Automated Manufacturing System Integration Education: Current Status and Future Directions

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1. Introduction

Automated systems play an essential role in manufacturing, from assembling complex electronic devices to mixing pharmaceuticals. Engineers must constantly design, maintain, reconfigure, and upgrade these systems to accommodate shifts in product design or manufacturing priorities. Their ability to rapidly complete such tasks is critical to maintaining our national economic competitiveness and security. However, automated manufacturing system integration is a complex cognitive skill that typically takes years to master. This paper will (1) define *automated system integration*; (2) survey current status of engineering education in this area; (3) present results from field interviews with industry practitioners; (4) identify gaps between industry needs and education curricula; and (5) propose an agenda for industry collaboration and curriculum development to remedy these issues.

An automated manufacturing system generally consists of processing equipment, material handling devices, and material transfer equipment. The processing equipment can be a computer numerical control (CNC) milling, lathe, turning machine or any other type of equipment that changes or alters the property of the work piece. Material handling devices include industrial robots, actuators, and others devices that handle the work-in-process work-piece at the workstations. Material transfer equipment, such as conveyors, is often used to move raw materials from their respective bins to a destination where they can be picked up by material handling devices. A system controller works behind the scenes to orchestrate and synchronize the operations performed by the equipment.

Most modern automated manufacturing systems use a programmable logic controller (PLC) as the system controller. A PLC is a solid-state control system with a user-programmable memory, used to read input conditions and set output conditions to control a machine or process. It has been said that the programmable logic controller is among the most ingenious devices ever invented to advance the field of manufacturing automation[1]. Thousands of PLCs are used in manufacturing plants for such applications as monitoring security, managing energy consumption, and controlling machines and automated production lines.

Integrating the various components of an automated manufacturing system requires knowledge of the characteristics of the various mechanical and electrical devices available to make up the system, including their functions, power requirements, and specific characteristics, and the ability to write PLC programs to orchestrate and synchronize the process being automated. It is a complex skill, and often one of the last subjects students are taught in school. New automation and control engineers are often not fully prepared to perform system integration tasks.

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2. Current status of automated manufacturing system integration education

There appear to be few if any engineering courses or curricula that comprehensively cover automated manufacturing system integration topics. Perhaps this is because automation-related courses are typically offered within departments of electrical, mechanical, and industrial engineering or engineering technology (rather than manufacturing engineering); and automation topics are often combined with material on control, instrumentation, or robotics.

There are a few reported educational efforts that address some facet of automated manufacturing system integration. For example, Schuyler describes two existing courses that teach about Man Machine Interfaces (MMI)—a.k.a., Human Machine Interfaces (HMI)—and Supervisory Control and Data Acquisition (SCADA) systems. These courses address man-machine and information integration issues, but do not appear to address hardware and software integration or visualization models[2]. Erickson describes two control courses for factory automation that emphasize programmable logic controller (PLC) related topics such as instructions, analog I/O, PID control, PLC languages, and factory communication[3]. However, these courses focus primarily on PLCs. Pena et al. describe a new undergraduate degree program in control engineering at the Federal University of Minas Gerais, Belo Horizonte, Brazil[4]. This program is oriented toward meeting industry needs and includes some automation courses, but has a heavy emphasis on control theory.

There have also been many attempts to teach enabling skills that underlie system integration skills, such as web sites or computer-based instruction that present introductory information about programmable logic controllers. One notable example is The Learning Pit's LogixPro, which employs animated educational simulations of various processes, such as traffic control and batch mixing, to show how a ladder diagram relates to an automated process[5]. Students can start and stop the animations, and study the corresponding ladder diagram for certain conditions or cases. However, students do not have the opportunity to build a system. In addition, the number of models available for students to explore is limited to those included in the package. An improvement would be to allow students to design and assemble their own automated manufacturing systems, run them, and view the associated control logic.

Another common approach is to use a capstone course or senior design project to allow students to design and develop a system level project[6]. The course/project can last for one or two semesters. The purpose is to give students the opportunity to integrate knowledge gained from previous courses. In this type of course, students are expected to learn by doing, and learning outcomes may vary depending on the type and difficulty of the selected projects. This is not the same as taking a structured course on how to do system integration.

Cambron, Mark and Lenoir[7] recognized the need to bridge the gap between the mechanical and electronic engineering disciplines, since many commercial systems blend technologies from both disciplines. They created a common course on industrial automation to serve mechanical and electronic engineering students in order to create a common language for both groups.

3. Field interviews

The author recently interviewed 15 senior engineers involved with system integration at nine U.S. companies. Five of these companies were in Texas, one in Tennessee, one in Missouri, and two in Ohio. Seven of the companies were system integration firms, including two major players in the industry. The other two were product manufacturers who had in-house engineers to do manufacturing process automation tasks. The following types of questions were asked during these interviews:

- What is a typical project like?
- What types of projects come up most frequently?
- What is your role?
- What are some of the constraints that you typically face?
- What tools or resources do you use to solve problems?

Below are a few facts about these engineers' experience and educational backgrounds:

- They had other manufacturing industry experience joining the system integration industry.
- Most started their careers with a two-year or four-year college degree. Two of the fifteen did not have a formal degree.
- They came from a variety of technical backgrounds, including electronic, mechanical, welding, aircraft, and industrial engineering.

4. Observations and findings

4.1 What is system integration?

One primary finding from these interviews is that system integration can be divided into three primary tasks: conceptual design, control logic design, and mechanical system design.

- *Conceptual design* is the process of coming up with an overall system design for an automated system based on a customer's requirements and existing processes. The outcome of the conceptual design process may involve a static or dynamic simulation model which includes the system layout and major components involved. The job title "application engineer" is typically used for engineers who do this type of work.

- *Control logic design* is the process of determining input and output devices for an automated system and programming control logic (such as ladder diagrams) to orchestrate the components of the automated system in order to produce products that meet a customer's requirements. The job title "control engineer" is typically used for engineers who do this type of work.

- *Mechanical system design* involves 1) the design of mechanical components-such as fixtures, grippers, palettes, brackets, and feeders-that link or facilitate the operation of mechanical systems; and 2) final integration, installation, and testing of an automated system. The job title "mechanical engineer" is typically used for engineers who do this type of work.

The boundaries between these tasks are not clear-cut. They may vary from firm to firm, depending on the size and structure of the company. Some companies also have additional job classifications, such as software engineer and electrical engineer.

4.2 What types of systems/problems do they work on?

Most of the projects reported are in the area of assembly, which includes not only discrete parts assembly using nut and bolts, but also the application of adhesive materials such as glue and joining operations such as welding. Some examples include (1) hard drive assembly, (2) cellular phone assembly, and (3) welding of recreational vehicle frames. Other examples include process automation projects, such as plastic forming of refrigerator linings. One engineer indicated that 70% of his projects were assembly related.

A project typically starts with a sales contact that indicates a customer has a need. Applications engineers will work with sales and the customer to develop a proposal, which includes a description of customer requirements, a conceptual design to satisfy the needs, and a contractual agreement, including the budget and payment format. The conceptual design will identify the sequence of operations and corresponding devices. Also, the cycle time of the line will be estimated and/or simulated using a computer model or static diagram. Once the proposal has been accepted by the customer, the control engineer and mechanical engineer will work side by side to design, integrate and test an integrated automated system. The control engineer often handles the control logic design and integration of associated devices such as PLC, sensors, and robots. The mechanical engineer usually works on tasks associated with mechanical components, such as gripper design, fixture design, and motor motion devices.

4.3 How do these engineers acquire their skills? What skills do they think should be taught?

Many of the interviewees' skills were experienced based. They may also look at previous projects to see what elements can be transferred. Or, they will go look at similar systems that have been built and installed in other companies. Some companies gradually develop their own basic platforms for different types of line configurations. These platforms may include structure, cabling and/or control architecture.

The interviewees commented that students should be taught the following:

- How to troubleshoot a system failure if there is an error
- How to work on a team
- The language used by other disciplines. For example, a control engineer needs to have at least a basic understanding of mechanical and electrical engineering concepts.
- How to work within timeline and budget constraints.
- How to work independently, but also know when and where to get help. Engineers commented that it is often helpful to call field experts, such as device vendors.

5. Conclusion and Future Directions

5.1 Summary of observations

Following is a summary of observations from the field interviews:

(1) The system integration industry is very dynamic. The work is very project-based, and every project is different, if not completely new. Timelines tend to be short. System integration firms must constantly be on the lookout for new projects and are among the first to feel the pinch when the economy isn't doing well and manufacturers are scaling back on investing in new systems. Perhaps as a result, system integration firms tend to be small—often ranging from 10 to 50 engineers. System integration engineers must be able to learn a lot in a short time and to work independently.
(2) System integration engineers acquire many of their skills from experience and from talking to field experts, such as device vendors.
(3) System integration firms prefer projects that are similar to previous projects.
(4) System integration engineers often don't use analytic tools, such as simulation software. Several interviewees claimed that the short design cycle for a proposal/work order precludes the use of such tools.

5.2 Automated manufacturing system integration course development

Based on findings thus far and current trends in manufacturing technology, an academic course on automated manufacturing system integration should cover the topics listed in Figure 1 below.

- Advanced programming methodology (based on research findings)
- Human machine interface (HMI) programming
- Industrial vision system setup and application design
- Advanced system integration methodology (based on research findings)
    - Mechanical/Electronic interface devices
    - Hardware/Software interface integration
        - Material handling equipment (such as robots) and PLC
        - Material transferring equipment (such as conveyors) and PLC
        - Processing equipment (such as milling machines) and PLC
        - Inspection station (such as industrial vision systems) and PLC
    - Information integration and visualization
        - Integrate information from different ladder diagrams (representing different assembly lines where each ladder diagram controls one assembly line)
        - Create HMI application that integrates with shop-floor ladder diagram to allow visualization of assembly line production conditions
        - Integrate data with database for management purposes
    - Case Study #1: discrete manufacturing process
    - Case Study #2: continuous manufacturing process
    - Case Study #3: batch manufacturing process

Figure 1. Proposed topics for course on automated manufacturing system integration.

Lab exercises for such a course would emphasize:

- Open-ended, industry supported, independent problem solving, and system integration
- Design and practice of system integration of discrete, continuous, and batch processes
- Integration of HMI and visualization software for information integration

5.3 Conclusion

The system integration industry is dynamic, challenging, and essential to maintaining our nation's competitiveness and productivity in manufacturing. Since projects are often unique, engineers from multiple disciplines need to work closely together in order to design, integrate, and develop robust automated manufacturing systems. The success of the system integration industry will increase this country's production efficiency. Needed is a better understanding of how engineers develop expertise in system integration and high quality educational curricula that will equip students with the necessary skill sets.

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