WIP: Industry 4.0 Robotics - An Interdisciplinary Approach to Deep Learning

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***Abstract*—This innovative practice work in progress paper describes an interdisciplinary course, "Industry 4.0 Robotics," aimed at fostering deep learning and innovation in students across Manufacturing, Robotics, Computer Science, Software Engineering, Networking, Cybersecurity, and Technology Management. The course, jointly taught by faculty from different domains, emphasizes interdisciplinary connections in Industry 4.0 (IN4.0) Robotics through a combination of lectures, real-world insights from industry guest speakers, and hands-on interdisciplinary project-based learning.**

The contribution of this work lies in its innovative approach that combines proven best practices in education, inspiring deep learning, and an appreciation of interdisciplinary teamwork. The course design builds upon education research on the benefits of leveraging student creativity and requirements engineering practices as learning tools that allow students to develop a deeper understanding. While the benefits of these practices, commonly cited for developing enhanced problem-solving and cognitive flexibility skills, are becoming well understood in many individual disciplines, far less has been published on best practices for achieving this in interdisciplinary thinking. This course design explores this through using hybrid experiential problem based learning and project based learning for students to develop an understanding of interdisciplinary challenges and opportunities.

While the benefits of individual educational practices have been studied within specific disciplines, this work extends the understanding of these practices when applied to interdisciplinary challenges, such as those encountered in Industry 4.0 robotics. The course design aims to bridge the gap between the technical aspects of individual disciplines and the social dimensions inherent in interdisciplinary work.

This work in progress seeks to share early results showcasing the benefits of interdisciplinary teamwork and problem-solving. By articulating observations of commonalities and differences with prior work within individual disciplines, the paper aims to highlight the unique advantages of this interdisciplinary learning experience, offering insights into the potential impact on student learning.

The chosen approach stems from the anticipation of future challenges increasingly necessitating interdisciplinary solutions. The goal of this work is to understand how best practices from individual disciplines can be effectively incorporated into interdisciplinary courses, maximizing student learning, and uncovering unique learning outcomes resulting from this innovative approach.

The course design intentionally bridges the gap between the technical aspects of individual disciplines and the social dimensions inherent in interdisciplinary work, to encourage effective communication and collaboration within mixed student teams. While this remains a work in progress, initial observations reveal a heightened interdisciplinary curiosity among students, driving deep learning as they explore the interconnectedness of their own discipline with others within their teams. This curiosity propels self-led exploration and understanding of how their expertise intersects with diverse knowledge areas, creating opportunities for innovative solutions at these disciplinary intersections.

This work contributes to the broader landscape of engineering and computing education by offering insights into the practical application of interdisciplinary learning in preparing students for the complex challenges of Industry 4.0.

***Index Terms*—Industry 4.0, interdisciplinary projects, robotics**

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I. Introduction

The industry is rapidly evolving through the integration of advancements in technologies like robotics, expanding sources of data through the Internet of Things (IoT), advances in augmented and extended reality (AR/XR), all combined with automated decision making and advances in artificial intelligence (AI). This integration of technologies is known as Industry 4.0 (IN4.0) [1]. This transformation necessitates a workforce equipped with the ability to work in interdisciplinary teams for problem-solving and innovation. However, education approaches that compartmentalize learning within specific fields run the risk of not preparing students to understand better how interdisciplinary teams can open up opportunities for innovation. This paper describes an innovative interdisciplinary course, "Industry 4.0 Robotics," that was designed to bridge this gap and prepare students for the challenges and opportunities of the IN4.0 era.

The Need for Interdisciplinary Learning

The complexities of IN4.0 robotics demand a workforce that can integrate knowledge from various domains. The goal of this course was to create an experiential learning environment that brought together students from a variety of majors such as Manufacturing, Robotics, Computer Science, Software Engineering, Networking, Cybersecurity, and Technology Management, to work collaboratively and develop an appreciation of the benefits that could be gained by multi-disciplinary teams.

By creating an environment of interdisciplinary exploration, the course equips students to:

Break down silos: Understand the interconnectedness of their own discipline with others and appreciate the value of diverse perspectives in problem-solving.

Develop holistic solutions: Approach challenges from a multi-faceted perspective, leading to innovative solutions that leverage expertise from various disciplines.

Enhance communication: Effectively collaborate and communicate with team members from different backgrounds, a critical skill for success in the modern workplace.

This paper examines the design and implementation of the "Industry 4.0 Robotics" course and the pedagogical approaches employed to foster interdisciplinary learning. We will also detail the selection of project themes and team assignments, designed to stimulate collaboration and innovation.

Contribution and Significance

This work in progress contributes to engineering and computing education by showcasing a practical application of interdisciplinary learning to prepare students for the complexities of IN4.0. By analyzing student outcomes and project successes, we aim to provide insights into the effectiveness of this approach. We discuss the commonalities and differences observed in student attainments of learning outcomes and reflect on the effectiveness of the implemented methods. This is concluded by discussing the lessons learned and opportunities to further build on this approach.

II. Prior Work

Our goal was to design a course that exposes students to current industry practices to foster deep learning and a sense of how interdisciplinary approaches drive innovation. We focused on practices promoting student self-discovery, demonstrated to enhance understanding [2]. Furthermore, incorporating creativity as a learning tool has been shown to enhance student learning outcomes [3]. Studies indicate that integrating creative exercises can lead to increased knowledge retention, self-efficacy, and problem-solving skills [4], [5]. The course was structured as a blend of problem-based learning (PBL) and project-based learning (PjBL) principles utilizing proven practices from various disciplines. The goal of this combination of practices was to create a rich learning environment that sparked creativity and utilized aspects of both PBL and PjBL.

We leverage PBL's strengths for interdisciplinary learning [6]. PBL starts with a complex, ill-defined, open-ended problem where students collaborate to identify how to approach the problem and what knowledge and skills they would need to solve it [7]–[9]. They then engage in self-directed exploration inspired by constructionist learning to acquire that knowledge. This fosters problem-solving, cognitive flexibility, and a deeper conceptual understanding [10].

With PBL, using an open-ended problem typically focuses the learning process on research and inquiry, whereas PjBL is characterized by a more well-defined project focusing learning on the production of a model [11]. Because of this difference with PBL, there is typically less intermediate delivery structure. In contrast, PjBL often lends itself to specific milestones managing the delivery of that project. Integrating PBL in interdisciplinary settings has been shown to improve learning outcomes, but can also be more challenging in engineering disciplines [6], [8]. As noted by Perrenet et. al., with the more extended timeline often associated with engineering projects, supervised practice is recommended for PBL practice [8]. Learning benefits of PjBL in computing and engineering disciplines are widely recognized in part due to their extended timelines and scope being similar to real-world projects [12]–[14].

To leverage the strengths of both PBL and PjBL, this course adopted a hybrid approach. The class used PBL's proven practice of broad problem definitions to promote independent research and inquiry at the beginning. Initially, students were presented with open-ended problems that were intended to benefit from knowledge of multiple disciplines to foster independent inquiry and research, but also to promote collaboration around what was learned. However, recognizing the challenges associated with open-ended problem solving within a fixed timeframe noted in [8], the course gradually transitioned towards a more PjBL model. Through weekly faculty interactions, students received guidance and support while the problem scope was refined to align with project-based deliverables. This iterative process aimed to balance the benefits of PBL-driven exploration with the structure and accountability inherent in PjBL.

We believe that the effectiveness of PBL, PjBL, and creativity in fostering deep learning within interdisciplinary computing and engineering contexts remains under-explored. This work is positioned to address this gap.

III. Interdisciplinary Course Design

The course curriculum was designed with learning objectives emphasizing the interconnectedness of various disciplines within the realm of IN4.0 robotics. The course structure incorporated a blend of pedagogical approaches, including:

Instructor Lectures: Provided foundational knowledge in key areas like robotics, automation, and IN4.0 concepts.

Industry Guest Speakers: Offered real-world insights and practical applications of how interdisciplinary collaboration was changing their business. The speakers were carefully selected so that they could cover the wide spectrum of individual IN4.0 technologies such as VR/AR, AI, Robotics, IOT, Additive manufacturing, Cyber-Physical Systems, etc, and the integration of those technologies and the benefits and challenges that the industry is facing.

Hands-on Interdisciplinary Project-based Learning: Formed the core of the course, allowing students to work in teams on projects that demanded the application of knowledge from various disciplines.

Faculty Collaboration and Expertise:

A team of faculty members with expertise in robotics, computer science, networking, and cybersecurity jointly developed and delivered the course content. This collaborative approach ensured that a comprehensive and interdisciplinary perspective was presented throughout the course. Project themes were chosen to require students to leverage expertise from various disciplines to achieve successful outcomes (examples in section IV). Students were strategically assigned to project teams with complementary disciplinary backgrounds to encourage interdisciplinary collaboration and communication. This group of faculty jointly discussed the projects that were selected and the team makeup that would be appropriate for each project. This group split the projects so each had a faculty project mentor who guided and met regularly with the project team. The faculty group also met on a weekly basis to discuss project progress and discuss best practices to involve students of each discipline as the projects progressed. In addition to the faculty mentors, the projects either had a project expert if the project was sourced from industry, or a related industry expert who could provide real-world scenarios and challenges for how the team could adapt their project to address a real business need.

Project Planning and Management:

This course's project planning and management benefited significantly from ten years of experience running the CCSU Software Engineering Studio. The Studio connects external project partners (customers) with student teams typically comprised of 4-5 seniors who work on software engineering projects lasting between one to four semesters. Since 2014, the Studio has worked with over 40 distinct project partners that engaged over 550 students. All projects facilitated by the Studio are embedded into several software engineering courses where student teams participate in all phases of the software development lifecycle with close cooperation of the project partner or their representative under the guidance of the course instructor.

The Studio's workflow has evolved into a sustainable framework that helps align software development projects with student learning outcomes and the corresponding course objectives. Formative and summative assessment of student work is facilitated by a broad range of project-related deliverables spread throughout the academic term that enables the course instructor to provide timely feedback and ensure that students meet their learning outcomes. At the same time, regular interaction with the project partner helps ensure that each team makes good progress towards meeting the project requirements. Our framework helps ensure the project scope aligns well with student team capabilities, technical project requirements, and academic term constraints [15], [16]. The framework includes four phases: *inception* which occurs before the project commences when the course instructor negotiates the project scope and other considerations with the project partner; *elaboration* when teams form and write their working agreements, and then undertake requirements engineering; *development* during which teams go through four to six two-week development sprints; and *transition*, when teams prepare for knowledge transfer, and either deliver their work to the project partner or transfer to the next team(s). Phase duration may vary depending on the nature of the academic course hosting the project.

The Software Studio framework has been successful with projects for a broad range of partners including commercial, non-profit, and community organizations. Our ongoing efforts of using this framework to support software projects for the common good are documented in [17]. To maximize the transferability of findings from the Software Studio, this course targeted primarily senior students, mirroring the population of the students working with the Software Studio. This work applies the Studio framework in a different context where projects are inherently interdisciplinary, and where course instructors play the additional role of being a project partner.

IV. Overview of Class Projects

Securing IoT Systems: Difficulty integrating diverse data sources into secure, scalable data collection systems for informed decision-making in manufacturing. *Solution: Modular design for flexible data acquisition.* Simulating secure data collection in an Industry 4.0 (IN4.0) manufacturing environment, this project aimed to modularize data collection for easier integration of diverse data sources. Students leveraged knowledge of robotics (PLCs), networking (configuration), and security programming to decouple hardware components and create a modular approach.

Technical Knowledge Transfer: Knowledge transfer inefficiency in manufacturing. Methods, like manuals, can be time-consuming to update and may not effectively capture tacit knowledge from experienced workers. *Solution: Modular design for flexible data acquisition.* Focused on automating knowledge transfer in manufacturing, this project aimed to generate technical documentation from video recordings. Diverse student backgrounds in technology management (challenges), equipment expertise, software design, audio/video processing, prompt engineering, project management, and software integration (LLMs) enabled addressing technical and non-technical documentation challenges.

Augmented Reality for IN4.0: Challenges in real-time detection and visualization of infrastructure damage for improved maintenance and safety management. *Solution: AI-powered AR system for crack detection and highlighting.* This project focused on creating a real-time AI model for detecting and highlighting infrastructure cracks in augmented reality using Microsoft HoloLens 2. The team's expertise in software development (AR application), networking (data integration), and technology management (work tasks) allowed for successful project completion.

Vision-based Part Inspection: Need for improved efficiency and accuracy in manufacturing quality control. *Solution: Integration of a vision system for automated deburring inspection.* Partnering with an industry partner, this project aimed to improve efficiency and accuracy in manufacturing by integrating a vision system for deburring airfoil parts. Expertise in robotics (positioning) and software engineering (image processing, inspection) was crucial. The team's diverse backgrounds, including quality control, 3D camera programming, and Cognex's Insight software, facilitated seamless integration.

***Enhancing Human-Robot Collaboration**:* Limited dexterity and control in existing VR glove-based robotic arm control systems. *Solution: Improved system design for fine-grained manipulation and enhanced safety features.* This team enhanced a VR glove-based robotic arm control system. Their backgrounds allowed them to redesign the interaction for fine-grained tasks, improve velocity and position control, and ensure safe robotic motions.

***Robot Gripper Lifetime Analysis**:* Lack of data on robot gripper wear and tear, hindering preventative maintenance and potential downtime. *Solution: Machine vision-based system for evaluating gripper health and predicting potential failures.* This project focused on evaluating robot gripper durability by measuring its six degrees of freedom using machine vision. The team's expertise in robotics and computer science was crucial for code development and robot manipulation for optimal camera imaging.

V. Results

Individual feedback:

Student surveys (n=20) revealed a strong positive response to the course's impact on interdisciplinary learning. The average score for the statement "This class has enhanced my curiosity about issues that may require collaboration of people from different majors" was 4.00 (on a 5-point Likert scale), indicating a high level of agreement. Similarly, students reported an expanded awareness of problems that benefited from knowledge from multiple disciplines (average score 3.90) and the value of collaborating with students from other disciplines (average score 3.85). These findings suggest the course effectively fostered student interest and appreciation for interdisciplinary teamwork.

However, there are areas for improvement regarding team dynamics and project management. The average score for the statement "I feel that all members of my team were able to contribute something of significance to the project" was 2.65, and the score for "I feel that our team had enough guidance on how to split the work according to our backgrounds/strengths" was 2.30. These results suggest future iterations of the course could benefit from incorporating student training and assistance on leveraging individual strengths within diverse teams.

Group feedback

1) Common benefits: Student teams overwhelmingly reported that their team's diverse backgrounds enabled them to tackle larger-scale projects. Every project required expertise from distinct areas. For example, the Robot-Based Part Inspection project demanded knowledge in manufacturing, quality assurance, and 2D vision inspection. Students needed to understand part positioning, lighting, and data acquisition, along with general programming, Cognex software, and ABB software to automate the process. This project would have been impossible without students from robotics, computer science, and engineering.

Many teams felt their projects fostered more creative solutions compared to past experiences. Diverse perspectives from team members proved valuable when tackling challenging aspects. The Knowledge Transfer team, with both technical and non-technical students, exemplifies this. Technical students offered programming insights, while non-technical students ensured clear communication in the resulting documentation. These interactions led to higher-quality project outcomes.

Students noted that project content and team composition mirrored real-world industry conditions. Those with work experience found the challenges similar to their jobs or aligned with desired skills for new hires. Students reported developing stronger technical and non-technical skills, like software expertise, project management, and communication. This experience strengthens their resumes for industry positions.

2) Common challenges - lessons learned: Forming teams with complementary skill sets proved crucial. Uneven expertise distribution could lead to situations where some members struggle to contribute meaningfully. Future iterations could benefit from incorporating strategies for assessing student backgrounds and fostering balanced team formation.

Bridging the communication gap between disciplines can be challenging. Future iterations could incorporate workshops or activities specifically designed to enhance interdisciplinary communication and collaboration skills.

While students appreciated the course's focus on independent learning, some desired clearer guidance on project management, particularly regarding workload distribution based on individual strengths. Universities replicating this course could consider providing resources or workshops on effective interdisciplinary project management.

Reflections on project selection and feasibility: While projects incorporated diverse knowledge, the balance wasn't always optimal. Teams distributed tasks, but not all students could fully utilize their expertise. Projects like Robot-Based Part Inspection and Robot Gripper Lifetime Analysis exceeded the scope achievable by a single semester's inexperienced team. Even for multi-semester projects, each team needs clear goals and deliverables for effective progress.

Suggested improvements for future implementations

Balancing PBL and Structure: While well-defined projects offer clarity, a key benefit of PBL is fostering student exploration and problem-solving. Future iterations could explore a balanced approach, providing a clear project framework while allowing some flexibility for student-driven solutions. This could involve clearly defining project goals and deliverables, while leaving some aspects open for student teams to determine the "how" through their interdisciplinary expertise.

Select Students Based On The Needs Of The Projects: For this first offering, roughly equal number of students per major enrolled in the course. Future iterations can explore enrollment strategies that prioritize matching the number of student majors allowed to enroll in the class to the skill demands of the specific problems to ensure more well-rounded teams where every member can contribute significantly.

Enhanced Course Communication: Building on research by Perrennet et al. [8], the additional uncertainty of PBL can be stressful for engineering students used to more clearly defined expectations. Because of this, more explicit communication of course expectations, time commitment, project deliverables, how projects leverage student skillsets, and grading criteria will improve student understanding and reduce anxiety.

Increased Early-Semester Project Advisor Interaction With Teams: More frequent meetings with advisors at the beginning of the project followed by shifting to regular check-ins (e.g., weekly) can clarify expectations, address questions, and ensure teams are on track as they delve into the project.

Interactive Guest Speaker Sessions: Transform guest lectures into interactive sessions with Q&A and guided discussions. This will help students connect the speaker's insights to their projects and broader industry trends.

Transferability of the Approach

The success of this work can be attributed to several critical factors: inherently interdisciplinary content, collaborative faculty, rich industry connections, and well-established lab facilities. IN4.0 robotics requires a seamless connection of diverse fields, as this course exemplifies (Manufacturing, Robotics, Computer Science, Software Engineering, Networking, Cybersecurity, and Technology Management). The framework can be easily extended to other disciplines such as Data Science, Business Analytics, Artificial Intelligence, and other engineering disciplines.

The course's success suggests the potential for offering joint capstone courses across these programs. However, achieving this vision necessitates additional considerations: faculty development for those teaching interdisciplinary offerings; increased industry engagement to enhance students' real-world experience; and interdisciplinary lab creation. Universities should consider creating central lab spaces designed to facilitate multiple disciplines working together. These "technology innovation hubs" would provide students with exposure to interdisciplinary resources, facilitate collaboration, and break down departmental silos. Without such hubs, projects risk being limited by discipline and face challenges in lab resource coordination and supervision. Disparate lab equipment locations can further hinder collaboration and project feasibility.

VI. Conclusion

This study examined the effectiveness of an interdisciplinary course in preparing students for today's collaborative workforce challenges. The course emphasized teamwork and communication across various disciplines. Analysis of project outcomes highlighted the benefits of interdisciplinary collaboration in devising comprehensive solutions. This work contributes to engineering and computing education by showcasing how interdisciplinary learning can be practically applied for IN4.0 readiness. The faculty collaboration model, where instructors with complementary expertise co-develop curriculum and mentor projects, offers a valuable framework for educators aiming to implement similar programs. Future research will investigate the long-term impact of this approach on students' career paths and industry readiness. Additionally, refining problem selection, team composition, and guidance will further enhance the course's efficacy.

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