ROBOTIC ASSEMBLY CELL*

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Abstract — *Results concerning the development of a Robotic Assembly Cell are presented. The main components of the cell are a Kuka KR3 robotic manipulator and an Amtec PowerCube reconfigurable robotic manipulator. This paper presents an overview of the Robotic Assembly Cell as well as results concerning its implementation and use. The various components of the cell were set-up by students as either team projects for their capstone senior design course or as independent senior projects.*

Index Terms —*laboratory, manufacturing, robotics*

INTRODUCTION

The development and implementation of a *Robotic Assembly Cell* that is used for educational purposes by undergraduate engineering and computer science students is considered. The Robotic Assembly Cell is located in the School of Engineering and Computer Science's S. and R. Sharf Computer Integrated Manufacturing (CIM) Laboratory at Oakland University. An overview of the Sharf CIM Laboratory is presented at the following URL.

http://www.oakland.edu/~vantil/sharflab.html (1)

Note that this webpage is updated whenever new results concerning the ongoing development and use of the Sharf CIM Laboratory are available.

Oakland University courses which will use the Robotic Assembly Cell include:

- SYS 101 Introduction to Systems Engineering
- SYS 422 Robotic Systems
- SYS 484 Flexible Manufacturing Systems
- SYS 490 Independent Project
- SYS 491 Systems Engineering Senior Design Project
- EE 491 Electrical Engineering Senior Design Project
- ME 492 Mechanical Engineering Senior Design Project
- CSE 447 Computer Communications

These courses are taken by undergraduate students with majors in computer engineering, electrical engineering, mechanical engineering, systems engineering, and computer science. The cell, or its various components, have been used by students in the SYS 422, SYS 484, SYS 490, SYS 491 and EE 491 courses to date. Note this list of courses is representative of the interdisciplinary nature of this project. The authors represent all three departments in the school: Electrical and Systems Engineering; Mechanical Engineering; as well as Computer Science and Engineering.

The Robotic Assembly Cell is the third major component in the Sharf CIM Laboratory, the existing components being a *Flexible Manufacturing Cell* and a *Factory Flow Simulator* (formerly known as the Intelligent Factory). Information concerning these two existing components is presented in a paper describing the predecessor to the Sharf CIM Laboratory, the *Artificial Intelligence and Manufacturing (AIM) Laboratory*, [1].

The AIM Laboratory was developed with funding from the National Science Foundation, [2] and [3] as well as with matching funds from Fanuc Robotics N.A. Inc. Further information concerning this laboratory is available from the URL given in (1) and then following the link to the Artificial Intelligence and Manufacturing Laboratory.

COMPONENTS OF THE CELL

The centerpiece of the cell are a six-axis Kuka KR3 robotic manipulator, Figure 1, and an Amtec PowerCube reconfigurable robotic manipulator, Figure 2. The PowerCube system consists of several interchangeable servo-modules that can be linked together to form a kinematic chain with up to six rotational axes and one translational axis. These servo-modules are "daisy-chained" together and the resulting kinematic chain is readily controlled using PowerCube software tools installed on a PC in an open-architecture environment.

The Kuka KR3 manipulator and the PowerCube manipulator are mounted to a large platform on which the various assembly components, such as flexible fixtures, can be arranged, Figure 3. The final component in the Robotic Assembly Cell is a Fanuc visLOC vision system. The set-up of the Fanuc visLOC vision system was completed by a student in the SYS 490 Independent Project course.

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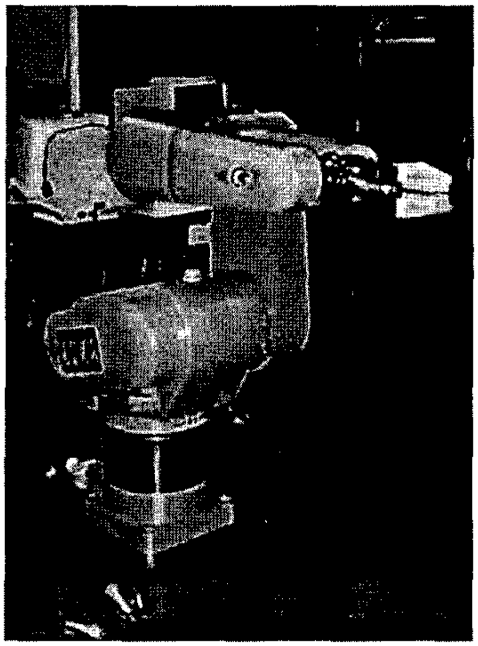

FIGURE 1
KUKA KR3 ROBOTIC MANIPULATOR

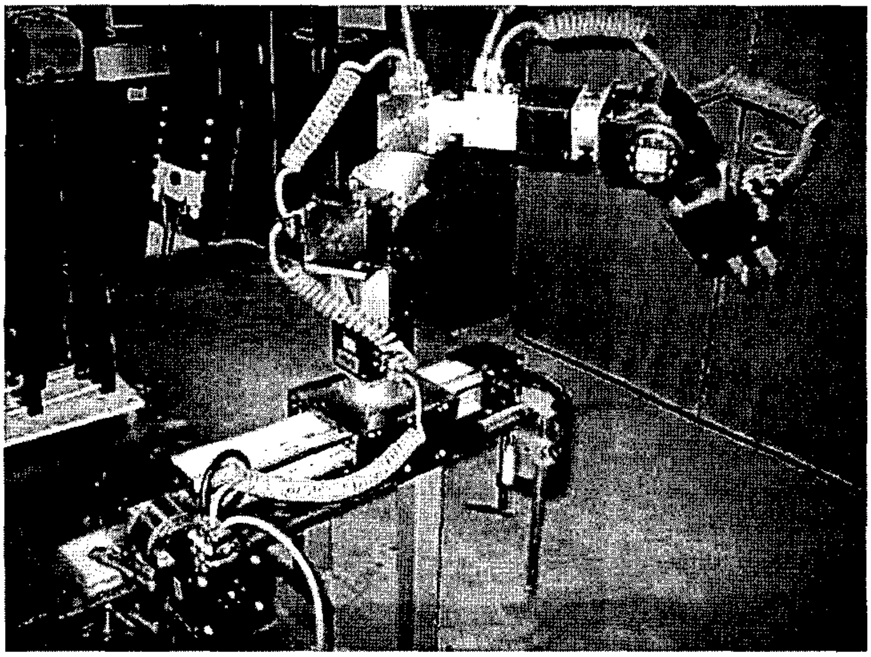

FIGURE 2
POWERCUBE RECONFIGURABLE ROBOTIC MANIPULATOR

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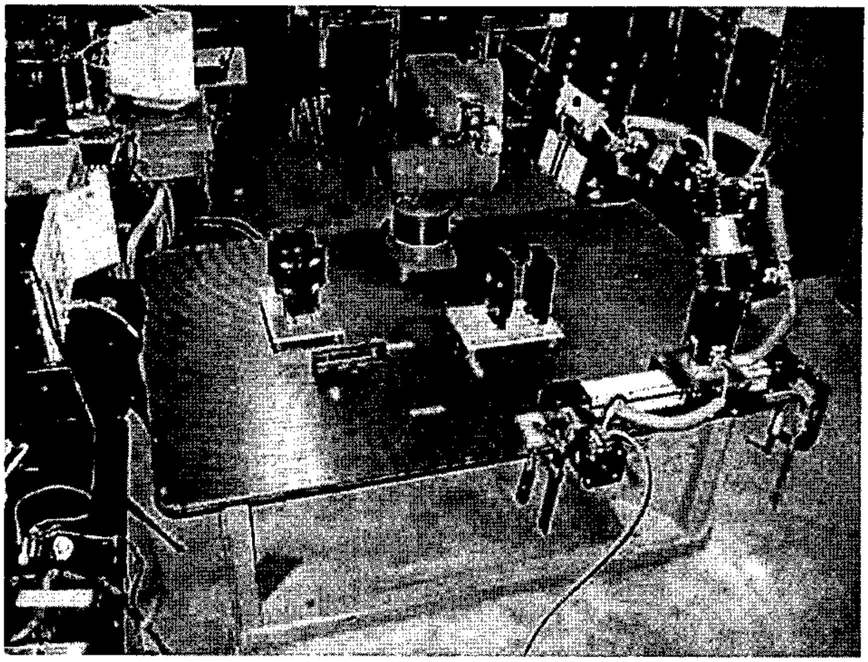

FIGURE 3
PLATFORM FOR THE ROBOTIC ASSEMBLY CELL

The set-up and implementation of the PowerCube manipulator was completed during the 2001-02 academic year by teams of students in the capstone SYS 491 Systems Engineering Senior Design courses. The results of their efforts are presented on a student developed website reached at the URL given in (1) and then following the link to the websites concerned with the PowerCube manipulator.

ASSIGNMENTS USING THE ROBOTS

The Robotic Assembly Cell is used for laboratory assignments and projects by undergraduate students in robotics courses as well as students in manufacturing and capstone engineering design courses. This section will focus on the use of the PowerCube and Kuka manipulators for robot based laboratory assignments and projects. These assignments consider manipulator kinematics and dynamics, trajectory planning and the programming of industrial robots, [4] and [5].

Robot based laboratory assignments and projects are conducted using either the Kuka KR3 robotic manipulator or the PowerCube manipulator, rather than the entire Robotic Assembly Cell. These type of robot based laboratory assignments and projects are primarily given in the SYS 101 Introduction to Systems Engineering, SYS 422 Robotic Systems, SYS 484 Flexible Manufacturing Systems and SYS 491 Systems Engineering Senior Design courses.

An example of a robot based assignment using the PowerCube manipulator involves the development and application of direct and inverse kinematic models to control a specified kinematic configuration. Another example considers the application of the Jacobian matrix for trajectory planning using this kinematic configuration.

The Kuka KR3 manipulator is used for robot programming assignments such as task planning (SYS 422 Robotic Systems and SYS 484 Flexible Manufacturing Systems courses) or simple pick-and-place programming (SYS 101 Introduction to Systems Engineering course).

Note that one of the primary topics considered in the SYS 422 Robotic Systems course is the design, analysis and control of an open kinematic chain. The open-architecture nature of the PowerCube manipulator allows students to implement and test the kinematic and dynamic models that they have studied and developed in the class on an industrial grade robotic manipulator. In addition, the configuration of the kinematic chain can be changed every semester due to the PowerCube manipulator's ability to be "daisy-chained" into different configurations.

The closed-architecture nature of most industrial robot controllers (including the Kuka KR3's controller as well as the controllers of three other robots currently in the Sharf CIM Laboratory: a Fanuc ARCmate 100; Fanuc SR100i and Fanuc LRmate) limit their usefulness to application based assignments. Such robotic systems are useful for

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introducing students to robotic manipulators, learning about robotic programming language environments, and for robotic application based assignments such as task planning or automated assembly operations.

An example of a robotic application based assignment may require the students to program the robot to track a specified trajectory. While such an assignment will require the students to learn and use the robot's programming environment for completing an assigned task, they do not gain any insight into how the robot controller implements their "high-level" tracking commands. When the students program the robotic manipulator to track a straight line, the closed-architecture nature of the industrial controller prevents them from observing how it converts this "high-level" command into the desired result.

The open-architecture nature of the PowerCube manipulator not only allows students to observe how such commands are implemented, but to design and implement their own kinematic and dynamic control algorithms. Hence, the use of the PowerCube manipulator in conjunction with the Sharf CIM Laboratory's Kuka and Fanuc robots greatly enhances the learning environment in Oakland University courses involving robots and robotic applications.

ASSIGNMENTS USING THE ENTIRE CELL

Next, design and application based laboratory assignments and projects for inclusion in the SYS 484 Flexible Manufacturing Systems, SYS 491 Systems Engineering Senior Design, EE 491 Electrical Engineering Senior Design, ME 492 Mechanical Engineering Senior Design and CSE 447 Computer Communications courses are considered. Assignments and projects for these courses will focus on using the entire Robotic Assembly Cell. Since the Robotic Assembly Cell has recently been completed, plans are for conducting such design and application based assignments beginning in the 2003 fall semester.

An example assignment for the SYS 484 Flexible Manufacturing Systems course would require the students to design and implement an automated assembly process. The students would be provided with a set of parts to assemble as well as a set of flexible fixtures. The students would be required to set-up the cell, write and debug all robotic programs as well as design and construct any specialized fixtures or tooling required to assemble the parts into a product or subassembly.

Note that while the design and implementation of a particular automated assembly process may seem to be straightforward, it is usually not a trivial task, [7]. Such assignments not only provide students with excellent manufacturing design projects, but they also provide them with an appreciation of the difficulty involved in automating an assembly process. Students will learn first-hand why the most efficient and flexible way to complete some assembly operations, such as many on an automobile assembly line, is to use manual labor.

An example assignment for the SYS 491 Systems Engineering Senior Design or the ME 492 Mechanical Engineering Senior Design courses would require the students to design and construct a force compliant gripper for the robot to be used during assembly operations, [8].

ASSESSMENT

Assessment data concerning the Robotic Assembly Cell were collected from two sources. The first source was students using the cell and its components while the second source was the project's *Industrial Advisory Team.* The Industrial Advisory Team contained three engineers from local companies with expertise in robotics and manufacturing. The team's mission is to provide feedback concerning the quality and appropriateness of the laboratory assignments and projects from the team members' industrial perspective.

The student assessment data was collected from the school's end-of-course student evaluation website and are presented in Table 1. Responses to the evaluation questions are on a 1-5 scale with (1 = unsatisfactory), (2 = poor), (3 = average), (4 = good) and (5 = excellent). Note that the average rating to all questions is a 4.5. This assessment data was collected from the SYS 422 Robotic Systems, SYS 484 Flexible Manufacturing Systems and SYS 491 Systems Engineering Senior Design courses.

Laboratory assignments #2, #3 and #4, referenced in the final two questions of Table 1, where first conducted using the Sharf CIM Laboratory's Fanuc LRmate robot. These same laboratory assignments were also conducted using the PowerCube robot during the 2003 winter semester.

Since the kinematics of the LRmate robot cannot be modified, students in future classes could obtain the solutions to these laboratory assignments for that robotic manipulator. However, the kinematics of the PowerCube robot can be modified before each semester. Hence, these three assignments can be reused in future courses by simply changing the robot's kinematic configuration.

Assessment data from the three members of the project's Industrial Advisory Team are presented in Table 2. The rating scale used for this assessment differs slightly from that of Table 1. The rating scale used in Table 2 is also a 1-5 scale with (1 = poor), (2 = fair), (3 = good), (4 = very good) and (5 = excellent).

Table 2 lists thirteen educational objectives for an engineering capstone design project, [6]. The Industrial Advisory Team was asked to rate how well the Robotic Assembly Cell and its components are, or could be, used to help students to obtain these educational objectives in their design projects. The team members were provided with copies of capstone design assignments using the Robotic Assembly Cell given in the SYS 491 Systems Engineering Senior Design course as well as the student's results. In

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addition, team members were given outlines for proposed capstone design projects using the cell. Note that the average rating to all objectives is 4.7.

TABLE 1
STUDENT ASSESSMENT

QUESTION	AVE. RATING	# RESPONSES
Rate the value of the laboratory component of the course.	4.7	87
In what shape was the equipment that you used in the Sharf CIM Laboratory?	4.5	87
In general, how well did the equipment in the Sharf CIM Laboratory help you to understand the concepts presented in this class?	4.4	87
How well did lab #1 help you to understand the operation of industrial robots?	4.7	87
How well did lab #1 help you to understand the structure of an industrial robotic language?	4.4	42
How well did lab #1 help you to understand the concept of task planning?	4.2	26
How well did lab #2 help you to understand the Denivat-Hartenberg rules for placing coordinate systems on a robotic manipulator?	4.6	42
How well did lab #3 and lab #4 help you to understand the construction of a robot's forward and reverse kinematic solutions?	4.4	42

CONCLUSIONS AND FUTURE PLANS

This paper considered the development of an Robotic Assembly Cell. Cell development involved the implementation of the Kuka KR3 manipulator and a PowerCube robotic manipulator as well as their use in class projects and laboratory assignments. The set-up of the PowerCube robot was conducted by engineering students in their capstone senior design course.

This project continues with the delivery of the Fanuc visLOC vision system. The vision system has been set-up by a engineering student as a senior project. Current plans are for a student capstone design team to integrate the vision system into the Robotic Assembly Cell.

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TABLE 2
INDUSTRIAL ADVISORY TEAM ASSESSMENT

EDUCATIONAL OBJECTIVES	AVE. RATING
Information Gathering: Information is identified and obtained to support the design process and design decisions.	4.3
Problem Definition: Design goals and specific design requirements are defined as targets for a successful design.	5.0
Idea Generation: New ideas and concepts are gathered and created for use in the design.	5.0
Evaluation: Appropriate methods and tools are used to determine how well concepts meet requirements.	3.7
Decision Making: Design decisions are based on proper consideration of evidence and issues.	5.0
Implementation: Design decisions are synthesized and converted into design products or systems.	5.0
Process Development: Design activities are managed and refined to support design effectiveness and continuous improvement.	4.0
Roles & Responsibilities: Design team members establish roles and perform responsibilities needed for their assignment.	5.0
Attitude & Climate: Design team members create and establish a climate supportive of team success.	5.0
Resource Management: Design team assess, accesses, and utilizes team resources to achieve its goals.	4.3
Operating Procedures: Design team establishes and uses processes to ensure effective team interactions and productivity.	5.0
Style & Language: Results are presented in language and style making it understandable and attractive to the target audience.	4.5
Value & Reliability: Results presented are complete, relevant to needs, and accurate.	4.7

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