Project-based curriculum for teaching construction robotics

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Abstract -

As innovations in construction robotics are being tested and deployed on site thanks to technological advancements in computing and sensing, Civil Engineering researchers must consider how to connect real-world innovations with research and teaching at a much faster pace. Observing the practice helps identify problems and test engineering solutions and models through research. As the research develops, engineering courses can foster innovation adoption in the industry. This cycle leads to a new practice and the recognition of new problems that feed the research and teaching. This paper focuses on teaching construction robotics through a project-based curriculum as an essential mechanism to enhance this ecosystem from research to practice. The project involves the collaboration of construction companies, robot companies, and students to analyze the potential Safety, Quality, Schedule, and Cost impacts of at least ten construction robots. The anticipated benefits for the students are engaging in real engineering problem solving and synthesizing academic and industry experience. At the same time, the collaboration between the students and the industry helps validate the research generality and contributions. This paper does not claim that this represents the only or best way to teach this topic but aims to open the subject for discussion.

Keywords -

Construction Robotics; Education; Automation; Construction Management

1 Introduction

Civil Engineering and construction practice still involve many aspects of a craft. Hence, real-world practice can help inform and test research. The Center for Integrated Facility Engineering (CIFE) at Stanford University focuses its research efforts on the built environment with a careful observation of practice to identify problems. These problems generate a solution intuition backed by a theoretical point of departure. Following research questions and methods inform the research tasks to solve the industry problem. The validation of the research results leads to contributions and practical impacts in the industry, like the adoption of cutting-edge technologies (Fig. 1). Examples are found in many CIFE Ph.D. projects and thesis [1, 2, 3, 4] and the integration of courses into the CEE curriculum at the graduate level. Examples are Building Information Modeling, Parametric Design and Optimization, Virtual Design and Construction (VDC), Industrialized Construction, Managing Fabrication and Construction, Project Assessment and Budgeting, and Computer-Integrated AEC.

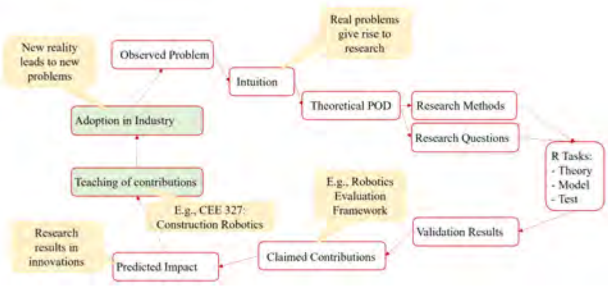

Figure 1: Connection of real-world innovations with research and teaching cycle based on CIFE's academic research method. Focus on the first project-based curriculum to teach Construction Robotics for Civil Engineering graduate students: CEE 327: Construction Robotics.

These courses foment innovation adoption and diffusion in the industry. According to Navon [5], such courses could reduce resistance to new technologies by enriching the knowledge and understating of future industry leaders. Custovic et al. [6] also highlight the role of construction management curricula in researching new methods and technologies and demonstrating their applicability and benefits for the industry. Once the adoption matures, it can lead to a new reality and new problems or observations that feed into the research cycle and the following teaching of the new concepts, methods, or techniques.

1.1 Construction Robotics

The Construction Automation and Robotics field has developed significantly in the last decade thanks to advances in the internet of things, artificial intelligence, sensors, and the use of Building Information Models (BIM). These advances materialize in new construction robots being developed and tested on construction sites. The International Federation of Robotics forecasts 4,200 construction robotics units to be sold from 2019 to 2021 [7], and Bock and Linner [8] outlined 24 categories of on-site task-specific construction robots. Given this new practice, researchers in Civil Engineering must consider how to connect real-world applications with research and teaching.

As robots mature and become suitable construction methods, innovation managers must consistently evaluate

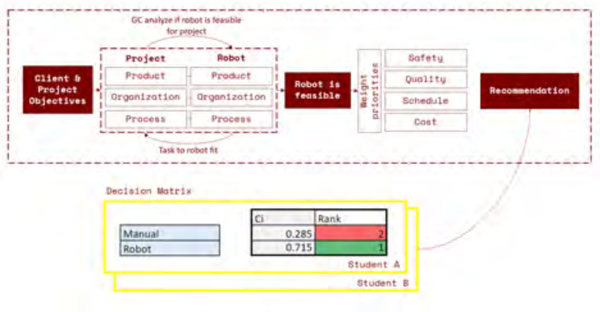

Figure 2: Project-based approach to analyze the Safety, Quality, Schedule, and Cost impacts of ten robots independently by two students.

the impact of deploying robots compared to traditional construction methods. However, construction robotics courses are not traditionally included in Civil Engineering, with only a few courses and programs available worldwide [9, 10, 11, 12, 13].

Based on the importance of teaching the academic foundations about innovation approaches [6] to support the cycle between research and practice, this paper focuses on a project-based construction robotics class for Civil Engineering. The course pairs real construction projects with on-site robots for about ten tasks. Two students are assigned per case to assess each robot's potential Safety, Quality, Schedule, and Cost impacts for the selected project. The 10-week course allows the students to work closely with industry partners from the General Contractor and the robot start-up or manufacturer. The collaboration in the class between the students and the industry helps validate the research generality [14] with real-world test cases. For the students, it directly connects the theory and practice. And finally, for the industry partners, the class presents an objective and repeatable method to approach robot evaluations, together with the direct collaboration with a student to resolve an industry problem.

In addition to the course project, we include five modules that cover 1) an introduction to construction robotics and a Robotics Evaluation Framework (Fig. 2), 2) robot examples, 3) the sustainability perspective, 4) human-robot collaboration, and 5) robots in the context of Virtual Design and Construction (VDC).

This paper aims to share the learning objectives and course structure of the proposed curriculum to open the subject for discussion with researchers and lecturers in the field. We present the course feedback from the first implementation in Winter 2021.

2 Related Work

A few universities have identified the need for including construction robotics education in Civil Engineering and Architecture courses. These courses introduce automation strategies for construction processes and their implications in the design outcome. A common thread of the existing studies is the interdisciplinary Architecture, Engineering, and Construction (AEC) approach that combines expertise from various sources.

The University of Maryland, A.J. Clark School of Engineering, offers a *Construction Automation and Robotics course*. The course aims to redesign traditional construction processes to utilize state-of-the-art automation and robotics technology [15]. Prof. Skibniewski's 12-week course covers 1) the history of construction automation and robots; 2) construction projects including ergonomics and the physical and cognitive requirements of construction labor; 3) an introduction to industrial robotics; 4) robot components; 5) feasibility of robot applications; 6) calculation of costs and benefits in robot assessment; 7) integration issues; 8) additive manufacturing; 9) safety and ethical issues.

The University of Sydney's School of Architecture, Design, and Planning provides a *Robotics in Architecture and Construction* masterclass introducing robotics for the fields of architecture and construction. The goal of the class is to understand what a robot is and how to consider robot methods in the design workflow [13].

ETH Zurich has also developed several courses focusing on digital and robotic fabrication in architecture, including a one-year *Master of Advanced Studies in Architecture and Digital Fabrication* to teach the fundamentals of technologies and methods of digital design and fabrication for architecture and construction [9].

The Institute for Advanced Architecture of Catalonia developed a *Master's in Robotics and Advanced Construction (MRAC)*. The program seeks to train professionals on the emerging design and market opportunities of deploying new robotic and advanced manufacturing systems. The curriculum involves seminars and studio projects investigating how robots and automation will change the existing building methods. A goal of the program is to develop processes and design tools that address these new methods from the engineer, designer, architect, workforce, and academic perspectives [12].

The Technical University of Munich, Department of Architecture, includes a newly established *Master's study in Advanced Construction and Building Technology* within the Chair of Building Realization and Robotics. The mission of this program is to design and build a future robotic society. A cross-disciplinary approach focuses on finding and creating technologies for robotic construction by target-value design [11].

Lastly, the Faculty of Architecture at RWTH Aachen University designed a Master's program in *Construction Robotics* to shape students in automated construction machinery and robotics. The program combines prototyping of machinery and processes with virtual design and simulation [16].

These courses and graduate programs evidence the importance and growing demand to teach a new generation of AEC students about automation and construction robotics. Most of the existing effort is led by Architecture schools, focusing on new design and fabrication methodologies enabled by robots. Civil Engineering programs should similarly address the potential on-site robot uses, especially from a construction managerial perspective, as outlined by Skibniewski [15].

3 Proposed Curriculum

3.1 Context

Construction Robotics (CEE 327) is part of Stanford's Civil and Environmental Engineering (CEE) graduate studies. The target students for the class include the Sustainable Design and Construction (SDC) students within CEE and graduate researchers at the Center for Integrated Facility Engineering (CIFE). CIFE aims to improve the built environment's planning, design, construction, and operation across all sectors and scales, including buildings, industrial plants, urban districts, manufacturing facilities, infrastructure, and cities. The CEE-SDC curriculum includes courses on engineering and management methods that improve the built environment's reliability, productivity, innovation, and sustainability.

The new Construction Robotics course adds to the existing engineering and construction management curriculum, focusing on evaluating on-site construction robots. An in-depth analysis of off-site automation examples is outside the class's scope, as an Industrialized Construction class and annual industry forum covers this topic.

Any CEE graduate student can enroll in the class. It is assumed that students are familiar with BIM, project specifications, and basic scheduling principles. However, students are not expected to have any prior programming or robot design experience, as the course focuses on the management of robot technologies.

3.2 Lecture Plan and Objectives

The first goal of this course is to introduce on-site construction robotic applications through academic and industry practice.

The second goal is to assess the applicability and potential impact of promising construction robots available in the market against traditional construction methods using a consistent, repeatable evaluation method.

Third, to gain a good understanding of basic robot principles and become familiar with state-of-the-art research in the field, including human-robot collaboration approaches.

Finally, to connect robot applications to the broader project and client objectives deploying the Equity, Environment, Economy (EEE) framework [17] and the Virtual Design and Construction (VDC) methodology [18] to manage projects.

The developed curriculum includes two 90-minute lectures per week over ten weeks. Table 1 provides an overview of the lectures' content divided into five modules: 1) Introduction to evaluating construction robots, 2) Robot examples, 3) The sustainable perspective, 4) Human-robot collaboration, and 5) Robotics in the context of VDC.

Table 1: CEE 327 Construction Robotics Curriculum

#	**Module 1: Intro to Construction Robots**	**Assignment**
1	Intro to Construction Robots	
2	Robots 101	A1. Product
	Introduce class robots	
	POP analysis	
3	SQSC and Decision Matrix	A2. Org and Process
4	Lessons learned from drilling robot	
	Meet industry partners	A3. Safety, Quality, Schedule
5	Off-site vs. on-site robots	
	Industrialized Construction	A4. Cost and Decision Matrix
6	Closing framework reflections	
	Layout robot guest lecture	A5. Off-site vs. on-site robots
	Module 2: Robot Examples	**Assignment**
7	Single-task robots intro	A6. REF Conclusions
	ETH Zurich's novel robotic processes	
	Hilti's Jaibot	
8	Canvas and Swinerton case	A7. Robots as a Service
9	Obayashi's robot examples	
10	Robot examples: TyBot, Kewazo	A8. Product Draft (Project)
11	Robot examples: Boston Dynamics, SafeAI	A9. Prep for guest lectures
12	Robot example: Civ Robotics	A10. Org and Process draft (Project)
13	TUM Guest Lecture: Thomas Bock	A11. Prep for guest lecture
14	Robot examples: Shimizu, Exoskeletons	A12. SQSC draft (project)
	Module 3: The sustainable perspective	**Assignment**
15	Overview of EEE	A13. Prep for guest lecture
	Equity and Economic perspectives	
	Silicon Valley Robotics	
16	Ecology perspective	A14. Individual REF template
	Demolition and urban mining	
	Economics, productivity, and employment	
	Module 4: Human-Robot Collaboration	**Assignment**
17	HRC Stanford Robotics Lab (haptics)	A15. Elevator pitch
18	Autodesk's perspective	A16. HRC Ocean One
	Module 5: Robotics in the context of VDC	**Assignment**
19	Robotics in the context of VDC	
	Expert panel discussion	A17. Opportunities and challenges
20	Project presentations	A18. Final report and slides

Module 1: Introduction to Evaluating Construction Robots

This module introduces the course objectives and key concepts to analyze robots in construction. First, we cover an overview of construction robotics history from a literature review of the International Association of Automation and Robotics in Construction (IAARC), Automation in Construction, the Cambridge Handbooks of Construction Robotics, and the American Society of Civil Engineers (ASCE), specifically the Journals of Computing in Civil Engineering and the Journal of Construction Engineering and Management. Second, we introduce basic robot definitions and principles, bearing in mind that the class audience is not likely to have any prior robotics background.

A Robotics Evaluation Framework (REF) based on case studies and the literature review is presented as a basis for the class project [14]. We introduce Assignments 1 to 4 as a mock-up of the class project with data provided from a previous layout case study [19]. Each of the four first assignments focuses on a different aspect of the robot evaluation. These assignments aim to deploy a consistent robotic evaluation method, develop process modeling skills, explore schedule representations, and study cost and benefit scenarios to purchase or use a robot as a service. This example allows students to exchange answers and assess their evaluation against the teaching team solution.

Finally, this module introduces the main differences between applying robots on site and off site.

Module 2: Robot Examples

The second module covers robot application examples. Guest lectures with industry leaders and start-up founders showcase the applications included in the projects and other relevant examples. We also engaged robot examples developed in academia, such as the construction robotics research at ETH Zurich and TUM.

Module 3: The Sustainable Perspective

This module introduces the Economic, Ecologic, and Equity perspectives through the triple "E" Sustainability framework. Topics addressed in this module include the role of robots in the circular economy, robotic deconstruction, statistical analysis of jobs in industry 4.0, and building new skills to grant access to construction robots. The guest lectures include different aspects of robots' sustainability to optimize revenue growth, public good, and health [20].

Module 4: Human-Robot Collaboration

This module addresses state-of-the-art approaches in human-robot collaboration from the academia and industry perspective. Topics include wearable technologies, haptics, virtual reality, and augmented reality. Robot examples include underwater humanoid bi-manual exploration robot: Ocean One [21] and haptic bolting, welding, and joint sealing [22].

Module 5: Robotics in the Context of VDC

The final module discusses the opportunities and challenges of robots within the broader context of Virtual Design and Construction (VDC) (Fig. 3). VDC is the management of integrated multi-disciplinary performance models of design-construction projects, including the product, work processes, and organization of the design, construction, and operation team to support project and client objectives [18]. Course materials present construction robotics as a controllable factor for construction managers to achieve desired project and client outcomes.

This module includes a final panel discussion with VDC experts that previously deployed construction robots in the field. The module aims to understand synergies between deploying the VDC methodology and construction robots and share lessons learned by GCs using robots in the field.

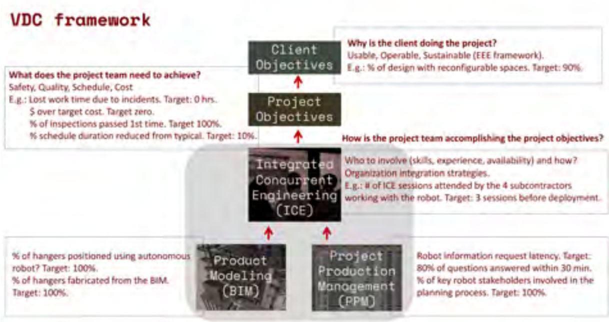

Figure 3: Managing the deployment of construction robots in the context of the VDC methodology.

3.3 Class Project

Finally, the industry project represents a significant component of the course. The teaching team matches pairs of students with a construction industry professional and a robot developer. In our experience, the student-professional collaboration enriches both parties as the students provide an objective lens to a robot evaluation problem. On the other side, the industry professionals on the robotics and the construction site helps connect the class concepts with reality.

Each student receives a blank Robotics Evaluation Framework template accessible online and four case study examples. The pair of students evaluating the same robot must do so independently without looking at their partner's results and tracking the hours taken in each analysis step. In the final two weeks of the class, the students share their finished templates and document differences in results and recommendations. Further, they prepare a joint final presentation, attended by the industry partners.

The robot evaluation method is based on prior work from the researchers [19, 14]. The main evaluation parameters are the analysis of the robot and construction site Product, Organization, and Process. Second, the breakdown of the robot's potential Safety, Quality, Schedule, and Cost impacts to the traditional method for the selected project.

4 Implementation

We offered the class for the first time in the Winter quarter of 2021, including ten Civil Engineering graduate students from Stanford University and nine from the University of Lima working in 12 case studies (Table 2). Due to Covid-19 restrictions, the course was held entirely online in Discord.

Table 2: Industry Partners Winter quarter 2021

#	GC	Robot
1	DPR	Hilti Jaibot
2	Obayashi	Material handling robot
3	Bechtel	Kewazo scaffolding
4	Megacentro Lima	Exyn autonomous drones
5	Produktiva	SafeAi autonomous machinery
6	NCC	Boston Dynamics Spot
7	Swinerton	Canvas drywall finishes
8	DPR	Canvas drywall finishes
9	HDlab	SuitX exoskeleton
10	MT Højgaard	Civ Robotics layout
11	Implenia	TyBot rebar tying
12	Traylor Brothers	TyBot rebar tying

The robot industry partners included five founders and CEOs, a CTO, one Vice President, a Chief Operating Officer, a Construction Technology Manager, and a Business Unit Manager. The GC partners included one Owner, five Innovation Managers/Directors, one Chief Financial Officer, three heads of VDC, and two project directors.

Even though construction robots on the field are at infancy in their deployment worldwide, the consistent student analysis of these examples showed how promising the technology already is for a range of robot types, mobility, autonomy, scale, business models, and locations.

4.1 Case Study Example: Material Handling Robot

One of the case studies analyzed Obayashi's interior material handling robot developed with Stocklin (Fig. 4). This subsection addresses the main conclusions of the comparative analysis to illustrate the type of insights achieved by the students in the course project. Future work will cover in detail the Safety, Quality, Schedule, and Cost impacts of the ten robots under study.

Material handling is a time-consuming critical task that is also hazardous for labor. The Ministry of Health, Labor, and Welfare in Japan identified 1,256 cases of material-related injuries in 2020, 15% of all injuries that occurred in the year. Labor shortages also motivated the Obayashi Logistics System to reduce the workload and burden of interior material handling to the desired floor, typically part of Obayashi's work scope.

The robot system consists of an Automated Guided Vehicle (AGV) that can carry palletized materials, a custom elevator, and a logistics management system that guides the robot's work. The robot requires a flat and clear floorplate with a maximum deviation of 40 *mm*. Obayashi developed a small lift for steps up to 350 *mm*. Following AGV ISO regulations, the robot detected humans with an onboard 2D Lidar scanner. Whenever a human is closer than 500 *mm*, the AGV reduces the speed to 0.3 *m/s* and stops if closer than 300 *mm*.

Figure 4: Interior robotic material handling on site.

The site elevator autonomously interacts with the robot without a human operator and can fit two AGVs. Each AGV can handle pallets up to 1,200 x 1,800 *mm*.

The logistics management system replaced 68% of manually transmitted material orders with digitally transmitted data, reducing rework from 3% to 1%. The robot failure rate reported was zero, but the 1% rework includes mistakes in communication from the operator regarding the placement of materials.

Obayashi's robot was designed to have the same productivity as the laborers. However, the site measurements showed it took 50% more time to carry the same amount of material with the robot than manually because it took more time to find the materials. Hence, the development team looked at ways to deploy the robot with human labor. A squad of two robots and two crewmembers achieved the same productivity as five workers. The robots worked during the day and night shifts with one operator, while the two laborers worked only during the day. This decision increased 68% of the traditional total daily carrying capacity of 125 *tons/day* by five workers.

Finally, according to the student analysis, the material handling robot achieved a 41% cost reduction when using two robots simultaneously. The conventional material handling team of five crewmembers costs $1,325/*day*. In comparison, the cost for a hybrid team of two crewmembers working during the dayshift and two robots with an operator working both the day and nightshift was $1,328/*day*. The robot's autonomous elevator added $12,000 per project, but the robot reduced coordination needs by the superintendents with $188/*day* savings. Overall, the conventional material handling cost was $10.6/*ton*, and the hybrid robot method cost was $6.32/*ton*. The robot service cost included maintenance and transportation to the project.

In this case, the hybrid use of two robots and two crewmembers outperformed the traditional team of five workers in the four key variables (Safety, Quality, Schedule, and Cost).

4.2 Course Feedback

During the first implementation, the teaching team collected student feedback to improve future offerings of the course.

The course evaluation inquired about: (1) the initial goals to join the class, (2) desire to participate in future robotics research opportunities, and (3) curriculum improvements to advance their goals.

4.2.1 Students' Goals

The 19 students stated achieving their course goals. The students' goals included:

- "To learn about the exciting robots being used in construction, all of which I was not familiar with coming into the class."
- "Learn more about how robotics is applied to construction tasks and the unique challenges that construction poses."
- "Acquire knowledge about many robots and the mindset of evaluating something through a framework."
- "I wanted to learn more about how the construction industry is trending with automation and technology and hear first-hand from the people involved in decision-making and bringing about this goal."
- "My main objective was to learn about the use of robots in the construction industry, and I came away with the necessary knowledge for feasibility analysis, so it was very satisfying to participate in the course."
- "Information on robotics available and their design. Impacts on traditional organizations, contracting methods and work break down structure."

4.2.2 Future Research Engagement

The general experience of the students in the course was positive. Thirteen of the 19 students stated as "highly likely" their participation in future research opportunities on this topic (Fig. 5).

4.2.3 Curriculum Improvements

The curriculum improvements suggested by the students included the desired for additional room "to exchange experiences and to know how other colleagues are progressing." Similarly, others argued that the online offering constrained the in-class discussions among students working on different robots.

Finally, students inquired about the possibility of observing the actual robots in use. Although visiting sites

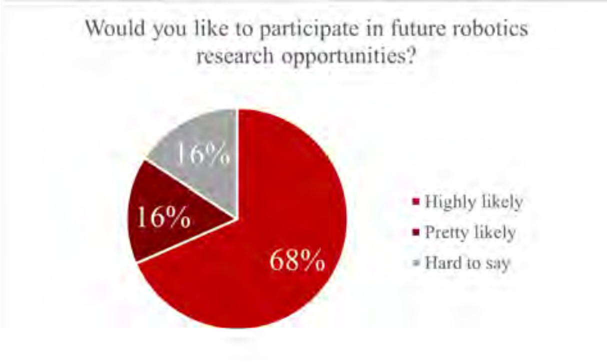

Figure 5: Future research participation.

or labs was not possible during the first offering due to Covid-19 restrictions, the second iteration of the class already included four in-person robot demonstrations.

5 Conclusions and Future Work

The researchers describe Stanford's first Construction Robotics curriculum to encourage discussion with other researchers and colleagues in Civil Engineering and Construction Management fields. We proposed a project-based course to connect real-world applications with the construction robotics research carried out at CIFE. Most of the existing construction robotic programs address on-site robots from a design and fabrication perspective. However, this curriculum emphasises the construction managerial perspective by matching the perspectives of construction managers and robot companies.

Our project-based curriculum included four main course learning goals (Table 3).

Table 3: CEE 327: Construction Robotics learning goals

#	Course Objectives
1	Introduce on-site construction robot applications
2	Assess the applicability and potential impacts of promising construction robots available in the market against traditional construction methods using a consistent evaluation method
3	Gain an understanding of basic robot principles and state-of-the-art research in the field, including human-robot collaboration approaches
4	Connect robot applications to broader project and client objectives deploying the EEE and VDC frameworks

Students without prior knowledge of construction robotics achieved comprehensive analyses and recommendations on using construction robots for the given projects. By collaborating directly with the industry professionals leading the development of construction robots, students learned a great deal about the strengths and limitations of the practical application of the technology. The students' effort helped the professionals identify opportunities related to construction robot adoption with a consistent, repeatable, and exportable process.

Reflecting on the first implementation of the proposed curriculum, the researchers noted one key limitation. The curriculum places high demands on the teaching team to engage many industry professionals and develop the initial pairing between robot technologies and construction projects. If this collaboration with the industry is not possible, the curriculum cannot be successfully implemented.

Our future research will expand on the Robotics Evaluation Framework deployed in the class and the quantitative results achieved by consistently evaluating ten robot cases. Moreover, the second offering of the course involved students in Computer Science and Mechanical Engineering majors to complement the analysis from a multidisciplinary perspective.

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