Problem-Based and Project-Based Robotics Engineering Program: An Integrated Approach

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Introduction

Robotics engineering (RE) is an interdisciplinary field that integrates competencies from the mechanical engineering (ME), electrical engineering (EE) and computer engineering (CE) disciplines. Industry is seeking engineers capable of simultaneously considering the mechanics, electronics, and computing aspects of robotics or system design. Also, robotics is widely used in activities at the elementary and secondary school levels, and students aiming to pursue a career in robotics are interested in receiving training in all three aspects and their integration, rather than being limited to choosing just one.

Robotics can be incorporated in engineering curricula through dedicated courses or capstone projects. To make it a specific engineering program, courses from the ME, EE, and CE disciplines can serve as the foundation on which robotics and integration skills can be developed. Problem-based and Project-based Learning (PPL) has been implemented since 2001 in the EE and CE at our university. We saw an opportunity to use this teaching method to address the integration challenges and skill development in robotics.

Our RE program is designed to train engineers with a focus on two specific professional situations: 1) be able to design robotic systems integrating mechanical, electrical, and computing components for a given application context; 2) manage robotics projects involving multidisciplinary teams. The program is an 8-semester co-op curriculum with ME, EE, CE, and robotics activities every semester. A semester consists of a series of problem-based courses that address disciplinary knowledge in mechanical, electrical, computing, and robotics fields. The first six semesters cover the common core for all RE students, with a special arrangement in the first year for those with technical backgrounds. The final two semesters focus on specialization in areas related to ME, EE and CE. Each semester addresses a specific theme in robotics, showcased through a semester-long design project undertaken by teams of six to eight students. The robotic design projects in the first four semesters help students develop project and team management skills while applying their disciplinary knowledge to robotic applications. The last four semesters involve open-ended design projects conducted by multidisciplinary teams with ME, EE, CE, or Business students.

Initiated in Fall 2017 and accredited since 2021, our PPL-RE program is graduating its fourth cohort in December 2024. This paper outlines the structure of our RE program, explains the PPL teaching approach, and provide an overview of the new robotic courses developed specifically for the program. It also presents both quantitative and qualitative assessments, such as the number of applicants, retention rate, and feedback from students, alumni, and employers.

Background

In universities around the world, robotics is mostly covered at the graduate level. A recent survey conducted as part of the IEEE International Conference on Intelligent Robots and

Systems (IROS) Forum on 'Formal Robotics Education Programs: Best Practices and Future Opportunities' identified the existence of 17 RE programs [1], listed in Table 1 ("X" indicates that the information is unknown, the blank entry is for our RE program to maintain anonymity). In North America, Worcester Polytechnic Institute (WPI) was the first to launch an undergraduate robotics engineering program in 2006 [2]. Most of the RE programs were recently created, and a small number have publications [2,3,4]. Only a few are managed by independent robotics departments. Since these programs were developed within specific departments, they often reflect the focus of those departments. For example, WPI's program is heavily oriented toward computer science, whereas the program at Lawrence Technological University emphasizes mechanics. Our RE program was set to be managed at the faculty level to bridge the ME and EECE departments, facilitating the allocation of resources for implementing the new program.

Table 1. Undergraduate RE programs around the world

Universities	Country	Department	Undergraduate Program
Worcester Polytechnic Institute (WPI)	United States	2020	2006
University of California, Santa Cruz	United States		2011
Lawrence Technological University	United States		2011
University of Detroit Mercy	United States		2011
			2017
Lake Superior State University	United States		2018
University of Michigan-Ann Arbor	United States	2022	2020
University Carlos III of Madrid	Spain		2022
University of Connecticut	United States		2022
University of Michigan-Dearborn	United States		2022
Carnegie Mellon University	United States	1979	2023
University of Lincoln	United Kingdom		2023
Kettering University	United States		X
Miami University	United States		X
Oregon State University	United States		X
Ritsumeikan University	Japan	1996	X
Tohoku University	Japan	X	X

Other programs closely related to robotics engineering are mechatronics, systems engineering, and automated production engineering:

- Mechatronics has been defined by the French standard NF E 01-010 [5] as "an approach aiming at the synergistic integration of mechanics, electronics, automation, and computer science in the design and manufacture of a product to increase and/or optimize its functionality." While it includes robotics, it is not limited to it. For instance, a hard disk drive is considered a mechatronic system because it incorporates both mechanical and electronic components. What distinguishes robotics from mechatronics is its flexibility, as robots can adapt to their environment through sensors, actuators, and a certain level of intelligence that enables them to make decisions.

- Systems engineering involves the development of complex systems with a focus on systems processes, lifecycle management, and optimization rather than the specifics of hardware or software [6]. It goes beyond merely integrating different disciplines by also incorporating techniques for risk management, lifecycle processes, and systems processes. Both fields require integration of multiple disciplines, but systems engineering covers a much broader scope, following a top-down integration approach, than RE which is more bottom-up.
- Automated production engineering focuses on industrial robotics applied to manufacturing contexts. It represents a subset of robotics engineering, not only due to the type of robots studied but also because of its limited scope of application. Moreover, it is centered around the use of robots rather than their internal functioning and development.

Motivation and Guidelines

Motivations to put in place our RE program came from three sources.

First, in our ME, EE, and CE programs, opportunities to learn about robotics were limited. For EE and CE students, an optional six-unit module in Semester 7 was offered to learn about robot programming, geometric and kinematic modeling, and control. Students could take on the design of a robot as part of a Major Capstone Design Project to experience the fundamental integration challenges of designing a robot [7]. For instance, cable routing in constrained spaces can be an issue with larger wires used for power; heat dissipation in constrained enclosures can become an issue; using more powerful motors requires more batteries, which increases the weight of the robot and incidentally the size of the motors; robot control must consider inertia, etc. Identifying these challenges occurred mostly at the end of the project, leaving insufficient time to address them correctly, with the most frequent explanation being to blame the other disciplines for the drawback. Learning opportunities about integration were clearly lacking in existing disciplinary programs.

Second, the industry, from robot integrators to robot and system designers, needs engineers capable of simultaneously designing and taking into consideration the mechanical, electrical, and computer aspects of robotic or integrated systems. A survey conducted with industrial partners involved in ME, EE, and CE, revealed that graduates had a restricted vision limited to their field of training, and very often engineers must take into consideration all the constraints, whether physical (mechanical or electrical) or software; lacked knowledge in industrial robotics, dynamics and kinematics, programming, image processing, and artificial intelligence.

Third, there are now many educational initiatives, such as the FIRST Robotics Competition, that use robotics in elementary and secondary education to enhance learning in science, technology, engineering, and mathematics (STEM). An annual survey of participants in FIRST activities in our region revealed that among the engineering disciplines, RE is the one towards which the most young people see themselves continuing their studies. However, with no RE program, young people must choose between ME, EE and CE, restricting their training to specific elements of robotics and not toward their integration.

To address these observations and in relation to the two professional situations outlined in the Introduction, we have established the following guidelines:

1. The RE program should build on existing ME, EE, and CE courses, and add new RE courses that addresses the integration challenges of robotics.
2. Each semester should have activities in ME, EE, CE, and RE, to provide opportunities to learn about the integration challenges of robotics.
3. Robot design, from robotic integration to complete design of robot manipulators or mobile robots, must be covered by the program.
4. Teamwork and communication are skills addressed every semester throughout the program.

At our Faculty of Engineering, the ME program is taught using the traditional lecture/lab format, and introduced 25 years ago project-based learning activities throughout their 8 semesters. The EE and CE programs took a step further by adopting in 2001 a problem-based and project-based learning (PPL) approach for their entire programs, as recommended by [8]. Basically, our PPL approach [9], adapted from [10], involves:

- Organizing semesters with several problem-based learning units, from one to four weeks (based on the ratio of 2 credits spread over 8 days), done in sequence, with one day per week dedicated to a design project that extends over the entire semester. Students therefore only have two activities in parallel, i.e., a problem-based unit and the project.
- Problem-based learning starts and ends with a tutoring session, having the teacher meet groups of 12 students at a time for 90 minutes. The first session is dedicated to review the problem to solve, identify keywords and what they know and must learn, establish a work plan, etc. The last session is dedicated to review what they have understood and learn. In between these sessions there are group problem-solving activities, lab periods, seminars and a validation of their resolution of the problem. These segments are followed by a self-assessment of the competencies covered in the unit (formative assessment), a report on the problem to solve (in teams of two to four students), and an optional consultation to address learning difficulties. The unit concludes with an individual summative assessment (theoretical or practical). A final exam is also given at the end of the semester. The collaborative dimension emphasized in this pedagogical approach greatly contributes to the development of the students' communication skills in the program.
- Project-based learning consists of semester-long projects aimed at transferring, applying, and generalizing knowledge and skills developed during the problem-based units of the semester. Students are grouped into teams of four to six. Projects are designed to be open-ended, with increasing complexity as the program progresses, and require full team involvement for success.
- The PPL approach helps contextualize learning by addressing real-world problems. It supports collaborative work, autonomy, and initiative. Students practice engineering, skill integration, and design starting from Semester 1 continuing throughout the program.

- To support collaborative learning, grades are not determined based on the group's grade distribution, but according to fixed 12-point grade scale (e.g., A+ = 85% or higher, A = 82 to 85, A- = 79 to 82, …). Specific competencies are associated with each learning unit, and students must get 50% or higher in each of the competencies to pass the course. Evaluation is also done using Criterion Referenced Assessment in relation to twelve Graduate Attributes (GA) in engineering. Each course provides an evaluation in relation to the GA associated with the competencies defined for the course.
- Before each problem-based unit, all instructors and support staff involved in the semester meet to coordinate actions to be taken, to collaborate, and to exchange best practices.
- As part of a continuous improvement process, after each problem-based unit, a meeting is held between representatives from the tutoring groups and the session coordinator to discuss feedback collected through an anonymous electronic form about the activities. These reports are shared with the instructors involved and the program management. At the end of each semester, a group debriefing with the entire cohort is conducted to discuss strengths, weaknesses and suggestions for improvement.
- Special activities, such as robotics seminars and social events, are also occasionally organized.
- An annual meeting is held with industry representatives and alumni to review and receive comments about the program and what are the needs of the industry.

Considering the focus on integration, teamwork, and communication, the PPL approach used by EE and CE programs was chosen for the RE program. ME courses and new courses in robotics were therefore adapted or designed accordingly. Adapting a traditional lecture-based course into a problem-based unit entails the following additional steps:

- Identifying the competencies (usually one for each credit unit of the course) to develop with the course.
- Writing a problem (from 1.5 to 3 pages long) that provides context to what is to be addressed, introduce the terminology, and set a problem to solve that allow students to apply what they must learn.
- Determine a timeline for the material to learn, considering that students are devoting all their time to the problem-based unit at least for four days a week.
- Select exercises that will be examined during the group problem-solving activities.
- Determine how the resolution of the problem will be validated.
- Prepare a formative assessment and a summative assessment for the unit.

Curriculum Structure and Robotic Courses

Figure 1 presents the organization of the first four semesters. It illustrates the topics addressed in relation to mechanics, electrical, computing, and robotics, along with the mathematic units that are non-discipline specific. Each semester addresses a theme, basically alternating between mobile robots and articulated robots in relation to an application area. Robotics is mainly covered in semester design projects.

In Semester 1, a small robot kit [11], programmable with Arduino and Raspberry Pi, is used to introduce problem-solving and design methodologies, along with communication and teamwork. Students are asked to design a robot prototype to help society.

In Semester 2, a prototyping production line with a conveyor belt, two CNC machines and two industrial robot manipulators, including a cobot, is used by students to learn about robot safety and time management because each team can only have access to the production line for a restricted amount of time (two hours) every week. Problem-based units on geometric modeling of robots and robot simulation prepare students for the project. Like the ME, EE, and CE programs, our RE program has co-op training internships. Introducing industrial robotics in Semester 2 allows to prepare students for possible internships in industrial robotics during their first internship (T1).

In Semester 3, student teams must model and design a functional mobile robot moving on rail to balance a load while move over an obstacle and dropping it in a bin. DC Motors and parts are available in a cabinet with restricted access, and teams must design their own set of wheels and program the controller on a Raspberry Pi based on simulations of their design.

In Semester 4, agile design methodology and open-source dissemination are the topics covered. Student teams determine their own project with the constraints that it must involve articulated robots.

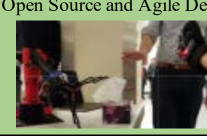
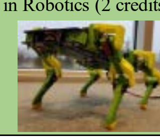
Semester	Mechanic	Electric	Computing	Robotic	Design
S1 (Fall) Robotics and Society	3D Modeling and Prototyping (2 credits) Materials Selection (1 credit)	Circuits (2 credits) Electrical Measurements (2 credits)	C/C++ Programming (2 credits)	Enginering Problem Solving & Design (2 credits) Communication & Teamwork (2 credits)	
	Differential Equations (2 credits)				
S2 (Winter) Robot Manipulator and Industry	Fluid Mechanics (1 credit) Statics (2 credits)	Combinatory and Sequential Logic (2 credits)	Programming (1 credit)	Geometric Modeling of Robots (1 credit) Robot Simulation (2 cr) Robot Safety (1 credit)	Industrial Robotics (2 
	Linear Algebra (1 credit) Discrete Mathematics (2 credits)				
S3 (Summer) Mobility and Transportation	Dynamics (4 credits)	DC Motors (2 credits) Power Systems (1 credit)	Operating Systems & Computer Arch. (2 credits) Object-Oriented Modeling & Programming (2 credits)	Mobile Robot Design (2 credits) 	
	Non-Linear Mathematics (2 credits)				
T1 (Fall)	Co-op Training Internship				
S4 (Winter) Interaction and Open Source	Strength of Materials (2 credits) Machine Elements (2 cr)	Digital Signal Processing (3 credits)	Real-Time Programming for Embedded Systems (2 credits)	Open Source and Agile Design in Robotics (2 credits) 	
	Continuous Time Mathematics (2 credits)				

Figure 1. Semesters 1 to 4 of our RE program.

Figure 2 presents the last four semesters. For Semester 5, we designed a robotic racecar, similar to [12,13] and programmable with a Raspberry Pi, to be used as an integration platform for the problem-based units of the semester. The Robot Operating System (ROS) is also integrated through a problem-based unit. The semester project is a multidisciplinary course involving ME, RE, and entrepreneurship students from the Management School, having to work in teams of 12 to identify, prototype, and pitch an innovative product idea.

The focus of Semester 6 is on industrial robot integration, with cases analyzed as part of the problem-based units. It is also the start of the Major Design Capstone Project (MDCP) course [15], which span over three semesters. For Semesters 7 and 8, specialized modules are offered to RE students, allowing them to receive specialized training in ME, EE, or CE. The Economic Analysis course is given in Semester 7, in support of budget planification for the MDCP. The Probabilistic, Statistics, and Technological Maturation course is oriented toward data analysis, which is useful for data analysis of the tests done on the prototype designed in the MDCP course.

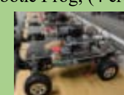
Semester	Mechanic	Electric	Computing	Robotic	Design
T2 (Summer)	Co-op Training Internship				
S5 (Fall) Control and Telepresence	Modeling of Servo Systems (4 credits)		Distributed Systems (2 credits) User Interfaces (1 credit)	Robotic Prog, (4 credits) 	Creation of Innovative Products (6 credits)
T3 (Winter)	Co-op Training Internship				
S6 (Summer) Industrial Robotics	Heat Exchange (2 credits) Differential and Jacobian Kinematics (1 credit)	AC Motors (2 credits)	Computer Vision (2 credits)	Robotics and Process Automization (2 credits)	Major Design Capstone Project I (3 credits)
	Robotics in Manufacturing				
	Professionnalism and Ethics (3 credits)				
T4 (Fall)	Co-op Training Internship				
S7 (Winter) Specialization	Specialized Modules: Advanced Mechanical Design OR Microeditoelectronic Design OR Traction and Electric Vehicles OR Deep Neural Networks OR Information Coding (6 credits)				Major Design Capstone Project II (6 credits)
	Economic Analysis (3 credits)				
T5 (Summer)	Co-op Training Internship				
S8 (Fall) Specialization	Specialized Modules: Automatic Control OR Bioengineering OR Artificial Intelligence OR Advanced Software Design (6 credits) Elective Course (3 credits)				Major Design Capstone Project III (3 credits)
	Probability, Statistics, and Technological Maturation (2 credits)				

Figure 2. Semesters 5 to 8 of our RE program.

Before the creation of the RE program, the capstone design projects in ME or in EE and CE were managed in silos by two departments, each following its own project-based learning approach [9,15]. The capstone projects in each program account for 12 credits out of 120-credit programs, and involve large teams, normally from six to eight students but sometimes going up as high as 14, working on open-ended design projects including fully functional prototype fabrication and testing. The large effort set on these capstone design projects explains why they are referred to as Major Design Capstone Projects. With project ideas coming from industry, research labs, engineering competitions, entrepreneurship initiatives and students, the scope of the projects frequently overlapped disciplinary boundaries. Students either had to acquire knowledge and skills missing in their training, or to find ways to work with teams from the other department, benefiting from their complementary expertise and creating a multidisciplinary learning experience. However, assessment tools, requirements from teachers, schedules, and evaluation criteria differed between departments, making it difficult to promote and support multidisciplinary teaching and learning in MDCPs. The launch of the RE program provided the opportunity to revisit the MDCP courses. It facilitated the development of a multidisciplinary framework [14] that enables ME, EE, CE, and RE students to effectively collaborate by combining and managing the disciplinary expertise required to achieve the project. At the same time, it enables RE students to address both targeted professional situations presented in the Introduction.

Results and Discussion

Table 2 presents the enrollment and retention numbers of the RE program since its creation. The preliminary budget analysis conducted for the creation of the program set a minimum of 35 students per cohort (with an 80% retention rate) to ensure financial viability once the first cohort had completed the program. In practice, the number of students admitted to the program is higher, with a high retention rate exceeding 80%. The R Score is a ranking metric (between 0 and 50) used to evaluate students' academic performance used for university admissions. Our Faculty of Engineering uses a fixed threshold method to enroll students. For the RE program, students are invited to write a motivation letter indicating their past experiences and special interests in robotics, allowing the program to invite students based on these letters within a -1 margin of the R Score ranking. This special treatment is granted to invite students as fast as possible because the demand is high and the number of places is limited. Also, higher R Score thresholds usually mean less enrollment of students with technical background because these groups of students are smaller, which makes it more difficult to increase their R Scores. A concern raised regarding the implementation of the RE program was its potential to negatively impact enrollment in the ME, EE, or CE programs. However, this effect was not observed, likely because the multidisciplinary nature of the RE program attracts students interested in integrating disciplines rather than those focused on ME, EE, or CE.

Table 2. Enrollment in the RE program

		1st cohort 2017-2021	**2nd cohort 2018-2022**	**3rd cohort 2019-2023**	**4th cohort 2020-2024**	**5th cohort 2021-2025**	**6th cohort 2022-2026**	**7th cohort 2023-2027**	**8th cohort 2024-2028**
	No. Applicants	160	181	215	182	208	219	400	274
	R Score	26.2*	28.3	28.9	28.4	28.6	28.3	29.6	30.0
Enrollment	Women	2	6	6	6	9	6	6	9
	Natural Science	28	35	29	29	31	30	36	38
	Comp./Math Sc.	1	6	4	9	7	2	5	9
	EE Tech	8	2	4	6	3	7	4	2
	CE Tech	0	1	0	2	4	3	4	0
	ME Tech	8	8	13	4	4	8	1	2
	Total	45	52	50	50	49	50	50	51
Currently	Women	1	5	5	5	7	6	6	9
	Natural Science	25	31	27	24	24	32	35	37
	Comp./Math Sc.	1	6	4	7	7	2	5	9
	EE Tech	6	1	2	6	3	7	4	1
	CE Tech	0	1	0	2	2	2	4	0
	ME Tech	6	6	10	4	3	6	1	2
	Total	38	45	43	43	39	49	49	49
	% Retention	84%	87%	86%	86%	80%	98%	98%	96%

Based on student debriefing sessions, alumni consultation, and employer feedback, the perceived strengths of the RE program are:

- Multidisciplinary ME, EE, CE, and RE training. The program integrates disciplinary skills from ME, EE, and CE, focusing on content relevant to RE and addressing the pressing need for integration of these disciplines in the industry. The cooperative internship program makes internship opportunities in ME, EE, CE, and RE available to RE students, resulting in a wide variety of training opportunities.
- PPL approach. Such pedagogical model is highly suitable for integrating the disciplines of ME, EE, CE, and RE. With sequential learning blocks (problem-based learning) and a parallel semester project (project-based learning), it is possible to organize the development of competencies over time and apply them effectively and meaningfully in session projects. Feedback from alumni and current students clearly indicates that RE students would not return to traditional lecture-based courses. PPL is a distinctive element of our RE program compared to the other RE programs, which are based on traditional course-based structure.
- Project coordination and component reusability. Coordination exists between semester projects to enable students to reuse hardware components (e.g., Arduino, Raspberry Pi) and software skills (C, C++, Python), maximizing time and cost investments. This approach supports the progressive development of technical and project management skills across semesters.
- Broad coverage of robotics using pedagogical platforms. Partnering with a college research facility provided us with access to an industrial robot production line, which revealed to be very valuable. Designing our own robot platforms and kits based on our local expertise also allowed us to align the educational tools with the course objectives, rather than having to adapt the courses to commercially available educational robot platforms.
- Multidisciplinary learning activities. The Creation of Innovative Products and the MDCP courses provide real experiential learning opportunities for students, allowing them to apply their wide set of skills.

The main challenges that came with the RE program are:

- Faculty-led program. This choice was made from the outset, rather than assigning responsibility to the ME or the EECE Departments, to facilitate access to resources (staff, space) and simplify budget management. However, it complicates the academic decision-making process, as authorization must be sought from both departments for all types of decisions (course creation, hiring, task allocation, staff, etc.). Faculty members hired for the program must choose which department to be assigned to, which makes it difficult to foster a sense of belonging and develop a specific culture for the RE program. Students also struggle with not to being associated with a single department: they have access to resources from both but are not specifically linked to either.
- Selecting what to cover in the RE program. A wide variety of subjects can be associated with robotics. Compared to PPL, traditional course-based programs provide more flexibility in providing different academic pathways, as problem-based and project-based

units are closely integrated. Extensive discussions were held to identify what is essential to cover in the RE program.

- Mismatch between expected and actual student skills during the first internships. For instance, employers recruiting RE students for pure software development roles traditionally held by CE students sometimes noted lower than expected programming skills. This gap stems from the RE program naturally offering fewer programming credits compared to specialized CE programs during the same timeframe. However, when recruited in multidisciplinary settings, RE students receive positive feedback for their systems-level understanding and ability to communicate effectively across different engineering fields.
- Lean development approach. The RE program started with only three new faculty positions, and we are currently at five. About 40% of new class material had to be developed, the remaining courses were taken or adapted from the ME, EE, and CE programs. We also took special care in maximize the use of materials over multiple semesters (Arduino, Raspberry Pi, generic parts).

Our RE program is now fully established and reached a mature and sustainable stage. The next steps aim to continue to expand. To this end, the creation of a dedicated RE department appears to be essential for promoting the program, hiring new professors, and developing new courses and graduate programs. In the short term, we plan to double the cohort size (up to 100 students per cohort) starting in 2026, and to open new faculty positions. We also plan to establish Master's and a PhD programs. Over the last three years, 12 to 14 RE graduates (~ 30%) continued their studies at the Master's level in ME or EE, highlighting the strong interest among RE graduates in pursuing further graduate education.

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