Developing the Workforce for Next Generation Smart Manufacturing Systems: A Multidisciplinary Research Team Approach

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Abstract

As real-world systems become more complex and connected, the industrial sector is requiring engineers that can solve problems across multiple disciplines and work with people across various educational backgrounds. This is particularly apparent in the manufacturing industry, as the integration of new manufacturing system technology requires knowledge in a diverse set of fields, such as physics, computer science, and engineering, to name a few. To properly educate the next workforce in manufacturing, engineering education needs to incorporate cross-disciplinary, project-driven learning that provides students with ample opportunities to work with cutting-edge manufacturing technology. At the University of Michigan, the Secure Cloud Manufacturing Multidisciplinary Design Program team focuses on developing the next generation of manufacturing engineers through research-driven, multidisciplinary projects. A group of 7-22 students work on several, multi-semester long projects that focus on providing hands-on, student-driven learning. Each semester, these students work closely with several faculty members, research scientists, post-docs, and graduate students to propose, develop, and conduct industry-relevant research projects on multiple manufacturing testbeds. Example projects have included the implementation of a smart quality-control camera, the development of Digital Twins for manufacturing processes, and the integration of secure, cloud-based infrastructures for industrial controllers. In these highly collaborative and multidisciplinary project groups, students learn from each other, take on leadership roles, and disseminate their work through technical reports and presentations to academic and industry experts. Students leave the group with an understanding of the capabilities and needs of future manufacturing systems, ready to become, and lead, the next set of manufacturing engineers.

Keywords: manufacturing education, engineering education, smart manufacturing, project-based learning, multidisciplinary projects

Notation

Table 1. A list of commonly used abbreviations found in the document.

Secure Cloud Manufacturing Project Team	
MDP	Multidisciplinary Design Program
C&A	Controls and Automation
M&S	Modeling and Simulation
C&C	Cloud and Cybersecurity
Manufacturing Research Trends	
SM	Smart Manufacturing
SDC	Software-Defined Control
DT	Digital Twin
API	Application Programming Interfaces
AM	Additive Manufacturing
SC	Supply Chain
IIoT	Industrial Internet of Things
VR	Virtual Reality
Manufacturing Testbed at the University of Michigan	
SMART	System-level Manufacturing and Automation Research Testbed
SMART 3D	SMART's fleet of 3d printers
PLC	Programmable Logic Controller
NAS	Network-Attached Storage
CNC	Computer Numerical Control
HMI	Human-Machine Interface
FDM	Fused Deposition Modeling
SLA	Stereolithography

1 Introduction

The manufacturing sector is an important part of the global economy, being responsible for 16% of the Gross World Product [1]. In the United States, manufacturing accounts for 11% of the Gross Domestic Product, provides 12 million jobs and supports many other services across the economy [2]. Recent technological advancements in the areas of sensing, computation, and communication have led to the promise of a new manufacturing paradigm known as Smart Manufacturing (SM) in the United States and Industry 4.0 in Europe [3]. The goal of this new paradigm is to increase personalized production, improve system flexibility, and enhance manufacturing productivity by connecting the different stages of the product lifecycle, gathering data from every stage, and using this data to dynamically adapt the system to variations in production demands and operating conditions [4].

The SM paradigm is driven by a number of advanced technological enablers [5]. As this advanced technology is integrated into the shop floor, manufacturers are beginning to require more college-educated personnel to understand and utilize the new technology [6]. Therefore, to meet this demand for advanced skills in manufacturing, education needs to incorporate manufacturing-specific projects and courses as part of the curriculum. Due to the connected, advanced nature of SM factories, the projects and courses have to be interdisciplinary - covering material in a large number of fundamental areas, such as engineering, computer science, data science, and statistics.

At the University of Michigan, the Smart Manufacturing group led by professors Dawn M. Tilbury, Z. Morley Mao, and Kira Barton focuses on conducting research in the area of SM. The group leverages various state-of-the-art manufacturing testbeds to develop and test methods and algorithms for analyzing and controlling these factories of the future. The research projects in the SM group provide an opportunity for students to learn about the SM paradigm and obtain hands-on experience with advanced manufacturing system technology. To provide a larger number of students with manufacturing and research experience, the SM group has leveraged the University of Michigan's Multidisciplinary Design Program (MDP) to start the Secure Cloud Manufacturing MDP team. Students on this team obtain education and research experience in the various areas of SM through a number of connected, hands-on, multidisciplinary team research projects.

The contribution of this paper is an approach to structure a Multidisciplinary Design Program team focused on Secure Cloud Manufacturing for college students to develop industry-relevant skills and obtain hands-on experience in smart manufacturing research and applications. The learning objectives are focused on developing students that have industry-ready manufacturing, research, and professional skills. During their time spent as part of the Secure Cloud Manufacturing MDP team, students gain a number of skills that allow them to understand and help address some of the existing needs of the manufacturing sector.

The rest of this manuscript is organized as follows. Section 2 provides background information about the Multidisciplinary Design Program and the Smart Manufacturing group at the University of Michigan. Section 3 describes the Secure Cloud Manufacturing Multidisciplinary Design Program team in detail. Some of the completed and ongoing research projects in the Secure Cloud Manufacturing team are discussed in Section 4. Section 5 describes some of the outcomes and lessons learned from the Secure Cloud Manufacturing team. Concluding remarks are presented in Section 6.

2 Background

2.1 Multidisciplinary Design Program

Based in the University of Michigan’s College of Engineering, the Multidisciplinary Design Program (MDP) provides over 1,000 experiential learning opportunities for students from across the university every year to prepare students to join the modern workforce. As a part of long-term, team-based projects, students partner with research faculty and industry leaders to bridge the gap between the classroom and professional experience. Established in 2007, MDP is focused on design-based engineering and data science projects, but the program is open to any student on campus through a competitive recruitment process each fall semester. First year undergraduate to master's students are eligible to participate and are recruited based on skills needed for the projects. The MDP staff has collaborative relationships with multiple colleges across campus, which affords the opportunity to recruit students with key skillsets beyond the College of Engineering (e.g., Art & Design, Statistics, School of Information).

The MDP approach has a number of similarities and differences when compared to other national and international engineering education programs [7], [8]. All of these programs focus on developing teamwork, communication, and leadership skills in students. However, some differences between MDP and these programs are that MDP projects are primarily residentially based programs, are long-term, and do not feature traditional lecture components. On the industry side, the industry-sponsored MDP teams have a curriculum that encompasses a full design cycle with an engaged industry partner. On the research side, the MDP faculty-led research teams are long-term, multidisciplinary organizations with the specific goals of advancing faculty research efforts while simultaneously producing high-quality educational opportunities for students. All MDP research teams have "apprentice" research positions for first-year students to allow for student leadership growth over an entire academic career. MDP works with larger scale student groupings (some teams are >40 students) and in aggregate at 500 students per calendar year in both of the MDP's main models combined (faculty research and industry-sponsored projects). MDP benchmarks with other similar programs including Purdue University EPICs, Georgia Tech University Vertically Integrated Programs, New York University, Michigan Technology University, Ohio State University, Howard University, University of Pretoria, University of Strathclyde, among others [9], [10]. The MDP program shares the goals of the National Academy of Engineering [9] to overcome barriers to including more applied engineering experiences in degree programs.

Central MDP resources are efficiently leveraged to support students' educational needs. These resources include an academic advisor who provides course enrollment, and a Ph.D. level research program manager, who oversees recruitment, initial student orientation, student intellectual property (IP) agreements, and MDP trainings (e.g., technical skills such as managing code building, machine learning, and other skills, and communication and leadership skills). Student recruitment occurs in the fall with a matching process similar to matching medical residents to hospital placement to maximize student participation. Selected students join a team in January, and students enroll for academic credit (typically committing to 2.0 credits/term for a minimum of 2 terms, Winter and Fall). Students may return to the team for a longer engagement, and more experienced students typically train the newer students and assume team and technical leadership roles. Research teams reserve opportunities for first-year undergraduates to allow for student leadership as students return for multiple years of participation. Typical participation in the MDP program for trainees consists of 2 to 6 semesters as a member of an MDP research team.

As of January 2020, MDP supports 11 research teams led by 14 faculty and over 215 students. The Secure Cloud Manufacturing team is one example. Once established, the student teams like Secure Cloud Manufacturing self-manage day-to-day operational functions including project management, technical sub-team development goals, documentation, team skill development, and recruiting with MDP support. MDP also pilots new models for experiential learning and conducts educational methods research to improve the quality of experiential learning [11].

Analysis of student exit surveys at other similar universities reported participation in these types of experiential learning programs correlated with an increase in three factors related to future career success: the degree to which students' education contributed to their ability to work in a multidisciplinary team; their ability to work with individuals from diverse backgrounds; and their understanding of technology applications relevant to their field of study [12]. This multidisciplinary model of capstone-like learning has been applied at the University of Michigan since 2015 to develop the workforce for next-generation smart manufacturing systems.

2.2 Smart Manufacturing Group

The University of Michigan's Smart Manufacturing (SM) group has been conducting research in various facets of SM. MDP students work on projects that help support ongoing research in the SM group. In this section, a brief overview of the work in the group is provided.

Software-Defined Control (SDC) is a methodology for controlling manufacturing systems that uses a global view of the entire manufacturing system [13]–[15]. Current research in this area has focused on developing a DT framework that incorporates SM capabilities such as predictive maintenance [16], real-time scheduling/dispatching [14], [17], throughput prediction and estimation, process and quality control [18], and anomaly detection [19], among others, in an extensible, reusable, and value-add fashion. The proposed framework provides the capability to construct aspects of a global view of the SM system that could be used for multiple purposes to improve SM systems operation. To take full advantage of DT's global view, easy-to-use SDC application programming interfaces (APIs) are designed to facilitate the development of SDC applications [20].

Additive manufacturing (AM) is an important enabling technology for SM. The AM research in the SM group involves modeling, analysis, and control of AM systems at machine and system levels. AM processes are often used in parallel AM fleets for increased throughput. An extension of the SDC framework for AM has been proposed to integrate AM fleets with existing SM systems [21]. Within this scope, several contributions on process modeling [22], DT-based anomaly detection and verification [23], and process control [24] are proposed to increase the reliability, repeatability, and autonomy of AM fleets.

In the human-robot collaboration area, current research is focusing on task allocation performed online using real-time information about the robot, the human, and their environment. Modeling the components of the human-robot system with a DT approach allows the capabilities of an agent to be richly represented and compared with peers, allowing tasks to be assigned optimally. DTs of the robot and the environment allow real-time evaluation of the robot’s ability to handle tasks, allowing partial automation of a task with high variability.

Multi-agent control has been proposed to improve the flexibility and adaptability of manufacturing systems [25], [26]. The SM group focuses on developing software architectures [27]–[29] and cooperation algorithms [30] for various types of agents to improve the performance of the multi-agent control strategy in a manufacturing environment. The multi-agent approach is being tested using simulation case studies [28], on a small-scale manufacturing testbed [29], and in a manufacturing testbed consisting of several industrial-sized cells [31].

In the Supply Chain (SC) area, a Production as a Service framework has been developed to optimize the utilization of small to mid-sized manufacturers [32]. This framework has the potential to connect manufacturers with customers that have customized production needs through a platform that preserves intellectual property, using optimization tools to present possible solutions to its users. Current research is focusing on the development of a multi-agent framework for comprehensive SC management. This framework is designed to integrate supplier selection in an SC and incorporation of product agents and resource agents [28] into the supplier SM system.

Finally, cybersecurity is another critical issue that is studied to prevent the factory floor from being sabotaged by cyber-attacks. The “air gap” myth where critical systems can be isolated from the outside world does not work in reality [33], [34]. This opens the potential for attack surfaces that can be exploited by both external attackers and insider adversaries. In view of this problem, the group is actively developing various security techniques across several critical components in SM. To detect potential safety violations in programmable logic controllers (PLCs), the automated safety vetting of PLC code is proposed [35]. The group is also working on designing novel access control and authentication mechanisms for the DT and SDC APIs to prevent unauthorized data access at runtime.

3 Secure Cloud Manufacturing MDP Team

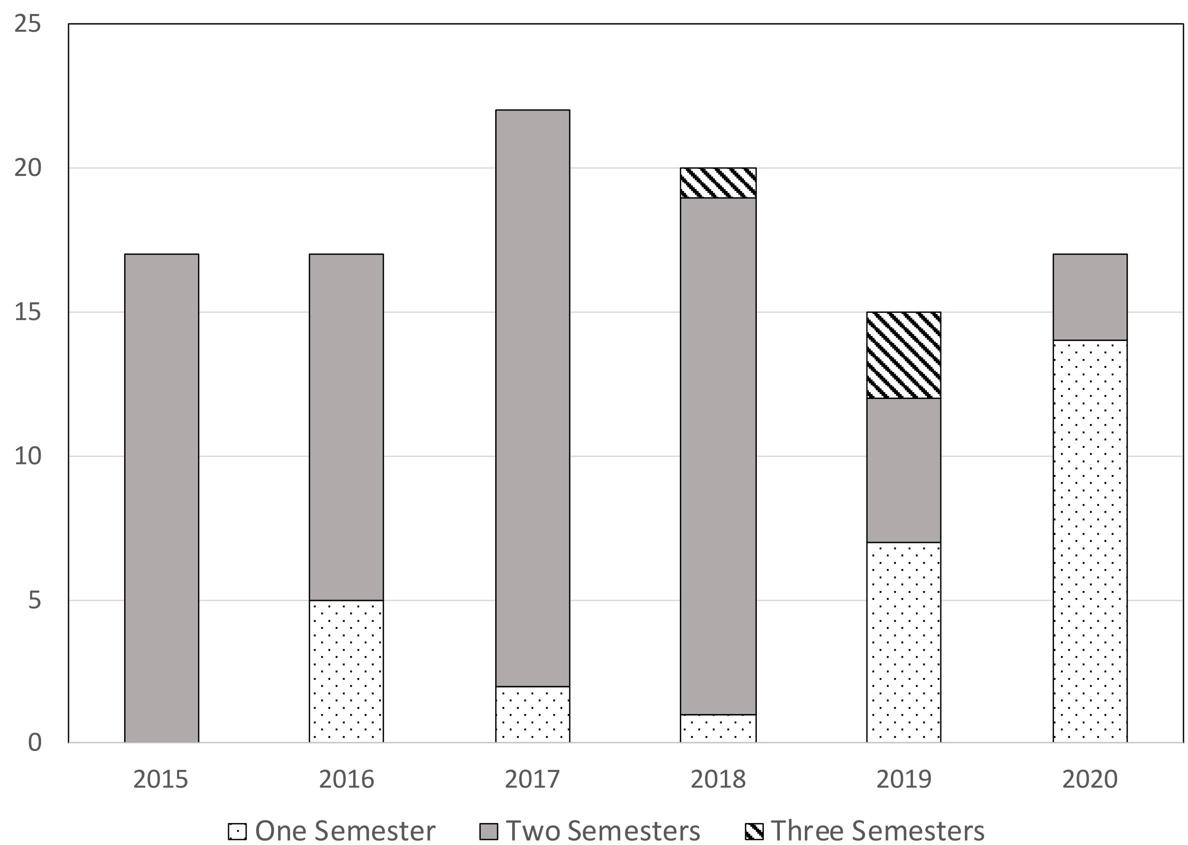

Figure 1. Enrollment in the Secure Cloud Manufacturing team from Winter 2015 to Winter 2020. In 2015 all students completed both Winter 2015 and Fall 2015 terms. In 2019 MDP recruited 5 students to start off-cycle during the Fall 2019 term to meet team needs. The 2020 data are students enrolled for the 2020 program, committing for 2 credits in the 2020 Winter term 2020 and 2 credits in the Fall term 2020.

The Secure Cloud Manufacturing Multidisciplinary Design Program (MDP) team was established with 17 students in Winter 2015, under the direction of Professor Kira Barton, Professor Z. Morley Mao, and Professor Dawn Tilbury. The Secure Cloud Manufacturing MDP team enables students to take part in emerging research in the field of smart manufacturing. As described in Section 2, students enroll in the

Secure Cloud Manufacturing MDP team over two semesters and are graded on their work based on the rubric provided in Appendix B. The students are supervised by a team of faculty, students, and post-graduates that have experience in the manufacturing industry. The supervisors help MDP students structure, develop, and work through their projects, continuously providing feedback to the students during the semester.

The MDP students use the System-level Manufacturing and Automation Research Testbed (SMART) [28], a fleet of 3D printers (SMART3D), and other manufacturing testbeds to develop, test, and analyze developed methods and techniques. MDP students are evaluated based on their technical contributions, presentations, and teamwork abilities throughout the course of the semester. Over their two-semester stay in the program, students are exposed to the field of manufacturing systems, explore state-of-art research, and leave the team with a better understanding of the needs of current and future manufacturing systems.

The number of students on the team has ranged from 7 to 22 students, with an average of 15.8 students participating in each term, as shown in

Figure 1. The students on the team are at various stages in their pursuit of a bachelor's or master's degree (1st-year undergraduate to 2nd-year graduate students) with a broad range of majors and concentrations. Most of the undergraduate students who have participated in the Secure Cloud MDP team were majoring in mechanical engineering and computer science. In addition, other majors included aerospace engineering, computer engineering, industrial and operations engineering, information sciences, data science, electrical engineering, and first-year undeclared students in the College of Literature, Science and the Arts. Masters students in mechanical engineering and electrical and computer engineering have also participated. In the current 2020 team, about a quarter of the students are majoring in mechanical engineering, a third are majoring in computer science, 16% in computer engineering, and the remainder are electrical engineering or undeclared.

3.1 Team and Individual Objectives

Figure 2. Team member objectives organized by manufacturing, research, and professional skills.

The goal of the Secure Cloud Manufacturing team is to develop new methods and technology to improve the safety, security, and productivity of large-scale manufacturing systems. The team works on a number of connected, multidisciplinary, industry-relevant projects that impact state-of-the-art manufacturing research. The objectives of the team are to work together to understand research problems, effectively develop new tools and techniques to address these problems, and analyze and present results to academic and industrial professionals in this field.

During their two-semester (or longer) participation in the Secure Cloud Manufacturing team, individual members focus on developing the manufacturing, research, and professional skills shown in Figure 2. At the end of their second semester, students should understand and be able to discuss general trends in manufacturing and be proficient in a skill that can be leveraged to work with smart manufacturing systems. Students gain skills in confronting an ambiguously scoped problem with an open-ended solution set. Accordingly, students should understand and contribute to an active research topic, have experience in working in a diverse team, and have the capability to develop and present technical content to a knowledgeable audience. The team structure, project management, and evaluation of the semester work are developed to enable the team and individual students to achieve these objectives.

3.2 Team structure

The Multidisciplinary Design Program provides an opportunity for undergraduate and graduate students to work on long-term and team-based engineering projects. The program bridges the gap between the classroom and professional experience using new models of experimental learning. This section describes the structure of the Secure Cloud Manufacturing MDP team and the roles played by the faculty members, postdocs, technical staff, and graduate students that are involved in this program.

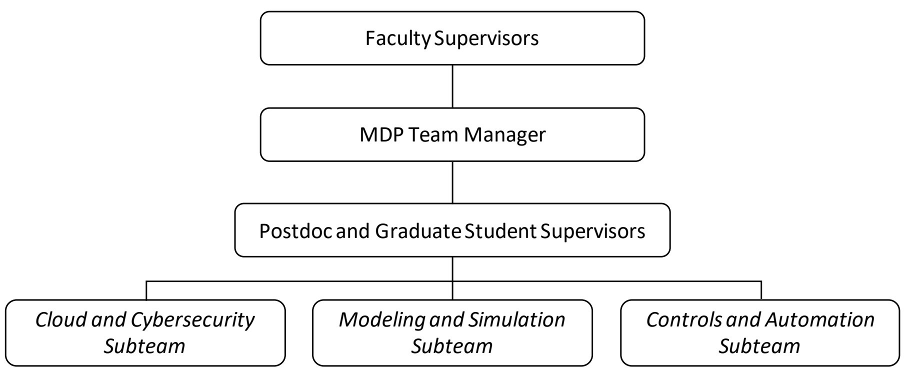

Figure 3. Organization of the Secure Cloud Manufacturing MDP team.

3.2.1 High-level structure

The MDP Secure Cloud Manufacturing team as part of the University of Michigan's Multidisciplinary Design Program applies a hierarchical organization structure as shown in Figure 3. The team is led by the faculty supervisors, Professor Kira Barton, Professor Dawn Tilbury, Professor Z. Morley Mao, and Dr. James Moyne. The faculty supervisors have a variety of research interests developed through years of academic and industrial experience. Faculty supervisors ensure that MDP students are working on industry-relevant research projects and provide continuous feedback throughout the semester.

The team is subdivided into three subteams: Controls and Automation (C&A) subteam, Modeling and Simulation (M&S) subteam, and Cloud and Cybersecurity (C&C) subteam. Each subteam is supervised by one to two graduate students/postdocs that propose the subteam projects based on research conducted by the Smart Manufacturing research group. Graduate student/postdoc supervisors continuously assess the MDP students, provide guidance through weekly subteam meetings, and ensure that the students are on

Subteam	Majors	Interests
Controls & Automation	- Mechanical Engineering (ME) - Electrical Engineering and Computer Science (EECS) - Industrial and Operations Engineering (IOE) - Computer Science (CS)	- Manufacturing processes - Mechanical design - Robotics - Sensors and actuators - Industrial automation - Computer vision - Quality control
Modeling & Simulation	- Mechanical Engineering (ME) - Electrical Engineering and Computer Science (EECS) - Industrial and Operations Engineering (IOE) - Computer Science (CS)	- Manufacturing systems - Operations management - Production optimization - Scheduling/Dispatching - Commissioning
Cloud & Cybersecurity	- Computer Science (CS) - Science in Information - Data Science (DS)	- Data engineering - Data analytics - Verification & validation - Cybersecurity

track to complete their objectives. The Secure Cloud Manufacturing MDP team is managed by the Secure Cloud Manufacturing team manager. The team manager is responsible for ensuring that there is a link between the MDP student projects, the various research projects, and industry-relevant problems/needs. In addition, the team manager organizes the various group activities during the semester (e.g. factory visits, midterm presentations, final presentations, etc.). The team is also supported by the MDP staff program manager who organizes campus-wide student recruitment, academic advising, centralized training, and other functions.

Table 2. Suitable majors and project domains for MDP subteams.

MDP students are assigned to the subteams based on their majors, skills, interests, and the needs of the smart manufacturing group. General guidelines for matching students to subteams are given in Table 2. It is important to build teams that are balanced in experience and other demographic factors, with members ranging from graduate students to first-year undergraduate students. The goal is to have experienced students work with and aid less experienced students with their projects. Experienced and novice students may work together on the same project as long as there is a clear separation between the deliverables expected from each student. Students report on their individual contributions during mid-term and final presentations.

In addition to the manufacturing experience that the MDP students gain, a major aspect of the MDP Secure and Cloud Manufacturing team is the development of leadership skills among the members of all subteams. With MDP faculty coaching, students develop their ability to solve ambiguous open-ended problems and communication skills; the development of communication and team-based skills have been documented in MDP and other similar programs [7], [8], [36], [37]. MDP student leadership responsibilities include organizing the team, leading subteam meetings, reporting issues to the subteam supervisor, managing the codes and programs developed by the subteam members, looking for opportunities to collaborate across teams, and other responsibilities. Leadership responsibilities are assigned to the subteam members as described below.

3.2.2 Subteam Structure

The students in each subteam have responsibilities that are divided at the beginning of each semester. For teams that have more than four students, some of the responsibilities may be shared between multiple members. A formal list of responsibilities for each position in a subteam is provided in Appendix C.

a. Subteam Scribe

There are weekly meetings for each subteam where team members discuss their progress as well as the problems they have faced with their work in the past week. The first responsibility of the scribe is to take minutes during the meetings and distribute the action items among the team members after the meeting. This is an essential task since the meeting discussions provide detailed feedback for the student projects and action items help team members keep track of what to do during the week. The second responsibility for a scribe is to take turns with other subteam scribes to perform the scribing task on the weekly group meetings where the large group meets to discuss their updates for the past week.

b. Subteam Document Manager

There are many documents generated within a semester, including student reports and presentations, instruction manuals, safety guides, and research documents. The team uses a network-attached storage (NAS) drive to store all the documents and the source code written by the students in the team. Subteam document managers are responsible for managing the documents generated by the subteam and making sure all the students in the subteam are updating the necessary documents, e.g. reports and safety guides. Additionally, subteam document managers are responsible for organizing the NAS structure so that there are instructions on where to find certain documents and all the subteam folders have a uniform structure.

c. Subteam Code Manager

All projects in the team require some level of code-writing. The subteam code manager is responsible for organizing and maintaining the code developed in the subteam. This responsibility includes implementing appropriate version control practices for the subteam, making sure that the most recent (and also a stable) version of the code is backed-up in the NAS drive. In addition, code managers make sure that everyone in the subteam has provided documentation for their own code with appropriate comments within the code for increased readability.

d. Subteam Leader

Each team has a subteam leader in charge of organizing subteam meetings, preparing and submitting final drafts of weekly, mid-term, and final reports and presentations. The subteam leader works with the subteam supervisors to make sure the subteam projects are provided with the necessary help and feedback. In addition, subteam leaders make sure that all the students are making progress toward their semester goals, and all individual responsibilities are fulfilled during the semester. Subteam leaders are in their second semester with the team and have a good understanding of the requirements for a successful project. As they are more senior members of the subteams, they are also expected to help get new members of the team up-to-speed in terms of the subteam responsibilities, objectives, and structure. To help subteam leaders, the university MDP organizers provide central training on leadership skills, including team leader roundtables and specific training on skills such as time management, delegation, communication, project management tools, and working collaboratively to develop abstracts or other research products.

3.3 Experimental Platforms

MDP students use the following experimental platforms to complete their projects.

3.3.1 SMART

The team uses the System-level Manufacturing Automation and Research Testbed (SMART) to gain hands-on experience with industrial equipment and get familiar with the software used in the industry [31]. SMART has four computer numerical control (CNC) machine tools, two conveyors, one gantry, and two industrial robots with an integrated industrial control system (provided by Rockwell Automation) connected through Ethernet/IP with industrial network switches. There are RFID (radio-frequency identification) sensors on the testbed, which identify parts in the system and provide their location to the central controller. There are pneumatic stops to halt the parts at certain pick-up/drop-off locations. There are inspection cameras on the conveyor system as well as some of the CNCs. An industrial human-machine interface (HMI) provides necessary interfaces to control various components in the system. Additionally, each CNC has a dedicated HMI for operators to interface with each machine.

A computer connected to the main programmable logic controller (PLC) in the system is used for programming the control logic (with Rockwell's Studio 5000 software) and implementing Industrial Internet of Things (IIoT) applications that send/receive data from cloud-based storage and computation resources. There are power monitoring sensors on the CNCs that are used to develop data analytics and predictive maintenance solutions. A gantry system on the testbed serves as an entry and exit point for the products in the testbed. SMART enables various research topics including control development and validation, learning-based control applications, system reconfiguration, scheduling and dispatch, cloud manufacturing, digital twins, in-line quality control, agent-based control, and cybersecurity. See Section 4 for a list of research accomplishments.

3.3.2 SMART 3D

To study the integration of AM processes with the commercial manufacturing processes in SM systems, SMART 3D is a research testbed equipped with multiple 3D printers connected through an Ethernet IP interface, and a data collection and analysis framework for implementing real-time data analytics. SMART 3D is an extension of SMART. To illustrate an AM fleet, SMART 3D has five 3D printers: two fused deposition modeling (FDM) machines and three stereolithography (SLA) machines. A custom data collection framework is developed with Applied Dynamics International (ADI) to work with the printers in the testbed. A customized interface is built to work with the ADI ADEPT software suite and real-time data is streamed and stored for data analytics. Through this interface, real-time implementation of customized DTs with verification and anomaly detection capabilities are illustrated in [23]. Student projects related to SMART 3D include developing of DTs for the 3D printers, integrating sensors of the printers for anomaly detection, and designing novel controllers for AM applications.

3.3.3 Fischertechnik

A small-scale version of a manufacturing testbed is also used for prototyping purposes. The Fischertechnik system is instrumented with four Raspberry Pi microcontrollers configured as programmable logic controllers and used to control individual manufacturing stations. This allows the system to easily simulate distributed-control approaches. Thus, the testbed is used for implementing control logic such as agent-based control on a small scale [29]. The agent system uses a java-based communication interface. Controllers utilizing this communication structure between agents are tested to understand the outcomes of the designed controllers on a physical testbed. The testbed also has RFID sensing capabilities to identify part information from tags. Additionally, PLC emulation tools are integrated into the microcontrollers, so that PLC logic can be implemented and simulated on the testbed. Studies involving human operators in the production control chain are also implemented to evaluate the role of human agents within the production line.

3.4 Project Management

Prior to the beginning of each semester, subteam supervisors, the team manager, and faculty supervisors identify a set of potential projects for the MDP team members. The MDP projects are decided based on the needs and current state of the research projects in the larger research group. As the research group works in multiple facets of SM, interdisciplinary research projects that include multiple subteams working in a coordinated manner are encouraged. Therefore, the projects for each sub-team are scoped with the larger research themes and goals in mind. This creates an environment where interdisciplinary research and collaboration can flourish. Additionally, since the projects are related to state-of-the-art research in the bigger research group, the MDP students get first-hand experience on the frontiers of SM technology and research. As the students work on the equipment and testbeds in the lab, they get hands-on experience in SM technologies such as industrial internet of things (IIoT), virtual reality (VR), controller (PLC or computer based) design and implementation, mobile robotics, additive manufacturing (AM), cloud infrastructures, cybersecurity, and data analytics.

To maintain project continuity, new students are recruited from a campus-wide competition to join the team each semester, with the main recruitment done for a Winter semester influx of a cohort. After the students are assigned to their individual projects, a proposal meeting with the faculty supervisors is arranged to get feedback on the approach and deliverables for each project. Students have midterm deliverables, which are presented in the midterm presentation with the faculty supervisors. A midterm report is prepared to communicate midterm accomplishments. Similarly, a final presentation at the end of the semester together with a final report presents the accomplishments and contributions of each student over the course of the semester. Visitors from relevant industries are invited to attend the final presentations for potential recruitment opportunities.

At the beginning of each semester, new students go through the safety and training materials prepared by the supervisors and the students from past semesters. Safety training is a prerequisite for using the testbeds in the lab and great emphasis is given for thorough training of each member of the group. Annual visits to the Ford Rouge plant in Dearborn, MI are planned to provide insights to new students about manufacturing facilities and assembly lines. Additional opportunities such as attending automation fairs or manufacturing conferences may also be provided.

3.5 Assessing semester work

To ensure that students are on track to complete all of their objectives and gain meaningful experience during their involvement with the Secure Cloud Manufacturing team, individuals are assessed over the course of two semesters using a number of criteria. Weekly participation, subteam role responsibilities, the completion of deliverables, and the project proposal are all worth 10% of the grade. Weekly participation includes attendance and input during weekly subteam and entire team meetings. The accomplishments of students in their respective subteam roles (scribe, document manager, code manager, and leader) are subteam responsibilities. The project proposal and completion of their individual and team deliverables are assessed as part of the completion of deliverables.

A large portion of a student's grade comes from the faculty and supervisor assessment of their midterm report and presentation (30%) and their final report and presentation (30%) (See Appendix B). The students are assessed using various criteria, including content, overall organization and flow, spelling and grammar, figures, and verbal articulation, among other categories. These criteria enable the assessment of the students' progress toward reaching the objectives shown in Figure 2.

Finally, to ensure that MDP team members are exposed to feedback from outside of the group, students are required to have at least one research outlet for every two semesters as part of their project. This research outlet can come in the form of a poster presentation or a peer-reviewed conference paper. Previous examples of research outlets include the publication of a conference paper at the Manufacturing Science and Engineering Conference [18], poster presentations at the Michigan Engineering Design Expo, and a poster presentation at the Michigan Institute For Data Science annual symposium [38]. In addition, some of the MDP student projects have also been showcased at the Rockwell Automation Fair and at various industry visit days.

4 Team Projects and Accomplishments

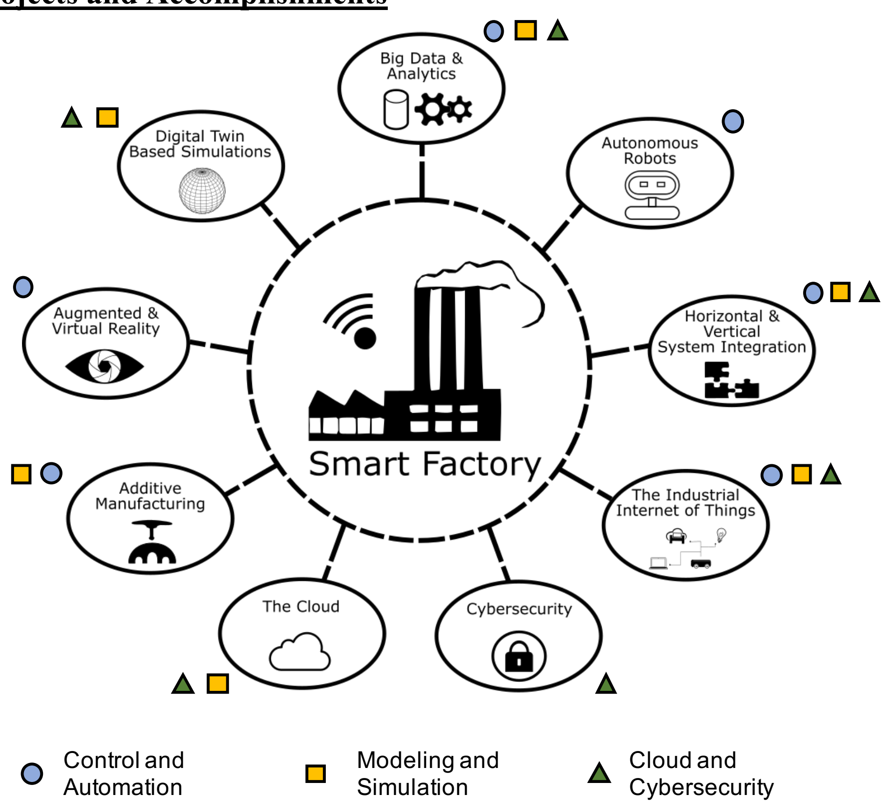

Figure 4. Project focus for the Secure Cloud Manufacturing MDP team (categories are based on [5]).

This section discusses the focus of the subteam projects and provides examples of some past and ongoing projects as illustrations. The focuses are presented for each subteam, but it should be noted that inter- and intra- subteam collaborations are encouraged and expected.

4.1 Control and Automation

The control and automation (C&A) subteam develops innovative software and hardware solutions for developing the next generation SM systems. SM systems are intelligent, cyber-physical, and integrated. Thus, controlling the resources in the system to be safe and efficient in an autonomous fashion is a crucial and challenging task for realizing next-generation SM systems. To fulfill this task, the projects in the C&A subteam cover augmented & virtual reality, AM, big data analytics, autonomous robotics, system integration, and IIoT (see Figure 4) to educate the next generation of engineers. Through the projects in this subteam, students work on (see Figure 5) and gain experience in designing and implementing controllers that leverage data analytics for integrated SM systems and develop a general understanding of SM technologies. The broad range of projects in the subteam are grouped under the following three themes: data analysis guided controls, robotics, and AM. A complete list of projects is provided in Appendix A.

Figure 5. Control and Automation students working on various components of SMART.

4.1.1 Data analysis guided controls

Using sensory data to analyze the current state of an SM system is essential to detect and predict anomalies so that reconfiguration actions can be implemented to improve system performance. The C&A subteam uses IIoT sensors implemented on manufacturing assets, and data streams from existing sensors and machine controllers to build and implement machine- and system-level controllers. The goal is to increase the performance and autonomy of SMART, an experimental SM system. This experience provides students with a familiarity with sensing, data analysis, and control tools (hardware and software) that could be integrated with SM systems, and build important expertise that is needed in the industry. Students work with IIoT sensors, CNCs, and industrial software, which provides them with fundamental tools to integrate SM solutions in their future careers. For example, one ongoing project focuses on building in-line quality control stations on SMART and using the data to analyze part quality, predict quality, and implement control actions [18]. This project has been a successful multi-year endeavor with multiple students from various majors. Through building the necessary modules for this project, students have worked with computer-aided design (CAD), computer-aided manufacturing (CAM), computer vision, data analytics, predictive maintenance, and industrial controllers. The resulting quality control system is now integrated with system-level controllers and DTs developed by the research group, an exemplary contribution of the MDP team results to enhance the research objectives of the SM research team.

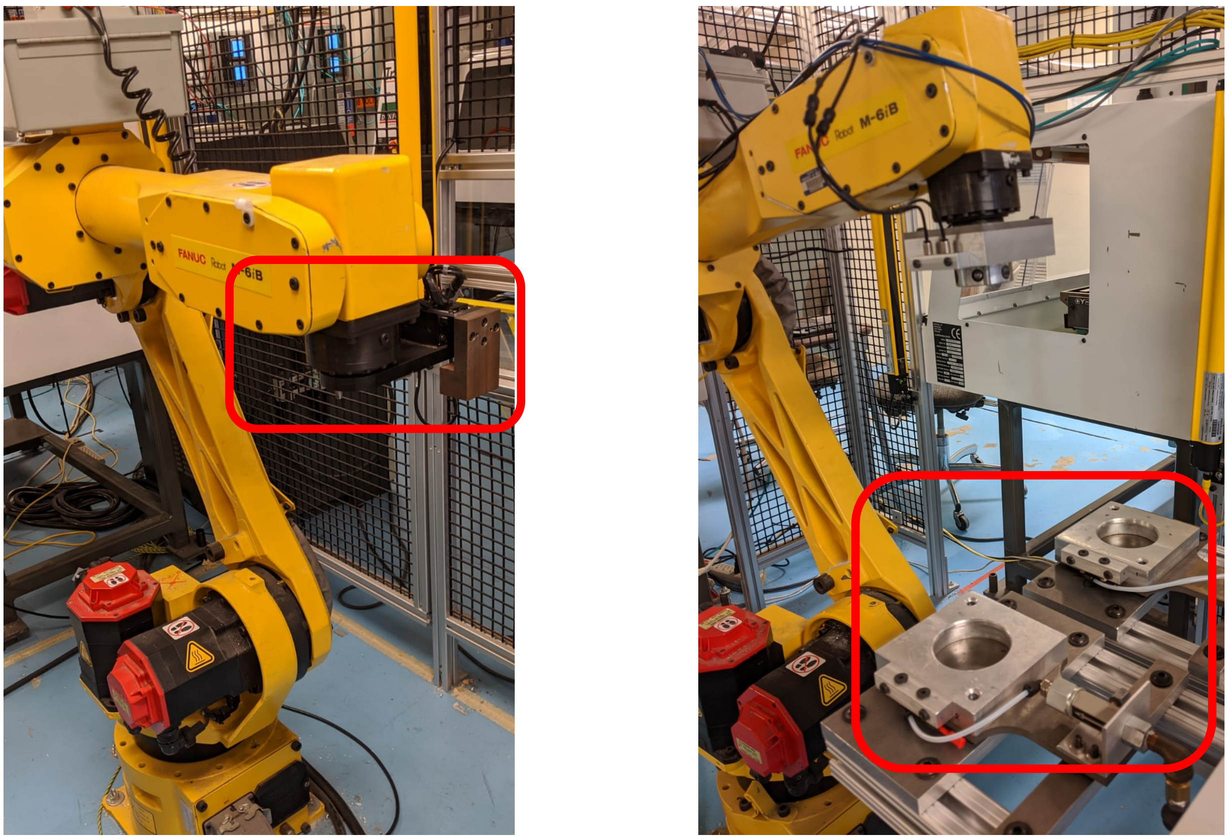

Figure 6. Industrial robots on SMART with fixed mechanical gripper (left) and interchangeable mechanical and pneumatic grippers (right).

4.1.2 Robotics

The industrial robots in SMART, shown in Figure 6, interface with other resources to schedule part pick-ups and drop-offs. As these robots are also used in industry, this gives the students valuable experience in applications they may implement in their future careers. The robot trajectories are stored, backed-up, and maintained by the control and automation subteam. Students working in related projects gain expertise in integrating industrial robots with SM systems; teaching trajectories to robots; object detection, localization, path planning for mobile robots; and designing human-robot collaboration tasks. As robotics is a fundamental driving technology for SM systems, these skills are crucial for building effective SM systems. One of the past projects focused on building mechanical and pneumatic grippers for industrial manipulators in SMART. As a part approaches the pick-up location on the conveyor, the PLC controller of SMART reads the part type from the RFID sensors, decides which gripper should be used and passes this information to the robot. The robot then executes the correct trajectory to attach the designated gripper to its end effector and transfers the part from the conveyor to a CNC. The grippers that were designed, manufactured, and integrated by MDP students have been actively used by the SM research team for the past several years.

4.1.3 Additive Manufacturing (AM)

Most AM machines used in SM systems today lack adequate closed-loop controllers and the aspect of management and control for AM fleets have not been addressed. This results in low yield AM fleets and analyzing the AM process to develop control actions is an important challenge for integrating AM with SM systems. Students working on these projects gain fundamental knowledge on sensorization of AM to collect in-situ data, anomaly detection algorithms to analyze AM processes, DT solutions to provide key metrics, and control solutions to improve process reliability and repeatability. These are key skills that are needed in the industry for integrating AM technologies with SM systems. Students also gain extensive insight on process dynamics and anomalies of AM as an advanced manufacturing process, which is a key technical skill in demand. Ongoing projects include sensorization of FDM processes with IIoT sensors and cameras to perform anomaly detection that identifies mid-print failures to implement control actions and reduce time and material waste. The setup developed and used by the MDP students for these projects is shown in Figure 7. The anomaly detection application uses DTs of the FDM process, and the developments are utilized in the SM research group for building intelligent process controllers for AM.

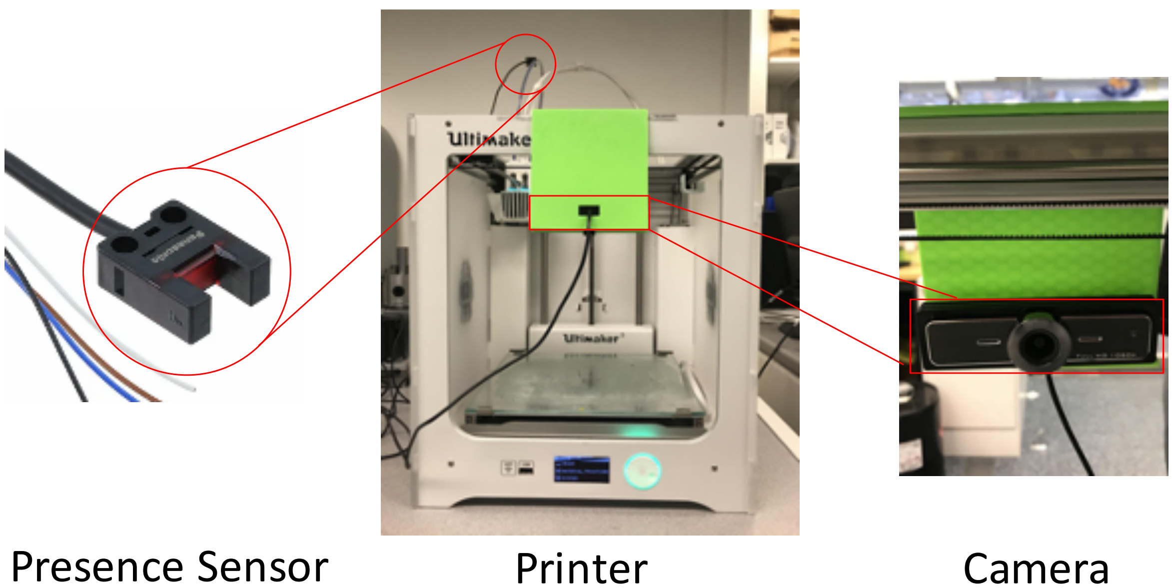

Figure 7. Sensorization of an Ultimaker 3D printer with a camera to monitor the printing process and a presence sensor for the material feed.

4.2 Modeling and Simulation

Modeling is the process of building a model, which is a physical, mathematical, or logical representation of a system of interest, while simulation is the process of operating a model to study and analyze properties concerning the system's behavior [39]. In the context of SM and Industry 4.0, modeling and simulation will be used more extensively in plant operations to leverage real-time data and mirror the physical world in a virtual model or a digital twin, which can include machines, products, and humans [40].

Teaching the concepts of modeling and simulation in the context of manufacturing is a big interest in training the new generation workforce for smart manufacturing and Industry 4.0. From this perspective, students from the MDP Modeling and Simulation (M&S) subteam get the opportunity to benefit from experience in digital manufacturing. Through the various projects, students understand the operation of manufacturing equipment and processes; get familiar with modeling, simulation, and emulation tools and methods; and apply this knowledge to physical systems (e.g., SMART). Several commercial software tools (e.g., Arena® from Rockwell Automation and Tecnomatix® from Siemens), as well as academic software tools (e.g., Uppaal and Supremica), are used by the M&S subteam to develop models and simulations of manufacturing systems. Different projects have been carried out by students from the M&S subteam focusing mainly on two levels of abstraction of models and simulations, namely machine-level and system-level. The projects have resulted in working simulation used by the research teams, e.g. the simulation shown in Figure 8. By leveraging existing software for projects in the M&S team, students are exposed to and gain an understanding of the latest state-of-the-art technology that is used in the manufacturing industry.

4.2.1 Machine-level modeling and simulation

Simulation is used to evaluate the performance of individual machines in a manufacturing system (e.g. CNC, robot, etc.) under different scenarios using machine models. Projects focus on using machine dynamics to build physics-based models, and data collected through the IIoT to develop data-driven models to monitor machine health, detect anomalies, and close the loop in the machine. For instance, discrete event models of a CNC machine were developed to monitor the operation of a machine while interacting with a workpiece during a milling process [14]. Other models were built to monitor the health of the cutting tool. These models were leveraged together into a DT that predicts tool wear. The DT is synchronized with the physical system (SMART) using IIoT data to continuously replicate and monitor the physical behavior of the machine in the virtual environment.

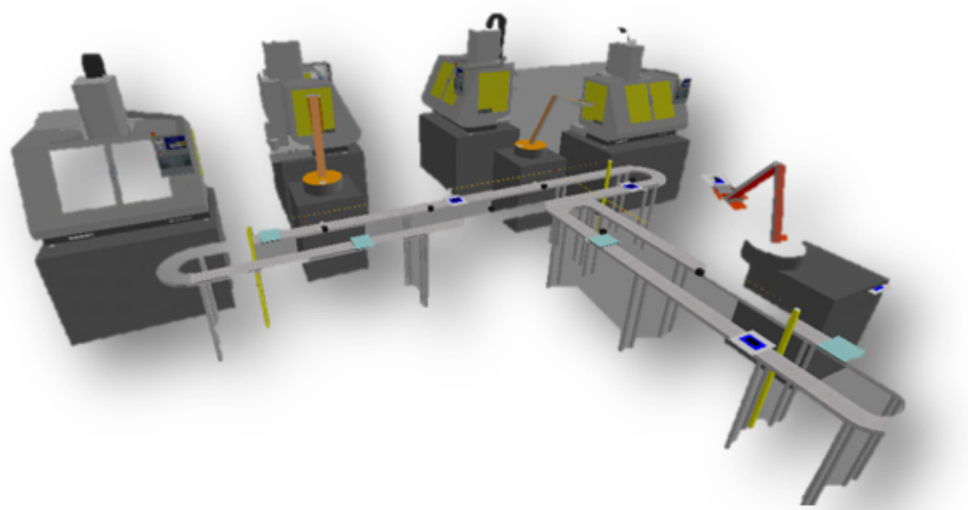

Figure 8. System-level simulation of SMART, developed by MDP students.

4.2.2 System-level modeling and simulation

At the system-level, models and simulations are used to monitor and evaluate high-level performance metrics such as throughput, work in process, processing times, yield, productivity, etc. Projects focus on using different discrete event methods to monitor and evaluate the performance of a manufacturing system. For instance, the modeling and simulation subteam built a large-scale simulation environment for simulating a semiconductor manufacturing system and generating monitoring matrices that could be used in further comparison with a real physical system. In this example, the simulation environment was used to test complex scheduling/dispatching algorithms and evaluate their effect on the throughput and yield as part of a virtual commissioning effort.

4.3 Cloud and Cybersecurity

The cloud and cybersecurity (C&C) subteam focuses on the design and implementation of cutting-edge software techniques tailored to the next generation of smart manufacturing systems. Students with computer science and/or electrical engineering background work with supervisors and other subteams to tackle challenges in collecting, processing, and securing machine/sensor data in a real manufacturing testbed described in Section 3.3. Broadly speaking, the two main directions that are explored by the team members are: (1) developing the cloud manufacturing infrastructure and (2) improving the safety and security of smart manufacturing systems.

4.3.1 Developing the cloud manufacturing infrastructure

Future smart manufacturing systems can benefit tremendously from centralized control with global visibility [13]. Aligned with this vision, several projects have been proposed ranging from software-defined horizontal & vertical system integration, big data analytics framework design, to web/mobile client API development. Students working on these projects develop a good understanding of database systems and gain rich experience with cloud computing. These students work closely with other subteam members with mechanical and manufacturing engineering backgrounds to understand the limitations of state-of-the-art software systems used in manufacturing environments and tailor their design and implementation in a manufacturing-friendly manner. For example, one past project focused on improving the efficiency of data collection and storage with heterogeneous devices in a manufacturing testbed where techniques for traditional distributed systems with less heterogeneity do not work well. This project allowed students to further understand the special characteristics of manufacturing devices and the data in manufacturing systems while proposing and developing a new cloud-based manufacturing framework [20].

4.3.2 Improving the safety and security of smart manufacturing systems

The increased connectivity and interoperability of smart manufacturing systems inevitably expand the potential for attack surfaces. IIoT devices such as PLCs are the core control units in smart manufacturing and other automation systems. To understand their safety violations, subteam members are conducting a systematic analysis of real-world PLC programs to identify their potential safety loopholes resulting from insufficiently protected data access and control interfaces. Deploying software infrastructures can also introduce vulnerabilities with which attackers can exploit the manufacturing systems. To address this challenge, students are learning and applying security mechanisms such as authentication, encryption, and access control to enhance the security of the cloud software.

4.4 Collaboration Between Subteams

To create a learning environment that mirrors multidisciplinary SM systems, students require input from various subteams. For example, for the system-level simulation project, M&S students were required to obtain, store, and analyze data from the IIoT sensors in SMART. Therefore, the students had to work closely with members of the C&C subteam to automatically store testbed data in a database. M&S students used the data collection pipeline built by the C&C members to accomplish this task. In addition, M&S students collaborated with C&A students when analyzing the data. As C&A students are responsible for integrating the hardware used by the software, the input from the C&A team allowed for M&S students to build a more accurate representation of SMART. Most of the other projects described in Appendix A required similar input from different subteams to ensure that projects were completed in a satisfactory manner.

5 Outcomes and Lessons Learned

Secure Cloud Manufacturing alumni have obtained a number of positions in industry and academia. Some of the alumni have remained in the manufacturing sector, e.g. working on the shop floor or developing new methods to improve manufacturing systems. The time they have spent with the Secure Cloud Manufacturing MDP team has provided valuable manufacturing and research experience while improving their professional and personal skills. A video with student testimonials can be found in [41]. In this video, one student highlighted her leadership experience as part of the MDP team: “It’s really amazing how much responsibility I’ve been given on this team.” Another student said, “I’ve gained so much valuable leadership experience as well as exposure to cutting edge research in my field.” Similar statements have been made by a number of students in the past several years as part of their end of year presentations. Future engineering education research will include obtaining quantitative results, e.g. through surveys, to better understand the placement of Secure Cloud Manufacturing MDP students and the impact that the experience on this team had on those students. The team structure and projects have been piloted in the past years, which resulted in the current structure of the MDP team. An important goal is to continue formalizing the team and project structures to have a well-established education program for smart manufacturing.

There have been a number of challenges and lessons learned from the past several years of the Secure Cloud Manufacturing MDP team. For the recruitment process, one of the major challenges has been the recruitment of underrepresented minority (URM) and women students into this team. The average among students participating in Secure Cloud over the years is <1% URM and 34% female (higher than University of Michigan College of Engineering average) of students on the team. The URM category does not include international students, so the percentage doesn't fully describe the diversity on the team. Creating a diverse, equitable, and inclusive environment in manufacturing and engineering is an ongoing challenge that needs to be addressed by the academic community [42]. Therefore, the Secure Cloud Manufacturing MDP team must look to recruit and provide opportunities to students from a range of backgrounds and identities.

Another major challenge for the Secure Cloud Manufacturing MDP team has been to address the steep learning curve for undergraduate students. Student engagement in MDP for less than 2 semesters is discouraged due to its deleterious effect on the overall group. New students require sufficient training and on-boarding time investment from established team members in the first term in order to develop domain knowledge before they become net contributors to the team. This has been shown in other vertically integrated student teams at other universities [11]. To address this issue, the Secure Cloud Manufacturing projects are developed so returning students can work closely with new students in the MDP team. In addition, the class seniority of the students is also taken into account when assigning subteams/projects (e.g., pairing graduate students with first-year undergraduates).

One of the biggest challenges from the SM research perspective is creating an environment where students are willing to learn and incorporate materials from various disciplines. In the past, both undergraduate and graduate students have had difficulty in stepping out of their comfort zone to develop their methods and techniques, especially because many students are still learning their foundational discipline. However, since SM systems require large cross-domain knowledge, students must understand, learn, and utilize information from other disciplines. Due to the diverse nature of the entire team and the subteams, students have been encouraged to work together and learn from one another during the course of the semester. However, in the future, formal criteria for incorporating a breadth of knowledge should be added when developing and assessing student projects.

6 Conclusions

As Smart Manufacturing systems become more common, there is a need to educate and develop students with advanced skills in a number of areas. One approach that has focused on using hands-on, multidisciplinary, team-based projects for manufacturing education is the Secure Cloud Manufacturing Multidisciplinary Design Program team at the University of Michigan. In this team, undergraduate and graduate students work closely together to accomplish multi-semester research projects in several areas. Teams are closely supervised by faculty mentors, team managers, postdoctoral scholars, and graduate students during the course of the program. To accomplish these projects and ensure a collaborative environment, students are split into three well-structured subteams (Control & Automation, Modeling & Simulation, and Cloud & Cybersecurity). These subteams combine various specialties from individual members and use knowledge from other subteams to address research problems in the area of Smart Manufacturing. Students gain a number of manufacturing, research, and professional skills during this process. However, as the team is ever evolving, a number of challenges remain in the areas of improving recruitment and establishing a formal structure for the student projects and the program.

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Appendix A. Project Descriptions

A.1 Control and Automation Projects

Project title	Project Description	Project Focus	Semesters
In-situ sensing and control for 3D Printing	Designing and implementing sensors for in-situ sensing with FDM for real-time data acquisition and control.	Additive Manufacturing	FA 2019 to Ongoing
Virtual reality for manufacturing	Implementing a virtual factory on a VR headset for a hands-on learning station for high-school students.	Augmented & Virtual Reality	FA 2019 to Ongoing
Controls for mobile robotics	Using libraries for object detection, motion planning, and end-effector motion on a Human Support Robot.	Autonomous Robots	FA 2019 to Ongoing
Anomaly detection for 3D Printing	Designed and tested an anomaly detection for nozzle clogging in FDM with external sensors and computer vision.	Additive Manufacturing	FA 2018 to FA 2019
Multi-agent control for manufacturing	Integrated a distributed, cooperative control strategy for system-level control of SMART.	The Industrial Internet of Things	WN 2018 to WN 2019
Logic for system-level control	Programmed a Programmable Logic Controller for SMART, integrating sensors, machines, and robots.	Horizontal & Vertical System Integration	WN 2015 to WN 2018
Sensor integration for data collection and anomaly detection	Mounted and tested various sensors that will be used to collect data in SMART, e.g. presence sensors, cameras, pressure sensors.	Horizontal & Vertical System Integration	FA2015 to WN2018
Gantry integration in SMART	Integrated a pneumatic gantry to add raw material to and remove finished parts from SMART.	Horizontal & Vertical System Integration	FA 2017 to WN 2018
Improving the human-machine interface	Adapting the human-machine interface to improve communication between SMART and an operator or programmer.	Horizontal & Vertical System Integration	WN 2017 to FA 2017
Interchangeable robot grippers	Designed and integrated two end-effectors for a material handling robot in SMART.	Autonomous Robots	WN 2015 to Sp/Su 2017

Note: FA = fall; WN = winter

A.2 Modeling and Simulation Projects

Project title	Project Description	Project Focus	Semesters
Emulation for virtual commissioning	Using virtual commissioning software to model robot kinematics and motions; validating PLC and HMI programs in a virtual environment for SMART.	Digital Twin Based Simulation	WN 2020 to Ongoing
Anomaly detection using Digital Twins	Using physics-based, data-driven models, and subject matter expertise to detect anomalies in a milling process in SMART.	Big Data & Analytics, Digital Twin Based Simulation	FA 2018 to Ongoing
Modeling and simulation of individual machines	Developing DTs using MATLAB to monitor the operation of CNC machines and robots of SMART in real-time.	Industrial Internet of Things, Digital Twin Based Simulation	WN 2017 to Ongoing
System-level simulation	Using commercially available software to develop a simulation that simulates the operation of SMART.	Digital Twin Based Simulation	WN2015 to Ongoing
Large-scale manufacturing system model	Used commercially available software to develop a larger manufacturing system simulation for productivity analysis.	Digital Twin Based Simulation	WN 2016 to WN 2018
Synchronization of a simulation with physical processes	Synchronized a simulation environment to run in real-time with SMART using the Industrial Internet of Things data for detecting anomalies and flagging alarms.	The Industrial Internet of Things, The Cloud	WN 2017

Note: FA = fall; WN = winter

A.3 Cloud and Cybersecurity Projects

Project title	Project Description	Project Focus	Semesters
Ubiquitous data access for SMART	Developing a distributed framework for generic data access, streaming, and analysis in SMART.	Horizontal & Vertical System Integration	WN 2020 To Ongoing
PLC code analysis	Analyzing real-world PLC code to detect potential safety violations.	Cybersecurity	FA 2019 To Ongoing
Network traffic-based anomaly detection	Demonstrated the effectiveness of identifies several types of anomalies with the help of the network traffic patterns.	Big Data & Analytics	FA 2018 To FA 2019
Security of the DT framework	Developed a threat model where attackers can hack into the DT framework to alter the control logic.	Digital Twin Based Simulations	WN 2019 To FA 2019
Software Defined Control with SMART	Prototyped the SDC Northbound and Southbound interfaces.	Horizontal & Vertical System Integration	WN2018 To WN 2019
Cloud-based data analysis for SMART	Tested various data-driven methods to analyze manufacturing system data in a cloud repository.	Big Data & Analytics	WN 2017 To WN 2018
Security of control logic for industrial testbeds	Identified and reduced the attack surface of the PLC based industrial testbeds.	Cybersecurity	WN 2016 To WN 2017
Cloud-based data visualization for SMART	Developed a visualization for manufacturing system data in a cloud repository.	The Cloud	WN 2015 To FA 2017
Cloud-based data collection infrastructure for SMART	Developed a cloud-based framework that collects data from the programmable logic controller (PLC) and stores it in a cloud server.	The Industrial Internet of Things	WN 2015 To WN 2016

Note: FA = fall; WN = winter

Appendix B. Grading Rubric

Category	Criteria	Scale	Weight
Weekly Participation	Attendance	1-5	10%
	Positive Contribution	1-5	
Team Role Responsibilities	Organization	1-5	10%
	Thoroughness	1-5	
	Timeliness	1-5	
Completion of Deliverables	Individual	1-5	10%
	Sub-Team	1-5	
Project Submission	Robustness	1-5	5%
	Team Member Grading	1-5	5%
Midterm Presentation	Presentation Content	1-5	10%
	Overall Organization & Flow	1-5	
	Spelling and Grammar	1-5	
	Graph Organization & Labeling	1-5	
	Verbal Articulation & Projection	1-5	
	Team Member Grading	1-5	5%
Midterm Report	Report Content	1-5	15%
	Organization & Flow	1-5	
	Spelling and Grammar	1-5	
	Graph Organization & Labeling	1-5	
	Source References	1-5	
Final Presentation	Presentation Content	1-5	10%
	Overall Organization & Flow	1-5	
	Spelling and Grammar	1-5	
	Graph Organization & Labeling	1-5	
	Verbal Articulation & Projection	1-5	
	Team Member Grading	1-5	5%
Final Report	Report Content	1-5	15%
	Organization & Flow	1-5	
	Spelling and Grammar	1-5	
	Graph Organization & Labeling	1-5	
	Source References	1-5	

Appendix C. MDP Roles and Responsibilities

Sub-Team Leader:

- Organize and manage the team project(s)
- Organize and manage team member assignments
- Manage sub-team meetings
- Same roles and responsibilities as members

Code Manager:

- Logically organize and manage code documentation in the shared drive site
- Same roles and responsibilities as members

Document Manager:

- Logically organize and manage in the shared drive site:
    - Reports
    - Presentations
    - Documentation created by the Scribe
- Same roles and responsibilities as members

Scribe:

- Document and publish assignments, feedback, and comments from:
    - Sub-team meetings
    - Weekly MDP meetings
    - Midterm and final presentations
- Same roles and responsibilities as members

Members:

- Actively participate in team meetings
- Actively participate in weekly MDP meetings
- Develop a report section for sub-team reports
- Develop a presentation section for sub-team presentations
- Complete project deliverables
- Create a project presentation poster, publication, or video in addition to required presentations