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Undergraduate Cross-Class Research Projects for Deep Learning in Engineering Education

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ABSTRACT

For many years, educators have been developing tools and techniques to improve the learning process in higher education; however, the vast majority of these do not focus directly on deep learning. In this work, an innovative teaching/learning tool is presented which focuses on deep learning of some engineering skills and principles. The tool is known as the undergraduate cross-class research project (UCCRP) which relies on hands-on projects that students can work on throughout their 4–6 years of undergraduate studies with a mixture of students from all undergraduate levels and mentored by peers, TAs, and instructors. The UCCRP was successfully implemented at Texas A&M University at Qatar and the details of one project and its results are delineated here. Student self-assessment, competency based assessment, and the "structure of the observed learning outcome (SOLO)" technique are used to assess the level of attainment of the intended learning outcomes (ILOs).

Key words: Experiential Learning, Project Based Learning, Achievement Goal Orientation Theory, Outcome Based Learning, Undergraduate Research.

INTRODUCTION

Most engineering schools are faced with the challenge of not only having to teach students disciplinary specific theories and concepts detailed in their curricula, but also develop skills that will make them experts in their own fields as well as lifelong learners (Chua, 2014, Bishop and Verleger, 2013, Levin and Rivka, 2008, Bitter and Pierson, 2001, Karkoub and Abdulla, 2018). This requires a specific approach to learning which requires involving students in deep critical approaches to learning instead of just repeating knowledge (Asikainen, 2014; Biggs, 2003; Asikainen and Gijbels, 2017). Higher education is constantly evolving under pressure from all stakeholders to produce lifelong learners and work-ready graduates. To date, there is no clear theoretical foundation or empirical evidence that shows schools are systematically applying deep learning approaches in their classrooms (Asikainen and Gijbels, 2017, Halinen et al., 2013; Murtonen et al., 2008). Countries around the world have been working for more than two decades on improving higher education methodologies to produce quality graduates capable of meeting the demands of fast evolving job markets. In 1999, thirty-one European countries got together and signed what is known as the Bologna declaration (1999) to overhaul and unify their education system. One important aspect emphasized in the declaration and stressed again in the Paris Communiqué (2018) is that students should be able to develop by continuously building their expertise and knowledge base in their fields and learn skills such as problem solving and critical thinking. It is agreed among stakeholders in higher education that successful learning and studying in higher education should involve students in deep-level learning and understanding of their own fields (Asikainen et al., 2014).

In the US, most reputable engineering schools are ABET accredited. ABET, formerly known as the Accreditation Board for Engineering and Technology, has changed their accreditation criteria in the late 90s from focusing on what is taught in the classroom to what the student would be able to do after taking a particular course (Prados et al., 2005). It is the goal of educators to produce deep learners who will be able not only to grasp what is taught in the classroom, but also connect it to real world problems. Therefore, based on exploration of students' conceptions of learning, approaches to learning, motivation and their experiences of the teaching-learning environment, educators can devise pedagogical tools that guarantee some level of deep learning. In addition, educators need to create successive contexts for learning, which might encourage students to progressively abandon surface learning approaches and adopt deeper learning ones (Biggs, 1993, 1999; Entwistle, 1998; Ramsden, 1993).

A learning enhancement tool that has proven to be effective for deep learning is presented here. It is the "Undergraduate Cross-Class Research Project (UCCRP)" which consists of an open-ended research project that students can take part in from day one of college. The UCCRP is intended to help students appreciate knowledge acquired in classrooms, improve their mastery of a skill or concept, and instantaneously apply these to real life problems. At any given time, freshmen, sophomores, juniors and seniors work side-by-side on different tasks related to the project requiring basic knowledge from specific courses in the curriculum. In the UCCRP, students interact with others from different levels working on the same project and, in the process, they learn from each other and can easily correlate between knowledge acquired and the growth of their capabilities. In fact, students

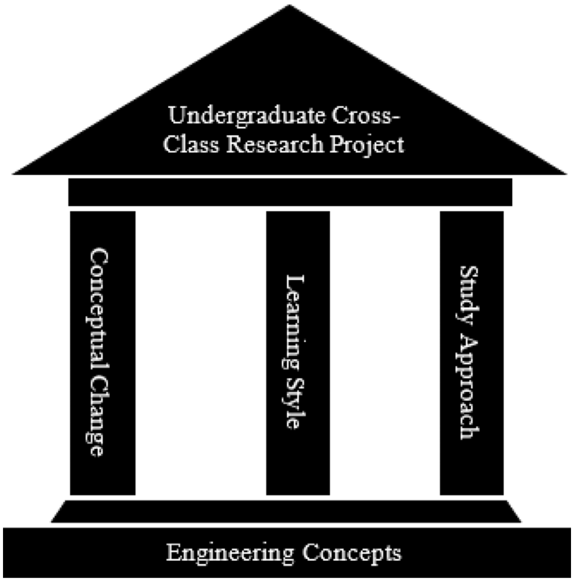


Figure 1. Undergraduate cross-class research project (UCCRP) structure.

evolve from watching things happen to making things happen as they progress with their work on the project. One common complaint from students is that they see various courses in the curriculum as a pile of "bricks", but not as a "wall". Tools, such as the UCCRP, is intended to help the students visualize the "wall" and where each "brick" (course) in the curriculum fits.

The UUCRP is designed based on three important learning factors (see Figure 1): (1) Creativity and conceptual change, (2) Learning style, and (3) Study approach. Following are brief descriptions of all three factors.

Creativity and Conceptual Change in the Learning Process

Learning is defined by Biggs (1999) as a way of interacting with the world. It is not simply acquisition of information, but it is more of structuring of the information acquired and thinking with it to bring about conceptual change. Conceptual change is very important in engineering education and usually takes place when the following three interrelated requirements are taken into account: (1) the objectives of the project/task are clearly defined and understood by the students, (2) students feel the need to achieve those objectives, and (3) students can work collaboratively with peers and teachers. It is believed that the type of activities undertaken in collaborative work shape, elaborate, and deepen understanding of the concepts, methodologies, and applications.

Therefore, the third requirement; i.e., collaborative work, is the first of three pillars that the UCCRP is built on.

Learning Styles: Visual, Auditory, and Kinesthetic

Learning styles and their influence on the learning process have been extensively studied in the past 3 decades. Many of the research findings showed that providing instruction based on individuals' preferred learning styles improves learning (see for example Dunn et al., 1994, Csapo and Hayen, 2006, Eyler, 2009, Koh and Chua, 2012, Ibrahim and Hussein, 2016, and Stirling, 2017, Felder, 2020). Other researchers, such as Rogowsky et al. (2013) and Norman (2009), conducted their own experiments and reviews and concluded that learning styles did not have significant effects on the learning process. However, almost all of the experiments used to refute the claim that learning styles improve the learning process were not related to engineering education. Based on experience teaching engineering courses at different levels of the curriculum and the work done by Koh and Chua (2012), Felder (2020), and many others, it is believed that leveraging learning styles in the learning process could be very beneficial in engineering education. Many definitions of leaning styles are available in the literature; however, the most appropriate one is found in (Dunn & Dunn, 1992, 1993; Dunn et al., 1994) where a learning style is defined as the way in which individuals begin to concentrate on, process, internalize, and retain new and difficult academic information. Three categories of learning styles can be found in the literature, namely, visual, auditory, and kinaesthetic (tactile).

Although, many can be classified as visual and/or auditory learners, most engineering students tend to be more kinaesthetic/tactile. In fact, experience has shown that engineering students are readily inclined to build, experiment, and analyse systems or parts of systems to learn new concepts, verify knowledge, and prove things work or do not work. Therefore, the proposed UCCRP relies on the kinaesthetic/tactile learning ability of engineering student, which constitutes the second pillar of the UCCRP.

Study Approaches: Surface and Deep Learning

Two study approaches have been defined in the literature: deep and surface learning (Biggs et al., 2001; Entwistle and McCune, 2004; Loyens et al., 2013). Surface or deep learning are not attributes of individuals, but rather methods of learning and processing of information that students utilize for learning new concepts. In fact, a person may have a preference for a particular approach (i.e., deep or surface learning) but, they may use both approaches at different times depending on the circumstances. Surface learning has often been defined as an approach to reproduce content using learning processes based on memorization and rote learning. However, deep learning is typically defined as an approach to understanding content, relating previous knowledge to new one and theoretical ideas to real life applications, organizing and structuring content into a coherent whole, and critically evaluating knowledge. The two approaches are also different when it comes to motivation since many researchers argue that students who use a deep learning approach are self-motivated and try to understand what they study (Trigwell et al., 2005). However, surface learners have external motivation coming from demands of assessment; hence, they mainly focus on passing exams, interviews, etc. In addition, it was shown in the literature that surface learning is more likely to occur when learning is isolated from practice (McIntyre and Munson, 2008). Therefore, deep and surface learning are defined by the students' intentions (or motives) as well as the accompanying learning activities and they are assumed to be related to the perceived demands of the learning environment (Biggs and Tang, 2007). Instructors wish all their students to be deep learners; however, intentionally or unintentionally, that rarely happens especially in mathematically intensive "abstract" engineering courses. In addition, the subject, method of delivery, and learning environment highly influence the student's choice of the learning approach.

In an article published on the Association of American Colleges and Universities (AACU) website written by Eyler (2009), the author states that "*Experiential education, which takes students into the community, helps students both to bridge classroom study and life in the world and to transform inert knowledge into knowledge-in-use.*" In fact, the aim of the UCCRP is to transform inert knowledge gained by the student in the classroom into knowledge-in-use through deep learning tasks.

Therefore, deep learning makes up the third pillar of the proposed learning enhancement tool and it is the intended target of all tasks of the UCCRP.

COMPARISON BETWEEN THE UCCRP AND OTHER PROJECT-BASED LEARNING/TEACHING INITIATIVES

The UCCRP is a project-based learning technique with distinctive differences from other project-based initiatives currently being used in higher education. The difference lies in the fact that the UCCRP focuses on decomposing a project into developmental level skills and tasks to be undertaken by individual students then fusing their outcomes into one functioning solution. Therefore, unlike other project-based learning initiatives where the focus is on the final product, the UCCRP targets students individually and provide each one of them a unique opportunity for deep learning through skill-specific tasks required for the completion of the project. Following is a description and classification of the vast majority of the available project-based teaching/learning initiatives in engineering education and how the UCCRP differs from all of these.

Over the years, many pedagogical activities, which fall under the umbrella of project-based learning, have been developed and successfully implemented in many higher education institutions. These project-based learning initiatives can be classified into five categories. The first category encompasses courses offered early in the curriculum, such as the I-Series at the University of Maryland, Strategies for Team-based Engineering Problem Solving (STEPS) at the Petroleum Institute (Scott, 2005), Engineering Practices Introductory Sequence (EPICS) at Colorado School of Mines (Olds and Wiley, 1991) and Introduction to Design at Rose-Hulman Institute of Technology. EPICS and similar courses allow teams of students to work with the local community (organizations and companies) to develop technology solutions for some real life problems. Although the students are given the opportunity to develop and apply old and new skills to meet the requirements of the assigned projects, there is no systematic targeting of skills and/or roadmaps and milestones for deep learning.

The second category of project based teaching/learning tools is represented by courses offered later in the curriculum, such as senior/capstone design, directed and independent study courses. These courses allow students to work individually or in groups on a particular project where they can apply some of the skills acquired in classrooms to solve a particular problem. Similar to the first category, the emphasis in these courses is on the design process and application of skills rather than targeting a specific one and deepening its understanding and improving its mastery by the student.

The third category encompasses extra-curricular project-based learning activities in the form of national and international competitions including the Shell Eco-Marathon, Baja Buggy, Solar car, Solar Decathlon, Invent for the Planet, Aggies Invent, ASME E-fest, etc. Some students participate in these activities independently from any course commitment and credits; however, others participate in these projects as part of some credit earning courses, which pushes these extra-curricular activities into the second category. Therefore, the learning benefits to students are also very similar.

The fourth category represents national and multi-national project-based learning activities such as the Engineering Projects in Community Service (EPICS) at Purdue University (Coyle et al., 2005; Ruth et al., 2019), the Massive Online Open Courses (MOOC), and the Vertically Integrated Projects (VIP) (Strachan et al., 2019; Cullers et al., 2017), now known as, the VIP Consortium Inc. The VIP program is an alliance of universities from around the world including Georgia Tech., Texas A&M University, Stony Brook, Purdue, University of Pretoria, South Africa, Inha University, South Korea, etc., where graduate and undergraduate students take part in long-term projects. The projects are led by faculty from the same or other schools in the consortium in a start-up company setting where students apply and develop technical as well as professional skills. The VIP program, for example, is a credit-bearing course counting towards the students' degrees, which makes the VIP, essentially, a modified version of the second category of project-based teaching/learning activities. However, engineering students registered in the EPICS program at Purdue University may earn 1-2 credits for their participation in the program, but these are often not counted towards their degree requirements. It is worth noting that EPICS at Purdue is different from EPICS at Colorado School of Mines (CSM). Unlike the Purdue EPICS where students from any level can voluntarily participate in the program, CSM-EPICS is a required lower division two-semester sequence intended to help students develop professional engineering skills early in the curriculum.

The fifth category of the project-based teaching/learning activities involves students in design projects at all levels of the curriculum such as Olin College of Engineering (OCE). The Philosophy of education of OCE is based on experiential and project-based teaching and learning. The main idea is for the students to look for what is needed in the community (or the outside world in general) and design something to meet that need which is similar to the Purdue EPICS in terms of goals, but different in terms of curriculum requirements and obligations. The students at OCE select the type of projects they want to work on and the faculty provides them with just-in-time instructions to build the students' background and help them find the resources needed. There are pros and cons to this style of engineering education, but more importantly, OCE is only 23 years old and to date, there are no comparative studies to show the effectiveness of this "just-in-time teach-and-apply" mode of education compared to the traditional "teach-then-apply" mode.

The UCCRP is similar to the aforementioned five categories, but differs in clear and distinctive ways:

1. The UCCRP is directly linked to specific courses in the curriculum. These courses could be the bottleneck courses where students' failure rate is relatively high and/or concepts are too abstract and not easy to grasp; or, any other course where students want to further develop specific skills with deep learning objectives in mind.
2. Each student in the UCCRP works specifically on a skill and not holistically on a project.
3. The skill is developed into systematic measurable intended learning outcomes (ILOs), specific teaching/learning activities (TLAs), and assessment tasks (ATs) in concertation with the student using the SOLO technique's levels 4 and 5 taxonomy.
4. Assessment rubrics are developed for a particular skill to evaluate the attained learning level as described by the SOLO technique.
5. Deep learning for each individual member of the UCCRP is directly and indirectly assessed by supervisors and other instructors. It is worth noting that deep learning is explicitly integrated in the UCCRP and not gained as a side effect as is the case in many other project-based teaching/learning techniques.

CHARACTERISTICS OF THE UCCRP

The UCCRP is basically a long term, open-ended, carefully selected research project that the students partially or fully commit to from freshman-to-senior year. The type of project, tasks, duration, etc. are selected such that each student has specific activities to work on throughout each semester. The project is not part of any course and participation is voluntary; however, students can link their work to their course with instructor's approval. The UCCRP allows students to apply acquired knowledge/concepts from specific courses and learn from peers through tasks from the same system throughout the four years of undergraduate studies. A set of courses are targeted as "knowledge Incubators (KI)" for the UCCRP and students registered in (or have taken) those courses are recruited to participate in the UCCRP. The students work on projects relevant to these KI courses, individually or in groups, and apply and further develop specific skills on a research testbed. The holistic approach to problem solving followed by other project-based teaching and learning initiatives is not the intent here. The UCCRP's goal is to provide deep learning opportunities for the students to further develop a particular skill and/or deepen understanding of a concept. Each UCCRP is divided into tasks for each level and each task is divided into sets of skills associated with a particular course (see Figure 2). Intended learning outcomes (ILOs) are carefully defined, for each UCCRP and for every semester, along with teaching/learning activities (TLAs) and assessment tasks (ATs) to meet the ILOs. The ILOs, TLAs, and ATs are developed in coordination with each student. As shown in Figure 2, students from all levels can take part in the UCCRP depending on the tasks and the skills required to achieve them. Collaboration between students from different levels may be required depending on the complexity of the tasks.

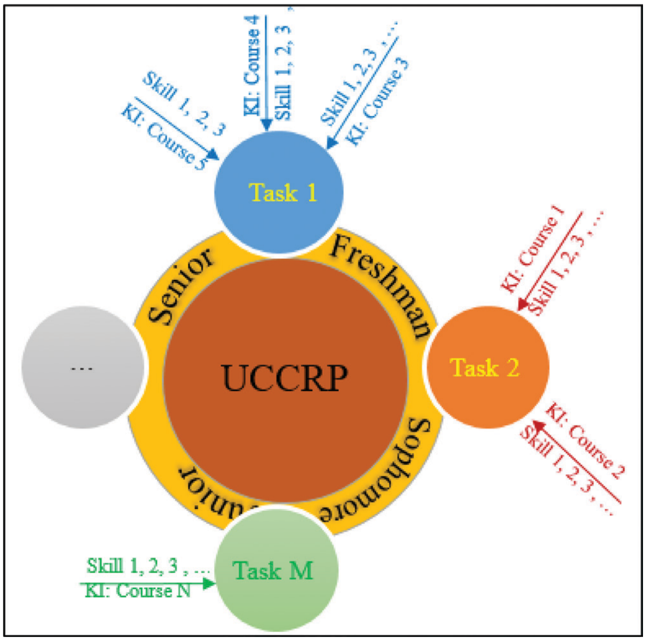


Figure 2. Elements of the UCCRP.

Procedure for Skill Development and Deep Learning in the UCCRP

Let us assume that the UCCRP has a task requiring a specific skill "*modeling of dynamic systems*" and/or application of a concept "*lumped mass technique*" taught in course "*MEEN364*". Or, suppose the instructor of course "*MEEN364*" wants a particular student to develop deeper understanding/learning of the skill "*modeling of dynamic systems*" or the concept "*lumped mass technique*." The instructor may develop a task and append it to an existing relevant UCCRP or even create a new one. The following steps explain how a particular task in an example UCCRP will be carried out.

1. Recruit a student from "*MEEN364*" to further develop the skill "*modeling of dynamic systems*" or the concept "*lumped mass technique*" required for a task in the UCCRP.
2. Develop measureable intended learning outcomes (ILOs), teaching learning activities (TLAs), and assessment tasks (ATs) for the skill "*modeling of dynamic systems*" or concept "*lumped mass technique*" in coordination with the student. Typical intended learning outcomes could be: (ILO-1) *Separate* complex systems into multi-degree-of-freedom lumped systems; (ILO-2) *Change* differential equations and integrate non-linear physical phenomena such as friction and nonlinear springs; (ILO-3) *Solve* the equations of motion through Matlab or Python; and (ILO-4) *Predict* and *explain* the time response of multi-degree-of-freedom systems. The teaching and learning activities could be: (TLA-1) Expressing energy transfer between subsystems and components through bond-graphs (2–3 hours) and (TLA-2) Application of Fourier transforms to spectrum analysis of signals (2–3 hours). The assessment tasks (ATs) could be: (AT-1) Write a 4-page report reflecting on the shortcomings of the lumped mass method and suggest ways to improve the accuracy of the models developed using this technique; (AT-2) Prepare a short presentation to discuss the speed time response of the car using the lumped mass method and provide extrapolated alternatives to improve the accuracy of the response, etc.
3. Develop rubric(s) to evaluate the assessment tasks (ATs) and the level of attainment of the ILOs with emphasis on deep learning criteria using the SOLO technique.
4. Supervisors of the UCCRP must observe that, as the student progresses in the project, his/her learning outcomes display deeper understanding of "*modeling of dynamic systems*" or concept "*lumped mass technique*". Otherwise, the intended learning outcomes (ILOs), teaching learning activities (TLAs), and/or assessment tasks (ATs) described in Steps 2 and 3 must be readjusted to make sure the student is on the right track. Experience and knowledge of the subject are crucial to adjust the TLAs and/or ATs. A few projects have been used as UCCRPs over the past six years and following is a summary of one of them to explain the details of the project and how it is planned and executed.

Table 1. Knowledge Incubator Courses for the Example UCCRPO.

Course #	Course title	Skill set
ENGR104	Computation Engineering Lab	Programming
PHYS207	Electricity and Magnetism	Electro-magnetism
MEEN210	Modeling for Mech. Design	Solid Modeling
MEEN225	Engineering Mechanics	Static/Dynamic modeling
MEEN260	Mechanical Measurements	Data acquisition
MEEN357	Engineering Analysis	Numerical Methods
MEEN360	Materials and Manufacturing	Machining
MEEN363	Dynamics and Vibration	Rigid body dynamics
MEEN364	Dynamic Systems and Control	PID and Lead-Lag control
MEEN401	Intro. To Mech. Eng. Design	Design
MEEN433	Mechatronics	High Level Programming and Hardware interfacing

Example UCCRP: Autonomous Vehicle

A UCCRP that is currently in progress consists of transforming a golf cart to an autonomous vehicle. The first phase of the UCCRP is to transform the vehicle to a drive-by-wire car, then, the second and third phases is to drive it semi- and fully autonomously, respectively. Each step of the transformation requires the synergetic efforts of many students from freshmen to seniors. The estimated completion time of the first phase of the project is two to three years depending on the number of participating students. Currently, the UCCRP is in phase 2.

The knowledge incubator (KI) courses and the associated skills, based on the Texas A&M University curriculum, are listed in Table 1. The tasks required for the completion of the first phase of the project are shown in Figure 3 and they are planned for the first two years of the project. For the subsequent years (phase 2), some of the tasks from the previous phase are modified, new ones are created, and some remained unchanged since they require a lot of effort and they are the subject of continuing research.

The tasks associated with the autonomous vehicle UCCRP can be grouped under four major ones as shown in Figure 4: (1) vehicle hardware transformation, (2) vehicle dynamics and control, (3) vehicle communication and data acquisition, and (4) road signs and traffic lights recognition (see Figure 4(a)).

First, the vehicle hardware modification/transformation requires retrofitting the brake and steering mechanisms with electrically controllable actuators, integration of low amperage power DC power supplies, sensors, and data acquisition systems. This task has been assigned to students who are taking or have taken one of the following courses: PHYS206/207, ENGR102/216/217 and MEEN210/260/360/364/401, but not involved in any other UCCRP tasks.

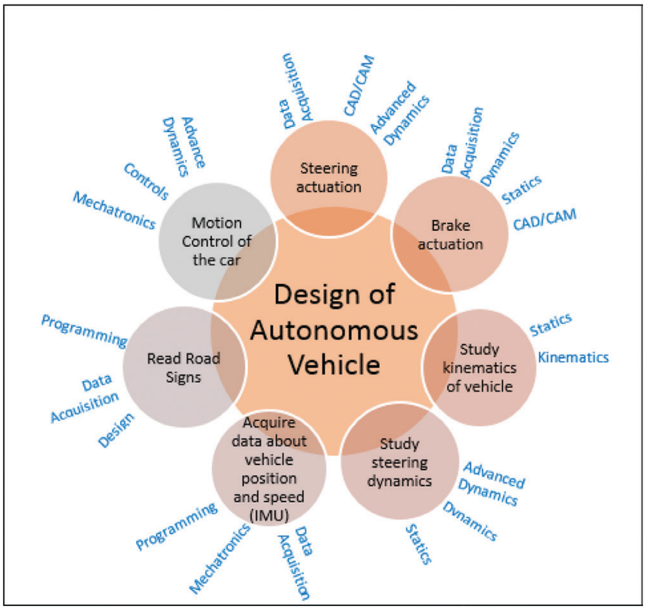
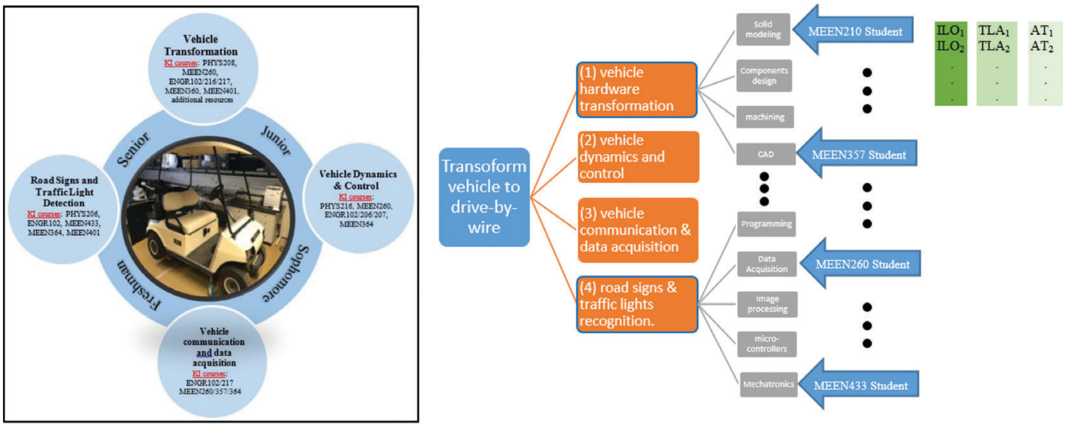


Figure 3. Elements of the Autonomous Vehicle UCCRP: Tasks and Required Skills.

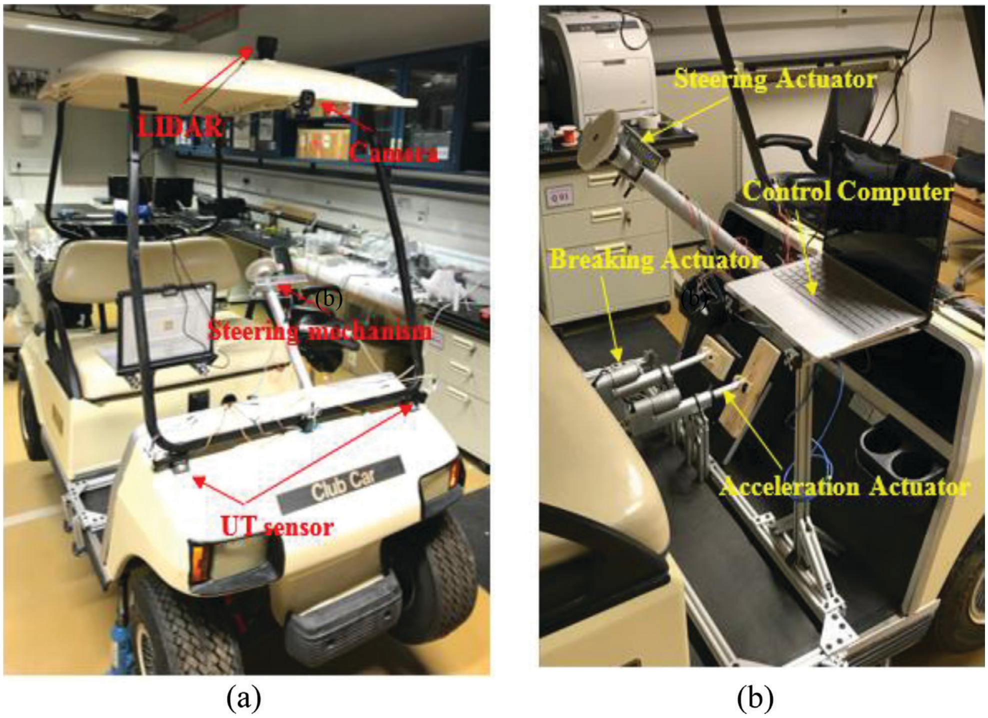


(a) (b)

Figure 4. Elements of the Autonomous Vehicle UCCRP: (a) Tasks and KI Courses, (b) break down of tasks.

Second, the vehicle dynamics and control requires the development of kinematic/dynamic model of the vehicle and developing a PID controller for it. Therefore, a unicycle model of the car is considered to design a PID controller for the heading and steering motions of the vehicle as required by the path tracking control action. This task is suitable for students who took or are currently taking MEEN225, MEEN363, and MEEN364. Third, the vehicle communication and data acquisition task requires advanced background in computer programming, image processing, and data acquisition skills; therefore, only students registered in (or already taken) ENGR102, MEEN260/364 and/or MEEN433 are involved in this task. Finally, the road signs and traffic lights recognition task requires high level programming and hardware interfacing using Python OpenCV. Therefore, students who are taking or took MEEN433 were highly encouraged to participate in this task. The transformed club car with all new sensors, actuators, and data acquisition and image processing computers is shown in Figure 5. A video of the UCCRP in phase 2 can be found here: https://youtu.be/trOg-ffOu9Y

Each of the four previously enumerated tasks are then separated into skill sets as shown in the diagram of Figure 4(b). Example ILOs, TLAs, and ATs for the four tasks are shown in Figures A1–A5 in the Appendix.



(a) (b)

Figure 5. Photo of transformed club car: (a) outside view, (b) inside view.

ASSESSMENT OF THE UCCRP EXPERIENCE

Student Self-Assessment

Surveys were conducted at the end of every semester for the past 5 years to collect feedback about the students' experience with the UCCRPs (see Figure A6 for a sample questionnaire). A total of sixty four (64) students participated in the survey: forty percent (40%) seniors, thirty percent (30%) Juniors, twenty percent (20%) Sophomores, and ten percent (10%) Freshmen. The results of the surveys are as described in the following sections.

Teams

The total number of teams that worked on the UCCRPs is 10 where some groups participated for several semesters and others for one semester only. The composition of the teams was dictated by the specific task requirements for the UCCRP. Ten percent (10%) of the teams had students from all four levels (i.e., freshmen, sophomores, juniors, and seniors), fifty percent (50%) from three different levels, thirty percent (30%) from two levels, and the remainder ten percent (10%) had only one level. The vast majority of the teams had a minimum of two levels and almost ninety percent (90%) of the teams had a junior level student in it.

The rest of the team members were from other levels with almost equal representation (see Figure 6a-b). Although most of the teams functioned as expected, about ten percent (10%) of the teams did not and the common complaints were: being not appreciated by "senior" team members, assigned subtasks were not challenging enough, and not receiving contribution of other team members on time. Although some of these issues were addressed by the mentors, some were not due to the fact that they were brought up at the end of the semester when the task was over. The vast majority of the teams expressed satisfaction with their team members and the execution of the allocated tasks. In addition, more than seventy percent (70%) of the teams expressed interest in continuing to work on the same UCCRPs the following semester (see Figure 6c).

Learning experience

In the end of semester survey, the student were asked for input about their learning experience. Based on the data gathered, the vast majority of the students were positive about their learning experience. The students appreciated the fact that they are applying knowledge from their current courses to real life problems and that the tasks did not interfere too much with other courses. The students were also asked if there were any difference between their experience in the UCCRP and other projects. Eighty five percent (85%) of the students stated that there was a major difference (or a difference) in their experience with the UCCRP which is the direct linkage between material learned in class and the UCCRP tasks (see Figure 6d). Another difference mentioned by the students

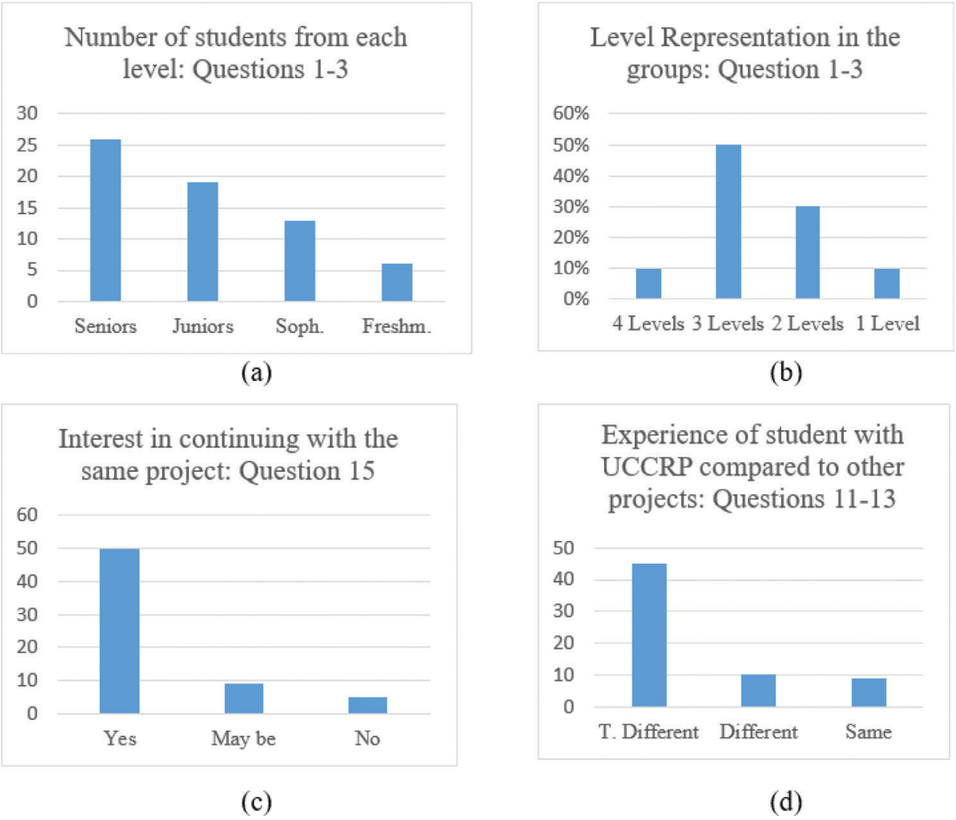


Figure 6. Results from the questionnaire in Figure A6.

is that the UCCRP gave them a chance to use the theories developed in the classroom to approximate solutions for real life problems. Interestingly, some students mentioned that the "UCCRP is like a lab, but with more interesting problems." This is in alignment with one of the objectives of the UCCRP; i.e., deep learning. The other fifteen percent (15%) of the students did not see major difference between projects they worked on before and the UCCRP. The survey data also revealed that although the majority of the students needed help with their projects frequently, they sought information mostly from their peers, TAs, and the professor, in that order. This information reflects the power of peer teaching which is one of the objectives of the UCCRP.

Creativity and conceptual change

One of the goals of the UCCRP is creativity and conceptual change. The solution to the assigned tasks were devised by the students themselves with minimal interference from the instructor(s) or the teaching assistants (TAs). This approach seemed to resonate well with the students. In fact, the vast majority of them appreciated the hands-off approach by the mentoring teams, which gave them a chance to explore different solutions without any kind of pressure. It is worth noting that even though these observations may not be unique to the UCCRP and that other project-based initiatives have boasted similar results, they are reported here to emphasize the semi-autonomy the students have to achieve the ILOs.

One thing found to be very encouraging to students is labeling any innovative correct solution by the name of the student(s) who was (were) behind it. This is done to acknowledge good work as well as give credit to those who came up with the idea. Moreover, successors and/or new students may directly contact the designer/creator/developer for additional information or clarification even if s/he is no longer a member of the UCCRP.

Structure of the Observed Learning Outcome (SOLO)

The main objective of the UCCRP is to create a learning environment for students and engage them in activities when executed properly would lead to a deeper learning experience of many of the engineering theories and concepts. As a result, when the students progress in the project, their learning outcomes display an increasing structural complexity quantitatively as well as qualitatively. In other words, the amount of details in their responses to specific questions increases and more coherent solution patterns for parts of the UCCRP start to emerge fortified by significant details about the problem. Although the definition of deep learning has been agreed upon by many researchers in the literature, assessing it still remains an open research topic. One assessment technique developed by (Biggs and Collis, 1982; Biggs and Tang, 2011) and available in the literature has received positive feedback from (Smith and Colby, 2007; Brabrand and Dahl, 2009; BoultonÐLewis, 1995; Hook and Mills, 2011; Martin, 2012) and can be adopted here to assess the depth of learning in the UCCRPs. The technique's framework is the Structure of the Observed Learning Outcome (SOLO) taxonomy, which can be used by educators to understand and examine the depth of teaching and learning (Biggs and Tang, 2011). Because the SOLO taxonomy classifies learning outcomes in terms of their structural quality, it makes them useful in defining levels of understanding.

Following is a list of levels of the SOLO taxonomy (similar to Bloom's Taxonomy) with appropriate active verbs (see Figure 7)

- SOLO 1: (Pre-Structural): student misses the point
- SOLO 2: (Uni-Structural): define, count, name, recite, follow instructions, calculate
- SOLO 3: (Multi-Structural): classify, describe, enumerate, list, do algorithm, apply method
- SOLO 4: (Relational): analyze, compare, explain causes, apply theory (to its domain)
- SOLO 5: (Extended Abstract): theorize, generalize, hypothesize, predict, judge, reflect, transfer theory (to new domain)

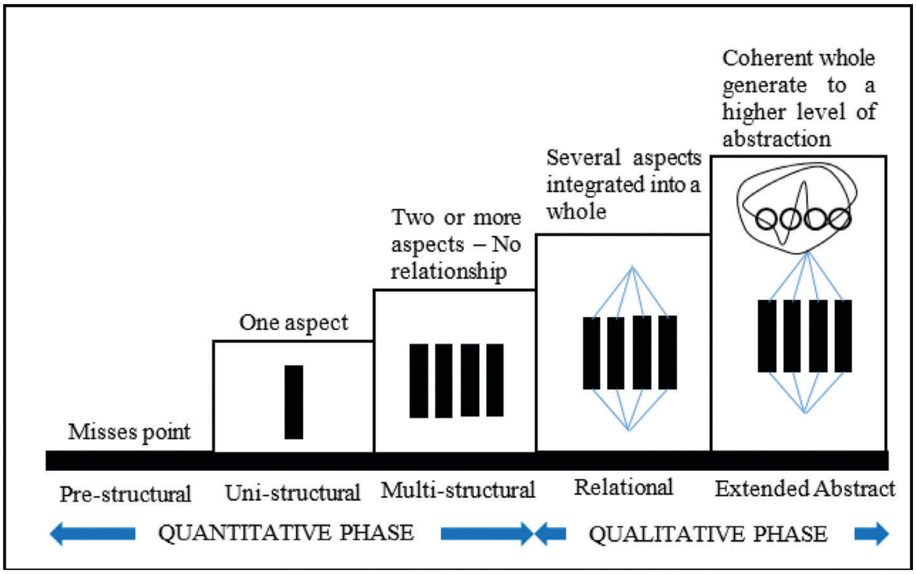


Figure 7. Graphic representation of the structure of the observed learning outcome (SOLO) taxonomy (Biggs 1999).

In a typical engineering course, the teaching and assessment are mainly focused on the quantitative aspect of learning; consequently, the higher more important qualitative levels are usually neglected due to time constraints, number of course learning outcomes, logistical constraints, etc. Therefore, the UCCRPs are designed in a way to take the learning process from the quantitative to the qualitative learning phase guaranteeing a deeper learning experience. The challenge here is to stress the qualitative aspects of the intended learning outcomes and support them by appropriate teaching and assessment methods. While SOLO levels 1 through 3 are usually addressed in the Knowledge Incubator courses, levels 4 and 5 are the main target of the UCCRPs. Therefore, intended learning outcomes (ILOs) have been developed every semester for each UCCRP and complemented by a set of teaching/learning activities (TLAs) and assessment tasks (ATs) agreed upon with the students. Sample ILOs/TLAs/ATs tables for specific tasks of the UCCRP presented here are listed in Figs. A3–A7. The number of ILOs per semester is limited to 2–3 per project task and developed based on the taxonomy verbs listed in SOLO levels 4 and 5 (see Figs. A1–A5). In addition to the creation of the UCCRP, the supervisors implement the important task of expressing the learning activities in terms of taxonomy verbs, which are subsequently asserted in the ILOs, nourished in the teaching/learning activities, and embedded in the assessment tasks (ATs). As a result, the assessors can confidently judge the level of attainment of the ILOs by the students using rubrics specifically designed for the learning activity targeted therein (see Figure A8–A9 for sample rubrics).

To assess the level of attainment of the ILOs, a number of faculty in the program have been asked to help with this effort in addition to the students' self-assessment. Through one-on-one interviews, presentations, and/or project reports, the faculty have been asked to grade the students understanding of particular topics, such as, analyzing a multi-component system, using electro-magnetism laws to model a DC motor as part of machine, applying realistic constraints, clearly theorize the effect of a particular phenomenon on the overall performance of the system, etc. The following grading scheme is used:

A. The student is able to reflect, formulate and apply theory (electro-magnetism, control, design, etc.) to the system at hand (autonomous vehicle or mine detection robot). S/he clearly show mastery of the topic.
B. The student is able to practice a holistic understanding of the project requirements, topics, and theories related to his/her assigned tasks.
C. The student is able to explain important theories and/or can describe other topics in an acceptable manner.
D. The student is able to explain some theories related to his/her assigned task.
E. Barely understands the topic/theory.

This exercise was repeated twice: in the Fall of 2014 and Spring 2018. The results of the faculty assessment showed 10% of the students received an A grade, 60% received a grade of B, and the remaining 30% received a grade of C or below. This clearly shows that the majority of the students have reached at least SOLO level 4, which reflects a deep learning achievement.

Competency-Based Assessment

Deep learners use higher-order meta-cognitive skills such as the ability to analyze, synthesize, and solve problems in order to construct long-term understanding. This translates into a set of life-long skills/competencies, which can be used to devise innovative solutions for other projects. In each UCCRP, a set of competencies can be achieved by the students, such as, developing control algorithms, analyzing dynamic systems, interfacing hardware, etc., required to achieve the targeted SOLO levels 4 and 5. Competency-based assessment can be used to measure specific skills that students have learned during the execution of the UCCRP; therefore, a survey has been conducted to collect feedback from faculty about certain skills that the students are expected to acquire by participating in the UCCRP. The targeted faculty are those who are teaching courses with UCCRP and non-UCCRP students who are conducting research or involved in course projects. The targeted skills are: design synthesis, design analysis, and interfacing of mechatronic devices (see a blank copy of the survey in Figure A7). Seven of the twelve faculty in the program took the competency assessment survey, which listed 16 students who participated in the UCCRPs during the past 4 years and

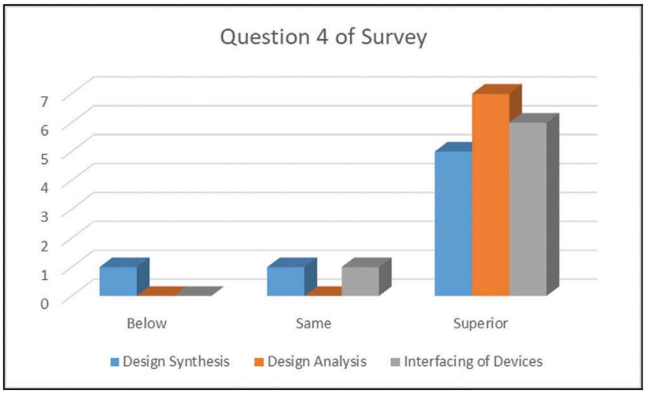


Figure 8. Results of assessment survey shown in Figure A7.

the results of the survey are depicted in the bar graphs of Figure 8. These results are based on oral presentations and reports written by the students assigned in terms of ATs. By comparison to their colleagues who did not participate in any UCCRPs, UCCRP students performed better on the three targeted skills (see Figure 8). Therefore, it is clear from the faculty point of view that the UCCRP students in fact demonstrated proficiency is some key skills necessary to achieve SOLO levels 4 and 5.

THE CHALLENGES

Although, there was no shortage of ideas for the UCCRPs, many challenges have been uncovered from the perspective of the mentors, students, and facilities. From the mentors' side, the amount of time dedicated to the UCCRPs, in addition to their other required duties (teaching, research and service), was found to be at times very high. This put additional pressure on the mentors and, occasionally, led to frustration of some participants whose schedule did not align well with those of the mentors. This is not an easy problem to take care of especially when the number of students is large; however, efforts have been made to accommodate the demands of the participants by providing assistance on weekends or additional TAs whenever possible. From the students' side, the challenges are mainly time management, integration in the group, and access to the labs whenever they want to. While the first two challenges are usually resolved by more one-on-one mentoring and communication sessions between the supervisors and the students, the third one is resolved by addressing the safety and security rules set forth by the University. The University has strict safety and security guidelines that all students, staff, and faculty have to abide by; therefore, students cannot access labs whenever they want to, but rather when all rules and guidelines are met. The students eventually came to terms with the lab access guidelines and found a suitable solution to the problem in coordination with the mentors.

CONCLUDING REMARKS

Deep learning requires involving students in deep critical approaches to learning and not merely repeating knowledge, they acquired from the classroom. That is the motivation behind the teaching/learning enhancement tool presented in this work, which relies on three major concepts: cross-level peer teaching/learning, hands-on experiential solutions to real life problems, and creativity and conceptual change. The technique known as the Undergraduate Cross-Class Research Project (UCCRP) has been applied with success in the Mechanical Engineering Program at Texas A&M University at Qatar. Students from different levels (freshmen, sophomores, juniors, and seniors) worked side-by-side to devise solutions, individually or collaboratively, to research questions set up by the instructors. The UCCRP's focus is on specific skill for specific student rather than on solution of a particular problem as is the case in almost all project-based learning initiatives currently used in engineering education. Each task in the UCCRP is divided into well-defined skills with intended learning outcomes (ILOs), teaching and learning activities (TLAs), and assessment tasks (ATs). The ILOs and ATs are designed in such a way that when properly executed will push the students into the qualitative phase of learning on the SOLO scale; i.e., deep learning. A sample UCCRP is discussed and a detailed procedure of the division of tasks, development of the ILOs, TLAs, and ATs are delineated here. Direct and indirect assessment techniques are subsequently used to measure the level of learning achieved by the student. Preliminary results from students' self-assessment, competency-based assessment, and the SOLO technique, are also presented to demonstrate the effectiveness of the UCCRPs in achieving deep learning levels as defined by the SOLO method.

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APPENDIX

UCCRP-Task	Skills	Courses	ILOs and ATs
Vehicle Transformation (brake and acceleration) **TLAs** TLA-1: Failure analysis of beams and cables (2–3 hours) TLA-2: Intro to finite element analysis (3–4 hours).	**Solid Modeling**	**MEEN210** **MEEN360**	ILO-1: *Describe* solid modeling techniques to produce a part starting from a profile, AT-1: Give a 10-minute presentation with simple examples. ILO-2: *Create* a functional system to perform a specific task, AT-2: Present sketches of two or more systems to transform to actuate the car pedals. ILO-3: *Apply* extrusion along any prescribed path and feature addition and subtraction, AT-3: Select one of the designs from AT-2 and draw all parts using SolidWorks and present work to group. ILO-4: *Apply* tolerance to fitting parts using manufacturing standards (e.g. ANSI 4.1), AT-4: For each joint in the selected design, apply the necessary tolerances and indicate which standards used, and write a short with orthographic views of all parts showing tolerances. ILO-5: *Construct* a functional assembly and animate it, AT-5: Assemble all parts of the system and create a video showing the system in action. ILO-6: *Analyze* the motion the critical stress points using built in FE module, AT-6: Show animation of the system with stress distribution superimposed.

Figure A1. Intended Learning Outcomes (ILOs), Assigned Tasks (ATs), and Teaching and Learning Activities (TLAs) for the UCCRP task "Vehicle Transformation".

UCCRP-Task	Skills	Courses	ILOs and ATs
Vehicle Dynamics **TLAs** TLA-1: Expressing energy transfer between subsystems and components through bond-graphs (2–3 hours) TLA-2: Application of Fourier transforms to spectrum analysis of signals (2–3 hours).	**Dynamics Modeling**	**MEEN225** **MEEN363** **MEEN364**	ILO-1: *Apply* laws of energy transfer and divide complex systems into multi-degree-of-freedom lumped systems, AT-1: Divide the car system into a chassis, passenger, and steering systems and write a short report depicting results. ILO-2: *Prove/demonstrate* the validity of the division using bond-graph theory, AT-2: Present the divided system along with bond-graph diagram to the group along with a memo. ILO-3: Using newton's laws, *generate* the equations of motion of all subsystems, AT-3: Write a 2-4-page memo showing the subsystems and the corresponding equations. ILO-4: *Analyze* the equations using Matlab/SIMULINK or Python and *reflect* on the short comings of the equations, AT-4: Write a short report showing the time response of the overall system and discussion of what physical phenomena must be added. ILO-5: *Generalize* the equations of motion by adding the contribution of physical phenomena such as friction and nonlinear springs, AT-5: Write a short report describing the difference in the output of the car with and without friction.

Figure A2. Intended Learning Outcomes (ILOs), Assigned Tasks (ATs), and Teaching and Learning Activities (TLAs) for the UCCRP task "Vehicle Dynamics".

UCCRP-Task	Skills	Courses	ILOs and ATs
Road Sign Detection	**Programming**	**MEEN433**	ILO-1: *Construct* an algorithm using Python OpenCV to parse pictures from a video, AT-1: Show a demo of the program parsing images to the group. ILO-2: *Apply* Eigenvalue theory to classify pixel colors and location in a picture, AT-2: Write a memo showing how the Eigenvalues are adjusted to match closely the colors. ILO-3: *Apply* filtering techniques to images to identify objects, AT-3: Present a demo of steps in the program including showing the filtering action and usage of the canny-edge routine to identify the edges of an object. ILO-4: *Apply* classification techniques to identify stop, yield, and other signs, AT-4: Collect images of stop and yield signs to train the neural network and use the resulting program to identify these signs. Write a report on the success of the program.
TLAs	TLA-1: Intro. to pixel search and color identification (2–3 hours), TLA-2: Intro. to machine learning (3–4 hours).		

Figure A3. Intended Learning Outcomes (ILOs), Assigned Tasks (ATs), and Teaching and Learning Activities (TLAs) for the UCCRP task "Road Sign Detection".

UCCRP-Task	Skills	Courses	ILOs and ATs
Data Acquisition	**Interfacing sensors and actuators**	**MEEN260** **MEEN364** **MEEN433**	ILO-1: *Construct* and program using Python to set up a micro-controller, AT-1: Write the necessary Python code to perform simple computation on a PIC micro-controller and output the result to an LCD screen and arrange for a live demo to the group. ILO-2: *Create* interfaces for digital input and output devices, AT-2a: Build a circuitry to interface a push-button output voltage with ability to de-bounce the switch, AT-2b: Analyze the signal output using an oscilloscope and discuss its suitability to be used as a digital input and write a report describing all elements in the interface and discussing the results. ILO-3: *Create* interfaces for analog input and output devices, AT-3a: Build a circuitry to interface a DC motor and control its speed and direction of motion using an H-bridge, AT-3b: Analyze the motion of the motor by recording the speed and position data and reflecting on its performance, and write a report describing all elements in the interface and discussing the results. ILO-4: *Reflect* on any mishaps in expected performance between the micro-controller and its peripherals *explain* the reason, AT-4a: Record any glitches in communication between the micro-controller and I/Os and give reasons why they occurred, AT-4b: Write a diary of all the glitches and how they were resolved.
TLAs	TLA-1: Intro. to micro-controller (1–2 hours) TLA-2: Intro. to serial communication (2 hours), TLA-3: Intro. to semi-conductors (2 hours).		

Figure A4. Intended Learning Outcomes (ILOs), Assigned Tasks (ATs), and Teaching and Learning Activities (TLAs) for the UCCRP task "Data Acquisition".

UCCRP-Task	Skills	Courses	ILOs and ATs
Vehicle Control	**Control design**	**MEEN364**	ILO-1: *Create* a PID controllers for the motion of the car which meets the necessary requirements of bandwidth, accuracy, time response, AT-1a: *Design* a P controller using Matlab/SIMULINK for the car model developed by other students, AT-1b: Add "I" and "D" terms to the controller and observe change in response and write a short memo describing the results. ILO-2: *Reflect* on results from ILO-1 and *explain* the reason for the change in response, AT-2: Write a short report comparing the results with all PID controller terms. ILO-3: *Create* PID controllers using Ziegler-Nichols technique, AT-3: Repeat AT1-AT-3 using Ziegler-Nichols controller design technique and write a report discussing the results. ILO-4: *Compare* results from both control design and *explain* differences, AT-4: Write a short report describing the results from both control designs and discussions of discrepancies in performances. ILO-5: *Create* an equivalent digital controller for the car system by *applying* common digitization techniques, AT-5: Obtain the state-space matrices for the car system and simulate response using Matlab Digital Control toolbox or Python. Write the results in a short memo. ILO-6: *Compare* digital and analog outputs and reflect on differences, AT-6: Write a memo describing results and reflect on the results.
TLAs TLA-1: Intro. to PID control design using Ziegler-Nichols method (2 hours) TLA-2: Intro. to Matlab Control Toolbox (1 hour), TLA-3: Intro. to digital control (2 hours).			

Figure A5. Intended Learning Outcomes (ILOs), Assigned Tasks (ATs), and Teaching and Learning Activities (TLAs) for the UCCRP task "Vehicle Control".

UCCRP-Title	....
1. Select one: I am	☐ Freshman ☐ Sophomore ☐ Junior ☐ Senior
2. Select task number you are involved in: (If you do not know the task number, write a brief description.)	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ....
3. Tick level of students in your group:	☐ Freshman ☐ Sophomore ☐ Junior ☐ Senior
4. Was the objective of the task clearly defined?	☐ Strongly agree ☐ Agree ☐ Disagree
5. How often did you seek assistance?	☐ Very often ☐ Often ☐ Not often
6. Whom do you usually seek assistance from (in order)?	☐ TA ☐ Professor ☐ Student teammates
7. Was interaction with your teammates helpful?	☐ Strongly agree ☐ Agree ☐ Disagree
8. Was interaction with your TA helpful?	☐ Strongly agree ☐ Agree ☐ Disagree
9. Was your interaction with your professor helpful?	☐ Strongly agree ☐ Agree ☐ Disagree
10. Have you participated in other open-ended projects before?	☐ Yes ☐ No
11. If yes, describe your experience in comparison with the UCCRP?	☐ Totally different ☐ Different ☐ Same

12. If different or totally different, in which of these area do you see the difference?	☐ Setup of project ☐ Execution ☐ Teams ☐ Requirements ☐ Other
13. Please describe your experience with the UCCRP.	☐ Very good ☐ Good ☐ Indifferent ☐ Bad
14. Describe your learning experience in the UCCRP:	…………………… ……………………
15. Please tell us what you liked about your experience in the UCCRP and if you would like to continue with same one:	…………………… ……………………
16. Please tell us what you did not like about your experience in the UCCRP.	…………………… ……………………
17. How do you think we can improve the UCCRP?	…………………… ……………………

Figure A6. UCCRP student self-assessment questionnaire.

1. Please select from the list the students that are/were in your class and doing/did research or participating/participated in a project with you.	[ ] Student 1 [ ] Student 2 [ ] . . . [ ] Student 16
2. At which level did you know these students?	[ ] Freshman [ ] Soph. [ ] Junior [ ] Senior
3. From the list of skills on the right, please select the ones that the selected student(s) showed proficiency in (proficiency means deep understanding of the concept, applied concept correctly, and capable of applying concept in other situations):	a. Design Synthesis b. Design Analysis c. Interfacing of mechatronic devices
1. Compared to other students in your class, please rate the selected students' performance with respect to each of the stated skills:	Design Synthesis [ ] Below [ ] Same [ ] Superior Design Analysis [ ] Below [ ] Same [ ] Superior Interfacing of Mechatronic Devices [ ] Below [ ] Same [ ] Superior
2. Please list any skills that you found commendable.	…………………… ……………………
3. Please comment on their level of confidence working on your project(s).	…………………… ……………………
4. Please list any skills that you expected the students to have, but they did not.	…………………… ……………………
5. Is there any other skills that we should target in our future UCCRPs?	…………………… ……………………

Figure A7. Competency assessment survey.

	Marginal D (1.0)	Adequate C (2.0)	Good B (3.0)	Excellent A (4.0)
Reflect	Student self-evaluated using available information and generally, but did not clearly identify any own strengths and weaknesses. Student did not suggest ways to improve and/or did not use theory to self-evaluate.	Student self-evaluated using available information and identified some aspects of own strengths and weaknesses. Student had limited suggestions to improve and applied limited theory in self-evaluation.	Student self-evaluated using available information and identified the full range of own strengths and weaknesses. Student showed improvement in self-evaluation based on theory and suggested ways to improve further with the respect the project tasks.	Student showed deep understanding of the concepts discussed in the report/presentation and capable of generalizing the findings beyond the project tasks. Student suggested creative ways of improving performance.

Figure A8. Rubric for assessing ILOs containing taxonomy verb "reflect".

	Marginal D (1.0)	Adequate C (2.0)	Good B (3.0)	Excellent A (4.0)
Create, Improve, or Invent	Student showed little or no creative ideas/models/designs and product satisfied a small number of constraints. Student explained very aspects of design/model impact with knowledge limited to material covered in incubator course.	Student showed limited creative ideas/models. The design/model created by the student is average, not too practical, and major components are missing. Student showed limited knowledge beyond that covered in incubator course.	Student showed creative ideas/models/designs with knowledge beyond what is covered in incubator course. The designs/ideas/models are practical and missing very few components/constraints for completeness. The students demonstrated well-rounded knowledge that can help look at the ideas/models/designs from different angles.	Student showed highly creative ideas models/designs which are clearly superior to templates and examples covered in incubator courses. The designs/ideas/models are extremely practical, functional, and commercially viable. The student explained well the impact of ideas/models/design from various angles.

Figure A9. Rubric for assessing ILOs containing taxonomy verb "create, improve, or invent".