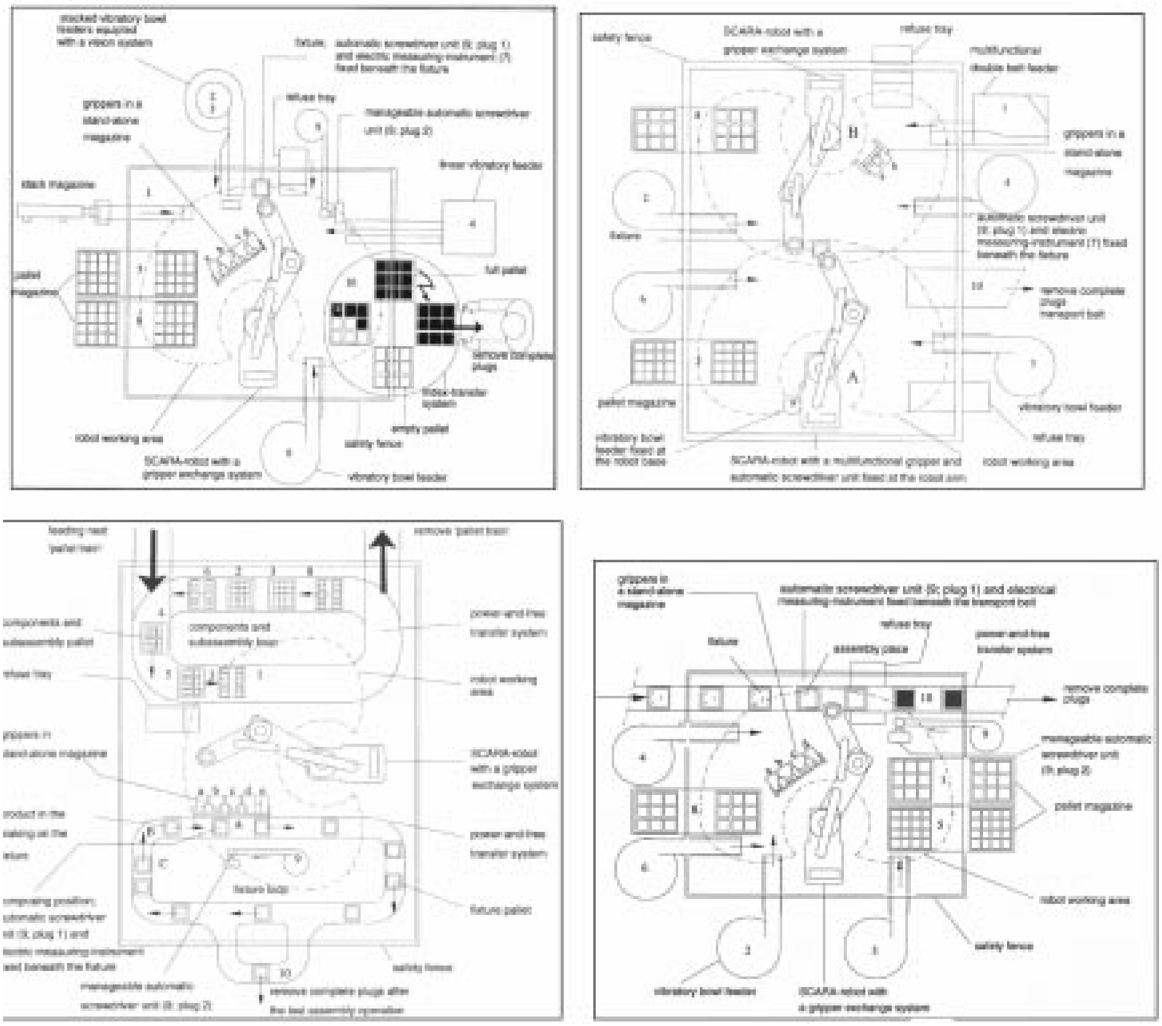
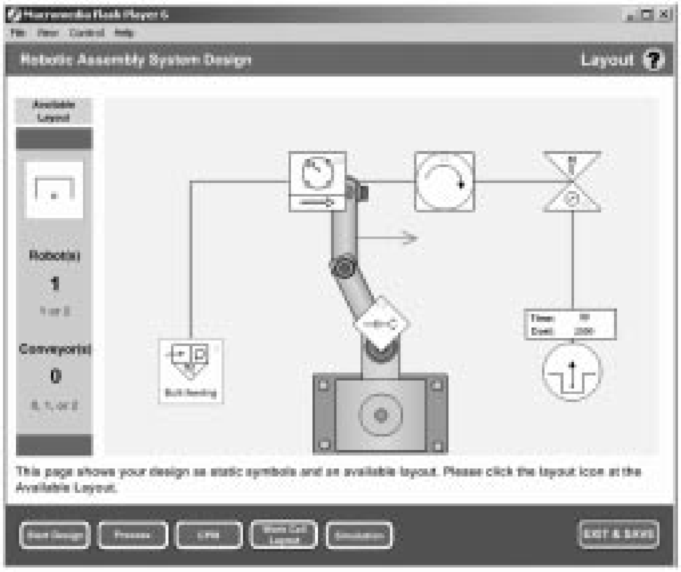


Fig. 4. Generic layouts for robotic workcell design [12].

with two robots, workcell with one conveyor, and workcell with two conveyors. The toolkit will automatically select one of the four available layouts based on the designed operations. These layouts are abstracted from the generic configurations shown in Fig. 4, which are adapted from Rampersad [26]. Figure 5 shows a snapshot of the Layout component.



This page shows your design as static symbols and an available layout. Please click the layout icon at the Available Layout.

Fig. 5. Layout for workcell with one robot.

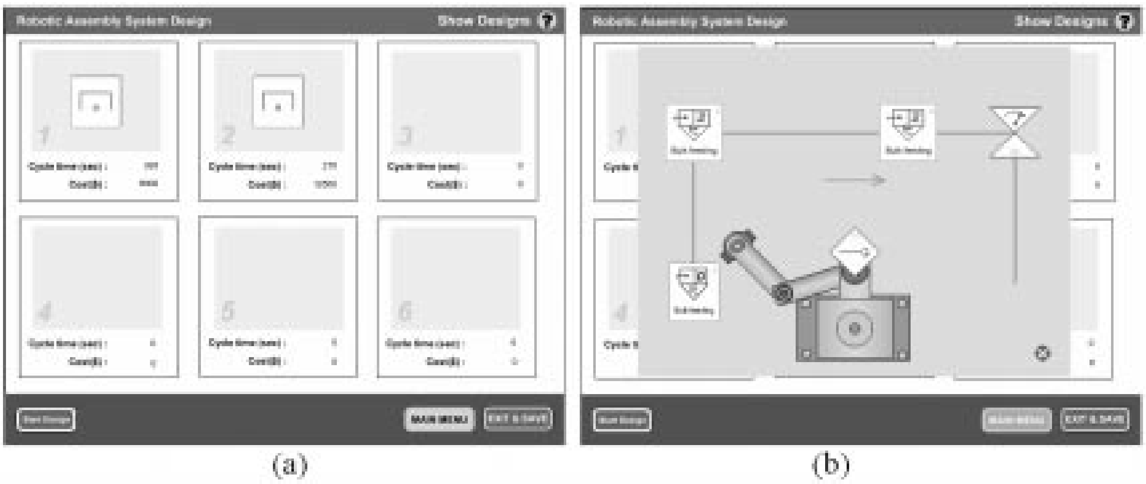


Fig. 6. (a) Design alternatives; (b) close-up of selected design alternative.

- *Simulation.* This component simulates the operation of the designed system. Users can evaluate a design by viewing an animation of the system.
- *Show Design.* The Show Design component records all the design alternatives created by the users. Users can click on a design to see the design details. Users can also compare and contrast design alternatives and return to the main menu to create an improved design. Figure 6 shows some screens from this component.

METHODOLOGY

A prototype version of the toolkit was evaluated by 27 undergraduate students in Fall 2005. The objectives were to find out:

1. Can student translate a series of operations into a network structure?
2. How do students use the toolkit? Can they enter data into toolkit?
3. Student opinions about various aspects of the toolkit, such as effectiveness, ease-of-use, and relevance to their education.
4. Student comments.

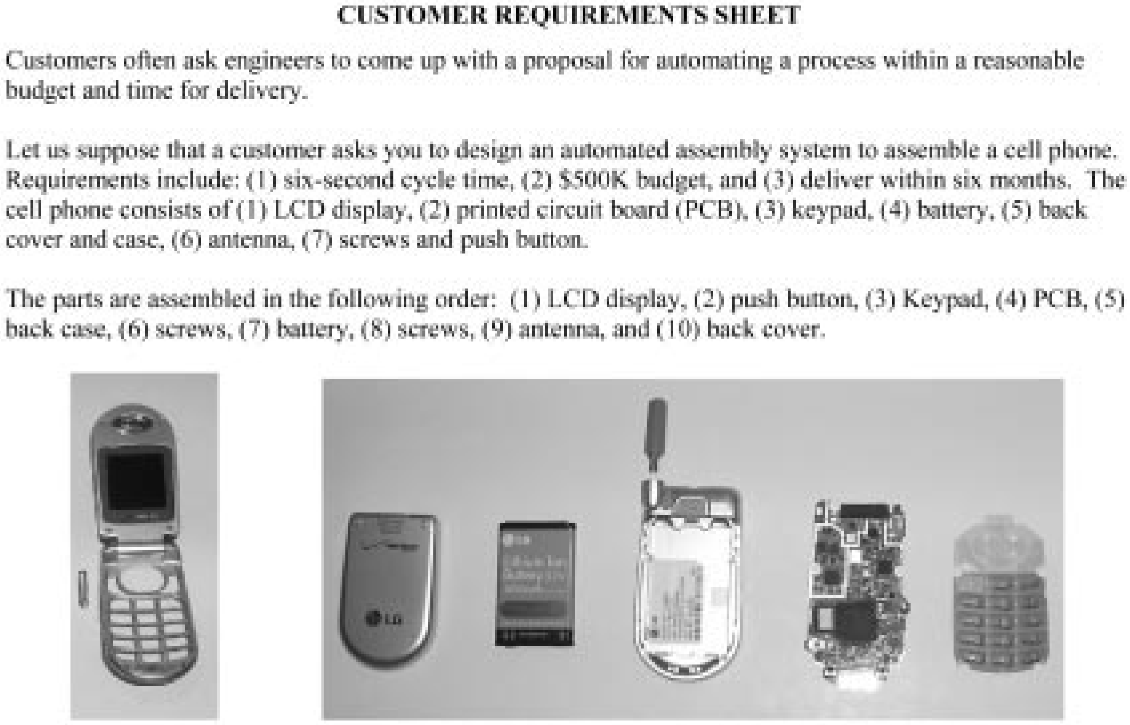
In addition, a learning styles inventory was administered to find out more about these students' learning styles in order to assess possible relationships between learning style and response to the toolkit.

Participants, materials, and experimental procedures

- *Participants.* Participants in this evaluation were 27 upper-level undergraduate students who were taking a Manufacturing Automation and Robotics course which emphasizes learning how to program ladder logic. Evaluation activities took place during lab time. There were two labs of 14 and 13 students each.
- *Materials.* Students were given a sheet describing customer requirements, a student opinion survey, and Felder and Soloman's Index of Learning Styles (ILS) survey [27]. The *customer requirements* described the product to be automated, the assembly operations and sequence, budget constraints, and desired cycle time and production rate (Fig. 7). The *opinion survey* asked students to rate various characteristics of the prototype on a 7-point Likert scale. The ILS is a 44-question survey that asks users about their learning preferences. The ILS ranks users along four attribute continuums: Active/Reflective, Sensing/Intuitive, Visual/Verbal, and Sequential/Global. Each attribute pair (e.g., Active/Reflective) represents opposite ends of a 12-point scale. More information about the ILS can be found at http://www.ncsu.edu/felder-public/ILSpage.html. In addition, the system automatically captured user data such as mouse movements, key presses, and time spent using the toolkit.
- *Procedure.* The ILS was administered first to assess students' learning styles. Students were then given the customer requirements sheet and asked to generate at least one design on a blank sheet of paper and then implement the design using the toolkit. Afterwards they completed the opinion survey. The evaluation activities were treated as additional lab activities and took place toward the end of the semester, to maximize the likelihood that students had been exposed to fundamental concepts such as facility layout design, balancing, network analysis, and automated system design. Not all of these concepts had been covered in the Manufacturing Automation and Robotics course; some should have been covered in other required courses.

DATA ANALYSIS AND RESULTS

This section summarizes the results of the evaluation in terms of the objectives listed above.



CUSTOMER REQUIREMENTS SHEET

Customers often ask engineers to come up with a proposal for automating a process within a reasonable budget and time for delivery.

Let us suppose that a customer asks you to design an automated assembly system to assemble a cell phone. Requirements include: (1) six-second cycle time, (2) $500K budget, and (3) deliver within six months. The cell phone consists of (1) LCD display, (2) printed circuit board (PCB), (3) keypad, (4) battery, (5) back cover and case, (6) antenna, (7) screws and push button.

The parts are assembled in the following order: (1) LCD display, (2) push button, (3) Keypad, (4) PCB, (5) back case, (6) screws, (7) battery, (8) screws, (9) antenna, and (10) back cover.

Fig. 7. Customer requirements sheet.

Can students translate a series of operations into a network structure?

All the students generated at least one design for an automated system for cell phone production. Figure 8 shows some of the network structures generated by the students.

How do students use the toolkit? can they enter data into the toolkit?

Figure 9 shows a sample of selected log data for a few students, with respect to time spent on the system and the number of alternative designs completed. This data log is created whenever a user logs into the system and is saved when the user pressed the Exit button. The students spent from 17 to 64 minutes in the system and all students completed at least one alternative design using the system. In addition, the students spent less than 7 minutes using the tutorial section on average.

- *Opinion Survey.* Student ratings were positive for all items. In general, students felt that the prototype was interactive, relevant, and easy to use and understand. For example, on a scale of 1 to 7, where 1 = strongly disagree and 7 = strongly agree, the mean response to the statement *I would like to have more tools like this to help me learn* was 5.1. The mean response to the statement *The animations help me to visualize the process* was 5.4.
- *Learning Styles.* Figure 10 shows a summary of results for all four attribute continuums from the Index of Learning Styles for the students in this study. These data suggest that many of these students had Active, Sensing, and Visual learning styles. Figure 11 shows results for the Visual/ Verbal attribute, indicating that the majority of these students considered themselves to be primarily Visual learners. This finding is consistent with results from the opinion survey; for

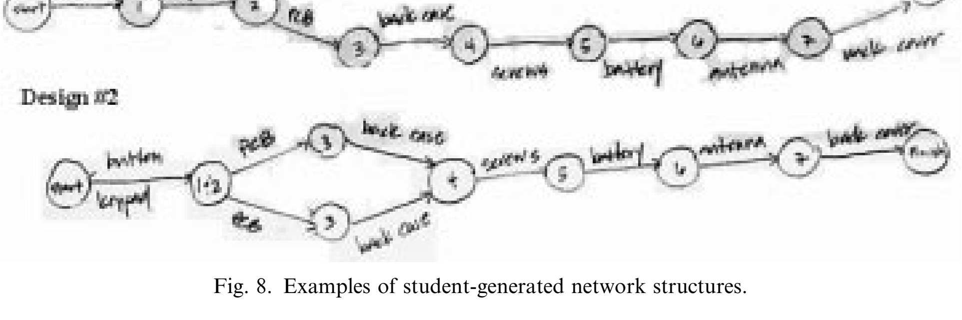
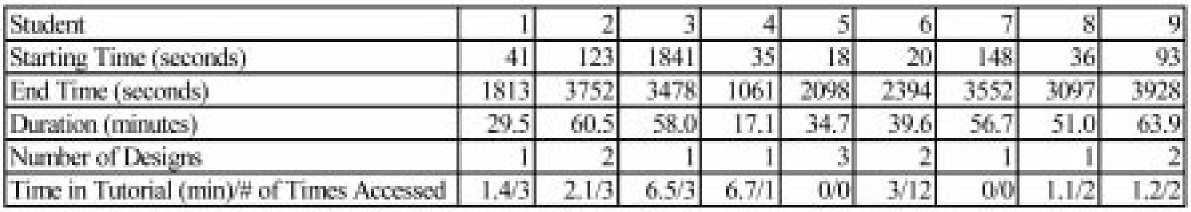


Fig. 8. Examples of student-generated network structures.



Student	1	2	3	4	5	6	7	8	9
Starting Time (seconds)	41	123	1841	35	18	20	148	36	93
End Time (seconds)	1813	3752	3478	1061	2098	2394	3552	3097	3928
Duration (minutes)	29.5	60.5	58.0	17.1	34.7	39.6	56.7	51.0	63.9
Number of Designs	1	2	1	1	3	2	1	1	2
Time in Tutorial (min)/# of Times Accessed	1.4/3	2.1/3	6.5/3	6.7/1	0/0	3/12	0/0	1.1/2	1.2/2

Fig. 9. Sample log data.

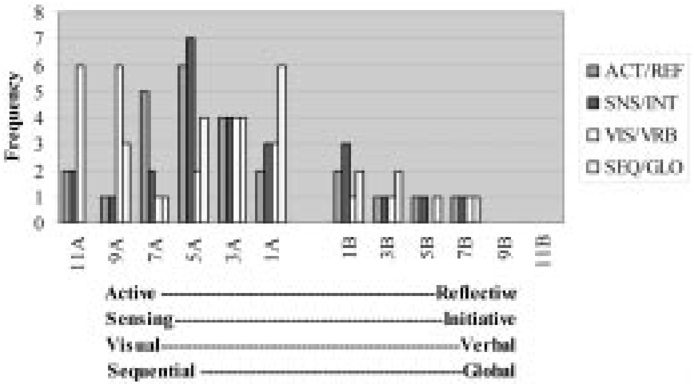


Fig. 10. Distribution of students' learning style characteristics.

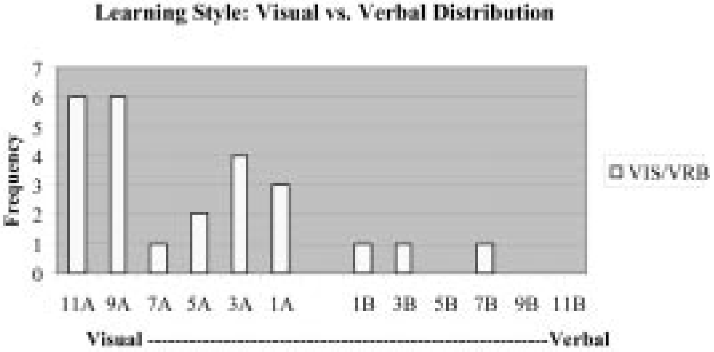


Fig. 11. Summary of ILS results for Visual/Verbal attribute.

example, the mean response to the statement *The graphics/animations helped me visualize the process* was 5.4 out of 7.

- *Student Comments.* Student comments can be summarized as follows: Many students liked the graphics and animations; they felt better able to visualize steps in system design. Some students saw the prototype toolkit as a good tool for building, studying, and testing different design alternatives. Some students suggested that inclusion of a comprehensive tutorial which covers basic concepts and includes case studies illustrating how an automated system is built would be helpful. Overall, students thought the prototype toolkit was helpful for learning system design and integration.

CONCLUSIONS

This paper described the need for a system to teach robotic workcell design and the contents of a prototype robotic workcell design toolkit, and presented evaluation results gathered from 27 students enrolled in a Manufacturing Automation and Robotics course. Students commented that the tool is valuable, because it allows them to build, analyze, and test the design of a robotic workcell system. They also suggested the addition of an on-line tutoring component to cover basic system design concepts.

Future directions include (1) addition of an interactive learning tutorial that includes case studies about automated system design; (2) testing the prototype with a larger student population, (3) soliciting industry experts' input about the prototype; and (4) comparing and contrasting how experts and novices solve similar problems.

In addition, the log files contain a tremendous amount of data for analysis. For example, the mouse tracking and key press data can be used to investigate how much time users spend on each event, page, and design step, as well as the sequence of user actions. Thus, if a user spends a lot of time on one page, this may suggest that he or she is thinking or does not know what to do next. If a page is not visited by most users, it may be because the users did not notice the controls to access the page. If a user moves back and forth between pages quickly, it may be because he or she wants to know the effect of changing a parameter. This type of analysis is extremely time-consuming, but can be very revealing. Future work will investigate these data more closely.

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