

An Interdisciplinary Laboratory for Teaching Artificial Intelligence and Manufacturing*

ROBERT P. VAN TIL, SANKAR SENGUPTA, RONALD J. SRODAWA, PATRICK E. DESSERT and CHRISTIAN C. WAGNER

School of Engineering and Computer Science, Oakland University, Rochester, MI 48309, USA.

E-mail: vantil@oakland.edu

The Artificial Intelligence and Manufacturing (AIM) Laboratory is an interdisciplinary facility for engineering and computer science education. The AIM Laboratory was conceived to educate both engineering and computer science students concerning the integration of computer systems in the manufacturing environment. Its facilities are used to conduct both small individual laboratory assignments as well as large team-based projects. These assignments and projects may primarily emphasize either the manufacturing systems or the computer systems as well as focusing on the integration of these systems.

INTRODUCTION

GLOBAL COMPETITION has played a major role in the awakening of US industry to the need to improve the understanding and control of their manufacturing processes. Hence, many universities in the US have in recent years developed manufacturing laboratories. One of these is the Oakland University School of Engineering and Computer Science's Artificial Intelligence and Manufacturing (AIM) Laboratory. Seed funding for the AIM Laboratory was provided by the National Science Foundation's Instrumentation and Laboratory Improvement (ILI) Program, [1, 2]. Additional funds and equipment were provided by Fanuc Robotics N.A. Inc., Siemens Energy and Automation Inc. and Carnegie Group Inc.

The AIM Laboratory is an interdisciplinary project proposed and developed by engineering and computer science faculty from Oakland University's Electrical and Systems Engineering Dept. and its Computer Science and Engineering Dept. Its purpose is to provide facilities for education concerning issues involving automated manufacturing as well as the application of artificial intelligence techniques and computer networks to manufacturing systems. Students also learn about the integration of people in the modern manufacturing environment through their involvement in team-based projects.

Currently, two major systems in the AIM Laboratory are used to satisfy its educational mission. These are the Intelligent Manufacturing Cell and the Intelligent Factory. The Intelligent

Manufacturing Cell and the Intelligent Factory were developed, and are continuously being modified, using several individual student projects as well as class-based projects. These projects allow students the opportunity to be involved in the design and development of hardware and/or software for a complex manufacturing system.

DESCRIPTION OF AIM LABORATORY FACILITIES

Intelligent Manufacturing Cell

The Intelligent Manufacturing Cell, Fig. 1, currently contains:

- an Emco Compact 5 Computer Numerically Controlled (CNC) lathe with several in-house modifications;
- an Emco F1 CNC mill with several in-house modifications;
- an Fanuc Arcmate 100 robotic manipulator with RJ2 controller for transporting parts within the cell;
- a PC-based cell controller with a SCO Open-Desktop operating environment;
- a PC-based Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) system (containing AutoCAD and Emco CAM software) with post-processing capabilities;
- networking connectors that provide an interface among all equipment in the cell.

One of the modifications to the CNC lathe involves the integration of an open-architecture controller (a National Instruments PC motor controller—the design and implementation of this interface was accomplished as a class project).

* Accepted 16 March 2000.

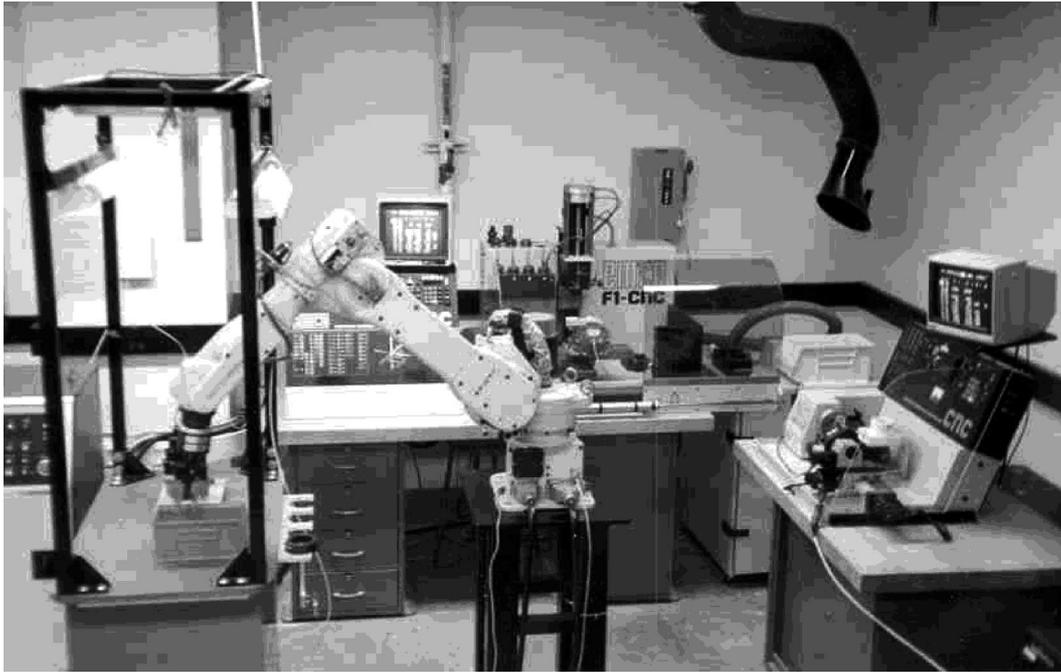


Fig. 1. Intelligent Manufacturing Cell.

Hence, the lathe may be run using either its Emco proprietary CNC controller or the open-architecture PC controller. This open-architecture controller allows for 'low-level' control assignments as well as assignments involving the development and implementation of 'high-level' machining algorithms, which may include the application of artificial intelligence techniques, to be conducted.

Laboratory assignments using the Intelligent Manufacturing Cell vary in complexity. Some assignments involve using individual components of the cell; examples include an assignment concerned with setting-up and programming the CNC mill or one to develop and implement a communication protocol for the cell's Local Area Network (LAN). Illustrative examples of such laboratory assignments are presented in the Appendix. Other assignments involve the use of the cell as an integrated unit. The design project for the Systems Engineering (SYS) 484 Flexible Manufacturing Systems course presented in the 'Course Projects Conducted in the AIM Laboratory' section is one such example.

Intelligent Factory

The Intelligent Factory, Fig. 2, consists of the several major components integrated into a complete manufacturing system. It currently contains the following five major components:

- *Computer Controlled Inventory System.* An Eshed Automated Storage/Retrieval System (AS/RS) fulfills this role. A Fanuc LRmate robotic manipulator is used for loading/unloading the AS/RS. The LRmate robot was donated by Fanuc Robotics N.A. Inc.

- *Simulated Manufacturing Cells.* This task is accomplished by four cells, each of which consist of a PC and a Minibot robotic manipulator. Each cell can be programmed to simulate the behavior of an actual manufacturing cell.
- *Computer Controlled Transportation System.* A computer controlled loop-conveyor provides this function. It is used to transport parts between the AS/RS and the various simulated manufacturing cells. The conveyor system was also donated by Fanuc Robotics N.A. Inc. Note that the conveyor can be controlled by either the factory controller or the PLC.
- *Programmable Logic Controller (PLC).* A Siemens SLC 500 PLC can be used to control the conveyor. The PLC was donated by Siemens Energy & Automation Inc.
- *Factory Controller.* All systems in the factory are networked to, and supervised by, a Sun Ultra SPARC work-station factory controller. Students design and implement processes for controlling the factory on this computer.

Note that the Intelligent Factory is a physical simulator of a real factory. It contains many of the physical constraints of a real manufacturing facility, for example, communication delays, buffers of finite size and transportation delays. A physical simulator offers the opportunity to identify constraints which are otherwise not recognized by a simulation model.

The Intelligent Factory is very effective in resolving design-related issues since it can capture spatial relationships among system components. It cannot replace the need of, and emphasis on, simulation studies of such facilities. In fact, the availability of a physical simulator in conjunction



Fig. 2. Intelligent factory.

with computer simulation enhances the learning environment.

The Intelligent Factory provides a standalone facility to study different components of a manufacturing system as well as the integration of these components into a Computer-Integrated Manufacturing (CIM) environment. Studying integration issues provides a number of benefits to the students. Students can identify and study problems associated with communications among the various components as well as the need for a standard communication protocol and its impact on the performance of a CIM system.

Scheduling is another important problem area that can be studied using the Intelligent Factory. The performance of different scheduling rules can be studied for different system configurations.

As with the Intelligent Manufacturing Cell, assignments involving the Intelligent Factory may be concerned with individual components, such as programming the PLC to control the conveyor system, or may involve using the entire system.

EFFECTS OF THE AIM LABORATORY ON CURRICULUM

With the implementation of the AIM Laboratory, the quality of five engineering and two computer science courses at Oakland University has been enhanced. The three courses which receive the primary benefits from this laboratory are SYS 484 Flexible Manufacturing Systems, SYS 684 Computer Integrated Manufacturing,

and Computer Science and Engineering (CSE) 412 Artificial Intelligence in Manufacturing. Other courses which benefit from the AIM Laboratory include SYS 101 Introduction to Systems Engineering, SYS 422 Robotic Systems, SYS 491 Senior Design and CSE 650 Advanced Operating Systems. In addition, engineering and computer science faculty members supervise many varied undergraduate and graduate student independent projects using the facilities of the AIM Laboratory.

Three short examples of how the AIM Laboratory's facilities are used in some of these courses are as follows. Examples of actual course projects conducted using the AIM Laboratory are presented in the next section while illustrative examples of laboratory assignments are presented in the appendix.

- *SYS 484 Flexible Manufacturing Systems Course.* The AIM Laboratory is used to study how computer controlled equipment improves the flexibility of the manufacturing environment. Laboratory assignments using individual components of the Intelligent Manufacturing Cell (CNC machines, CAD/CAM system or the robot) as well as those of the Intelligent Factory (PLC or the robots) are given. In addition, a team-based project to design and produce products using the Intelligent Manufacturing Cell is assigned.
- *SYS 684 Computer Integrated Manufacturing Course.* Assignments highlight how the automated equipment in either the Intelligent Manufacturing Cell or the Intelligent Factory

can be used in an integrated environment. These assignments focus on the manufacturing applications of this environment rather than the design and development of the network hardware and software used to integrate the systems.

- *CSE 412 Artificial Intelligence in Manufacturing Course.* Assignments using the AIM Laboratory examine how artificial intelligence techniques can be used to improve manufacturing systems. For example, students may build diagnostic expert systems for one of the manufacturing components or systems in the laboratory.

COURSE PROJECTS CONDUCTED IN THE AIM LABORATORY

In this section, examples of three team-based course projects conducted using the AIM Laboratory's facilities are presented. The first two example projects focus primarily on manufacturing and computer science issues, respectively, while the third project is interdisciplinary in nature. While these example projects contain a high level of design content, both teamworking and communications (intra-team and inter-team) are also highly stressed.

Example of a sys 484 flexible manufacturing systems design project

The entire class participates in the design and manufacturing of two products, such as a pneumatic cylinder and a positive contact clutch. The products are to be constructed out of plastic and manufactured using the AIM Laboratory's Intelligent Manufacturing Cell.

The class is divided into five three/four person teams: two product design teams (one for each product); two CAM teams (one for each product); and one process engineering team. Team responsibilities are summarized as follows.

1. *Product Design:* Responsible for the design concept and engineering analysis, selection of raw materials, selection of purchased parts (e.g. bolts, O-rings, etc.) and the finished CAD drawings for all components of the products.
2. *CAM:* Responsible for the development and debugging of all CNC programs for the lathe and mill.
3. *Process Engineering:* Responsible for designing and constructing the lathe and mill fixtures (a single fixture for each machine tool which holds all components that are to be machined), developing a process plan for each product, selecting and ordering all tooling as well as developing and debugging all robot programs.

A timeline for each team is given which require all the teams to work in parallel, rather than series, to successfully complete their assignments. Each team submits, as well as presents, to the entire class two progress reports and a final report. In addition, each individual must submit an engineering log

describing their activities. The product design teams are also responsible for writing a final project summary. Individual grades are dependent on the team reports (2/3) and overall class performance on the project (1/3). The entire class is responsible for producing ten copies of each product.

The SYS 484 design project is run using a concurrent engineering format in order to avoid the 'over the wall syndrome', where the design engineers work independently of the manufacturing engineers. In order to consider Design For Manufacturability (DFM) issues, the Product Design teams receive constant feedback from the CAM and the Process Engineering teams. Time is reserved in each class lecture period during which each team presents an update of its progress and any preliminary design concepts, then it receives feedback from the other teams.

Note that all components of the products being designed must be manufacturing using the machine tools in the AIM Laboratory's Intelligent Manufacturing Cell. In addition, both the cell's CNC mill and its CNC lathe are restricted to a single fixture per machine tool. Finally, all loading/unloading of the cell's machine tools is handled by the cell's robot manipulator which is required to use only one gripper. Hence, all components of the products must be designed such that they can be satisfactorily manufactured subject to these restrictions.

Example of a cse 650 advanced operating systems project

The goal of this project is to develop a system-independent distributed processing program to control a manufacturing shop using the Java programming language. The problem solution must meet the following specifications:

1. *Shop Configuration:* The shop floor contains a loop-conveyor, five robots and an Automated Storage/Retrieval System (AS/RS). The shop control computer is a Sun Ultra SPARC workstation running the Solaris Unix operating system. The five PC's controlling the remaining equipment are running the Linux Unix operating system. The six computers are connected by a small Ethernet subnet.
2. *Database:* A relational database system named *MySql* is available together with a Java programming language interface. The relational database is used to store all elements of the problem solution such as the process descriptions, schedules, statistics, etc.
3. *Network:* All computers in the shop are connected by a 10-base-T dedicated ethernet. Network communication is to be completed using TCP/IP support in Java. Network utilization must be analyzed and a token-based system over the Ethernet must be designed and implemented if network load indicates this is necessary to assure timely communications.

4. *Shop Control*: A Graphical User Interface (GUI) for the Ultra SPARC workstation is to be designed and implemented which controls the shop.

The GUI must provide the following services:

- process specifications;
- real-time status of the shop's equipment;
- scheduling of jobs with just-in-time (JIT) capabilities;
- statistical analysis of the system's performance;
- system fault monitoring;
- system fail-safe with automatic shutdown capabilities.

Deliverables are to be submitted in html and must include:

- annotated programming listing;
- description of the design of all components, how they mesh with the other components of the system and how they meet the design goals.

Example of an cse 412 artificial intelligence in manufacturing project

The goal of this project is to design and implement an artificial intelligence system to make needed information available to any decision maker in an engineering design/manufacturing environment at the moment that a decision is required. The engineering/manufacturing environment consists of the following four teams.

1. *Design*: Responsible for parametric design of a component from a set of primitive features; the synthesis of optimal part design considering manufacturability; costs, performance, quality and plant scheduling; and the criticism of complete designs.
2. *Manufacturing*: Responsible for the evaluation of parts' DFM subject to the machines available in the AIM Laboratory; synthesis of optimal process plan for the parts; and accurate estimation of cycle times for part production.
3. *Cost estimation*: Responsible for the evaluation of part design for cost subject to the proposed process plan, part geometry and plant schedule; and case-based reasoning for accurate estimations of costs with incomplete specifications based on artificial intelligence techniques such as neural networks or genetic algorithms.
4. *Scheduling*: Responsible for the creation of master production schedules based on plant orders and a hypothetical plant containing multiple copies of the machines in the AIM Laboratory; modeling and simulation of the plant floor to create schedule information required for accurate cost estimation; and the provision of schedule adjustments caused by resource availability.

A computer whiteboard architecture is used. Each team may either place or read messages on the whiteboard. Each team develops rule-based artificial intelligence systems to react to changing

conditions represented on the whiteboard. The *Clips* expert system developed by the US National Aeronautical and Space Administration (NASA) is used since it can be implemented on both PC's and workstations.

As an example of the messaging system in use, consider the design of a specified component (e.g., a shaft). The design team may post a whiteboard message requesting a cost estimate for a proposed shaft design. The cost estimating team would respond to this message by carrying out a search for a good cost estimate (including posting the appropriate messages to the manufacturing and scheduling teams) and then posting their response on the whiteboard.

EVALUATION

The Oakland University end-of-course student evaluations ask the students to rate the value of the laboratory component of the course. The students respond with a rating of 1 (unsatisfactory) to 5 (excellent). The average response over the past five years for the SYS 484 Flexible Manufacturing Systems course is 4.0. The average response during this period for all engineering and computer science classes is 3.2.

Some comments from student evaluations concerning the AIM laboratory are as follows.

- '. . . helpful in understanding more real-world applications in contrast to all theory based material. It is very insightful in this sense, especially the project portion of the class.'
- 'A very good experience. Finally, hands on labs.'
- 'Very interesting—a learning experience. I really enjoyed this class laboratory.'
- '. . . nice change from theory-based engineering to reality-based engineering.'

The average number of students in each course using the AIM Laboratory during an academic year are presented in Table 1.

CONCLUSIONS AND FUTURE DEVELOPMENT PLANS

A primary goal in developing the AIM Laboratory was to provide a facility for students to

Table 1. Students using AIM Laboratory.

Course	Number of students
SYS 101 Introduction to Systems Engineering	5
SYS 422 Robotic Systems	15
SYS 484 Flexible Manufacturing Systems	25
SYS/CSE 490 Independent Project	5
SYS 491 Senior Design	5
SYS 684 Computer Integrated Manufacturing	35
CSE 412 Artificial Intelligence in Manufacturing	15
CSE 650 Advanced Operating Systems	10

conduct realistic engineering/computer science design projects. This goal has been achieved. Oakland University students in Computer Engineering, Electrical Engineering, Mechanical Engineering, Systems Engineering and Computer Science are working together on such interdisciplinary projects using the laboratory's facilities. This reflects the real world where an engineer or computer scientist has specified responsibilities for some portion of a project and must interact with other people on the project whose responsibilities and educational background differ from their own.

In addition, the AIM Laboratory allows students to conduct these projects using physical systems, rather than in a simulated virtual environment. While simulations are an important component for teaching students about general system behavior, they cannot always account for all the details that must be considered in designing and analyzing a physical system in an interdisciplinary, team-oriented environment. Students using the AIM laboratory learn the importance of solving the various problems that arise from these details. While it is easy to lecture about this concept in the classroom, the experience of the authors show that students get a better appreciation of the importance of responding to these details for the successful completion of a project through hands-on experience.

Initial plans for the AIM Laboratory centered on setting-up its facilities, the Intelligent Manufacturing Cell and the Intelligent Factory, for their use in laboratory assignments. For example, performing a scheduling assignment using the Intelligent Factory. While the laboratory's facilities have been put to good use in this regard, projects which concern the integration of the AIM Laboratory's components into manufacturing and computer networking systems has

become a major focus of use. Such integration projects have proven to be excellent hands-on tools for teaching design, teamworking and communications.

It was initially envisioned that the only computer science topic to be taught using the AIM Laboratory would be artificial intelligence. However, the laboratory is also currently being used to study other computer science issues such as computer communications (e.g. networks) and operating systems. Hence, the facilities of the AIM Laboratory have been merged with those of the school's S. and R. Sharf Computer Integrated Manufacturing (CIM) Laboratory due to this increase in coverage of computer science topics.

Current plans for the continued development of these laboratories are concerned with two projects. The first is the development of a Flexible Assembly Cell. Initial support for the development of this cell has been obtained from S. and R. Sharf as well as Trellis Software and Controls Inc. (a subsidiary of Kuka Robotics Inc.). It is envisioned that many individual student and class projects will be used to design and implement the cell.

The second development project involves using the facilities of these laboratories for conducting interactive engineering/technology projects between some of Oakland University's engineering/computer science courses and local secondary schools' engineering technology and mathematics courses. These interactive projects are conducted using the Internet (workstations with interactive video, audio and document sharing capabilities) and video conferencing facilities. This project is called the *Remote Design/Manufacturing Program*. Initial support of this program is being provided by the National Science Foundation's ILI Program [3] and DaimlerChrysler Corp.

REFERENCES

1. National Science Foundation Grant number USE-9251110, *Improving Manufacturing with Artificial Intelligence Techniques* (1992-94).
2. National Science Foundation Grant number DUE-9551971, *The Intelligent Factory: A Platform for Improving Manufacturing Using Artificial Intelligence Techniques* (1995-97).
3. National Science Foundation Grant number DUE-9851567, *Remote Design/Manufacturing Laboratories* (1998-2000).

APPENDIX

Illustrative examples of laboratory assignments given to the students for use in the AIM Laboratory are as follows. Note that these assignments are shorter in nature than course projects and are usually completed by students working individually or in two person teams.

CNC programming assignment

The objective of this assignment is the design and implementation of a G-code program for a CNC machine tool. Each laboratory group is to set-up and program the Intelligent Manufacturing Cell's Emco CNC mill to cut the part similar to the one presented during the lecture. A 6 mm end mill is used to cut the part.

Make sure to perform a dry run (spindle off and z-axis set such that all motion is done well above the part so the tool will not collide with the chuck) before trying to cut the part. Also, please review the *Notes on Manufacturing Laboratory Safety* handout before operating the CNC mill.

Each lab group will receive two pieces of raw stock. Any additional stock may be obtained at the cost of a 5% reduction in you lab score for each additional piece of stock.

You must turn in the sample part that your lab group used for the dimensional accuracy calculations portion of your report. The instructor must check-off your G-code program by watching the CNC mill cut a part. However, you do not have to turn in the part that is cut during the check-off.

Your report should include an introduction and a discussion section including the following:

- diagram of the part with all dimensions;
- tool path diagram;
- listing of your G-code program including comments;
- initialization procedure for cutting your part;
- the dimensional accuracy of your part;
- the causes of dimensional inaccuracies for your part (the mill accuracy is ± 0.05 mm).

Robot modeling assignment

The objective of this assignment is to construct and verify the forward kinematic solution for an industrial robotic manipulator. Consider the Fanuc LRmate five-axis manipulator in the Intelligent Factory:

1. Determine the homogeneous coordinate system transformations for each of the five links of the manipulator. Measure the length and offset parameters for each link directly from the manipulator.
2. Determine the forward kinematic solution for the manipulator.
3. Develop a C++ program using your forward kinematic solution. If the user enters the joint angles, then the program will display the corresponding position and orientation of the tool coordinate system.
4. Verify your forward kinematic solution using the LRmate robot. Note any differences between the position and orientation predicted by your forward kinematic solution and that of the robot's operating system for a given set of joint angles. Discuss possible reasons for these differences.

AI knowledge base assignment

The objective of this assignment is to build a rule-based system for a diagnostic problem. The diagnostic problem should concern one of the systems in the Intelligent Manufacturing Cell (a CNC machine tool or the robot). The knowledge base is to be constructed using the *Clips* expert system and satisfy the following specifications.

- The topic problem should pass the telephone test, that is, be solvable by describing the problem to an expert using the telephone.
- The knowledge should be diagnostic or classification-type in nature.
- The knowledge should not be trivial or contain only yes/no type answers.

The following criteria should be considered in building the knowledge base.

1. *Completeness of the rule base:* While some problems may be very expansive, the rule base should be reasonably complete. However, the rule base should consist of less than one hundred rules.
2. *Phases of diagnosis:* The problem domain should include a multiphase approach that will be evident in the discourse with the system. This must be controlled through the rule base.
3. *Use of variables:* The knowledge base should rely heavily on the use of rules with variables, few rules should be 'hard-coded'.
4. *Creation of functions:* Demonstrations of user create functions and the use there of should be in the knowledge base.
5. *Clarity:* The source code should be adequately commented.

Robert P. Van Til is an Associate Professor in the Electrical and Systems Engineering Department with a Ph.D. degree in Mechanical Engineering from Northwestern University. Dr. Van Til's academic interests concern the modeling and control of manufacturing systems as well as digital control theory. He has served in visiting positions at universities in the Netherlands and Australia.

Sankar Sengupta is an Associate Professor in the Electrical and Systems Engineering Department with a Ph.D. degree in Industrial Engineering from Clemson University. The educational and research interests of Dr. Sengupta in the areas of manufacturing system design and planning evolve from years of industrial experience as a process engineer and are focused on quality control in a flexible manufacturing environment.

Ronald J. Srodawa is an Associate Professor in the Computer Science and Engineering Department with a Ph.D. degree in Computer Science from the University of Michigan. Dr. Srodawa's expertise concerns operating systems, computer communications and computer center administration.

Patrick E. Dessert is an Assistant Professor in the Electrical and Systems Engineering Department with a Ph.D. degree in Systems Engineering from Oakland University. Dr. Dessert's academic interests concern manufacturing and artificial intelligence. He is the founder and Director of Oakland University's Product Development and Manufacturing Center.

Christian C. Wagner is an Associate Professor in the Computer Science and Engineering Department with a Ph.D. degree in English from Michigan State University. His scholarly interests are in the areas of artificial intelligence and system integration.