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Development of an Undergraduate Multidisciplinary Mechanical Design Laboratory Sequence based on Faculty Research

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Abstract

Researchers have shown that the incorporation of hands-on design projects in the first two years of college provides mastery that increases the likelihood of success in engineering [1-8]. Integrating real world design problems, based on faculty on-going research, into the curriculum during the freshman years is without a doubt extremely beneficial; however the process requires a heavy commitment in faculty time and sometimes resources.

This paper discusses preliminary results of introducing faculty on-going research to undergraduate students, in a form of a lab sequence, focusing on student-centered approaches such as active cooperative learning. The labs aim to address the need for combining multidisciplinary theoretical knowledge with practical hands-on experience and are specifically focused on involving undergraduate students in research and preparing them for the capstone senior design project class. Each of the labs is related to one or two recently published by the faculty papers, which the students are asked to get familiar with before each lab session. Preliminary results on the learning outcomes, based on students' perception were assessed through anonymous survey questions. Next, the desired learning outcomes from faculty viewpoint, regarding critical thinking, responsibility for one's own learning and intellectual growth were assessed through anonymous survey. The latter required the students to outline the questions that they were asking themselves while working on each project. The preliminary results show that presenting a series of different lab projects, which complement each other, brings to successful results. For the limited time of one semester, the results show students' improved critical thinking, intellectual maturity, as well as taking more responsibility for their own learning. In addition, the inductive methods used in the labs prove efficient not only for learning new tasks, but also in transferring earned skills to tasks of greater difficulty. The next step will be to assess how well the students work under the whole series of lab projects and share our experiences. Here, we would like to note that the lab-based alternative to other undergraduate research engagements is a novel idea and provides interesting perspectives.

Introduction

Involving undergraduate students in research projects can be seen as a form of inductive teaching [1], an instructional strategy that comes close to emulating research, and is frequently cited as an effective way to link faculty research to undergraduate teaching. Unlike traditional teaching methods, inductive teaching introduces topics by presenting specific observations, case studies or problems. Theories are taught or the students are helped to discover them only after the need to know them has been established. Bransford, Brown, and Cocking [2] survey extensive neurological and psychological research that provides strong support for inductive teaching methods. Ramsden[3], Norman and Schmidt [4] and Coles [5] also demonstrate that inductive methods encourage students to adopt a deep approach to learning. Felder and Brent [6] show that the challenges provided by inductive methods serve as precursors to intellectual development. Prince and Felder [7] review applications of inductive methods in engineering education, and state the roles of other student-centered approaches, such as active and cooperative learning, in inductive teaching. Sabatini [8] discusses several examples of how undergraduates and high

school students can be involved in engineering research. The NSF Research Experience for Undergraduates (REU) program [9] promotes and supports research involvement, and this activity clearly has the potential to benefit students. Pascarella and Terenzini [10] note several positive outcomes for students who participate in undergraduate research programs, among them greater retention in the curriculum and greater likelihood of enrolling in graduate school.
On the other hand, Seymour et al. [11] argue that most studies of undergraduate research did not include proper control groups, used biased samples or failed to provide sufficient details of their evaluation methods. However, Kevin Gibbons et al. [12] have developed an approach to involve a group of senior mechanical students that were taking a specific course in improving a relevant lab learning experience for other undergraduates. Overall academic performance for both two categories has been improved and results showed that most students who have experienced hands-on work felt that this approach helped them with meeting the course requirements.

The sections that follow provide an overview of our efforts to improve the learning environment for undergraduate engineers and discuss the early accomplishments that our working group has achieved.

Motivation, Course/Lab Description and Desired Student Outcomes

Our main goal is to let undergraduate students experience being engineers by introducing open-ended research problems in the form of lab projects, thus forcing the students to link engineering theory to research and real-world applications. Preparing students to actively participate in the learning process, by exercising original thinking, evaluating alternative solutions, making decisions and defending them, was our motivation. The developed labs can be presented as a separate one-semester lab or as a part of our Kinematics of Mechanisms course, which currently does not include any labs. The Kinematics of Mechanisms is a junior course, which introduces kinematics and dynamics of mechanisms and their applications. The course covers analysis and design of linkages, gears, cam and follower systems, as well as static and dynamic analysis of mechanisms. The outline of the class is listed below:

1. Machines and Mechanical Advantage. Introduction to Linkages
2. Planar Robotics. Forward and Inverse Kinematics. Mobility
3. Gears and Gear Trains
4. The Slider Crank and the Four-Bar Linkage
5. Cam Design. Displacement Diagrams
6. Static Force Analysis
7. Dynamic Force Analysis

Since the goal of the "Development of the Articulated Suspension Exploratory Platform System ASEPS" laboratory sequence is to prepare the engineering undergraduates for their capstone design project class, the following new material will be added to the class, which further enhances the multi-disciplinary flavor:

8. Digital I/O Signals.
9. Simple electrical circuits.
10. Simple Communication Radio Controllers.

The course activities were then mapped to the desired project lab development and outcomes. Specifically, the process for integrating inquiry techniques into the lab projects, contained the following phases:

- Determine faculty goals and objectives; analysis of potential students (students, who take the course are juniors and do not have a prior knowledge in the field of mechanical design and it's applications);
- Determine faculty role in the learning process and develop an instructional plan;
- Design lab activities, assignments, and assessments that are congruent with four major desired student outcomes: (a) improved critical thinking, (b) greater capacity for independent work, (c) taking more responsibility for one's own learning, (d) intellectual growth, congruent with the lab project goals mentioned below.

Lab Project Specific Goals

The goal of the ASEPS laboratory sequence is twofold: to relate faculty research and education and to prepare the mechanical engineering undergraduates at California State University Fullerton for their capstone design projects giving them knowledge such as:

(1) Hands-on activity in analyzing and designing real world mechanisms;
(2) Sketching and drawing, in order to communicate design ideas in team environment;
(3) Kinematics, in order to understand what will work and what will not and evaluate alternative solutions;
(5) Controls, in order to be able to look and solve multidisciplinary problems;
(4) Statistics, to be able to work with data;
(5) Materials and manufacturing, to understand materials and processes;
(6) Test plan preparation;
(7) Making decisions and defend them.
(8) Communication skills in order to learn how to work on multidisciplinary projects and understand relationships between mechanical and electronic concepts;

Laboratory Projects Sequence

Here, the authors present the development of a multidisciplinary engineering design-based laboratory "Development of the Articulated Suspension Exploratory Platform System ASEPS", with the main goal of involving undergraduate students in faculty research, enhancing their interest, excitement and comprehension of mechanical engineering concepts and preparing them for their senior design projects. The Articulated Suspension Exploratory Platform ASEP is a small robotic rover platform, previously designed by some of the faculty and students at Texas A&M University [13-16]. The overall goal was to develop a reproducible, low-cost wheeled robot suited for operation on rough terrains in remote environments, to support current and future education and research activities. The developed platform is shown in Figure 1. There are currently six of these platforms at California State University.

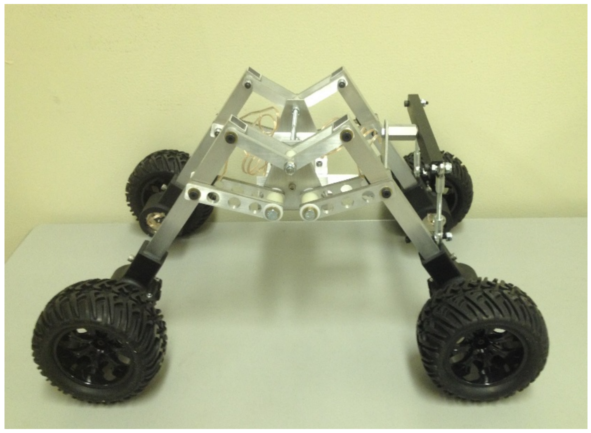
Figure 1. The developed Articulated Suspension Exploratory Platform ASEP

Recently, the faculty and students at California State University attached a robotic arm to the ASEP platform and the assembled new arm-rover system was called Articulated Suspension Exploratory Platform System (ASEPS).

There are twelve planned weekly labs during the semester, each consisting of two portions. The first portion covers the description of the lab project, including objective(s), required parts/part description and step-by-step tutorial instructions. The second part requires the students to apply the knowledge learned from the lecture and the first lab portion to solve the specific project. To increase the quality of writing [13] and presenting, the students will be asked to submit design overview reports in the end of each lab and give bi-weekly oral presentations on their progress.

The ASEPS lab projects were developed, by following the lecture sequence. Each new project is built upon the previous one. The twelve developed lab projects are:

Lab Project 1: Kinematic Analysis of a Planar Robotic Arm using Reverse Engineering Techniques

The goal of this lab is to introduce students to reverse engineering techniques and give them an insight of the kinematics of a simple planar three-degree of freedom robotic arm, shown in Figure 2. The arm is a simplified model of the five-degree of freedom ALD5 Lynxmotion arm. For this lab, the students are asked to disassemble, analyze, evaluate and propose improvements to an existing Lynxmotion robotic arm, using provided device analysis format. For the analysis part, the students have to present the inverse kinematics for the robotic arm, choosing any task positions from the workspace of the arm (see Figure 2).

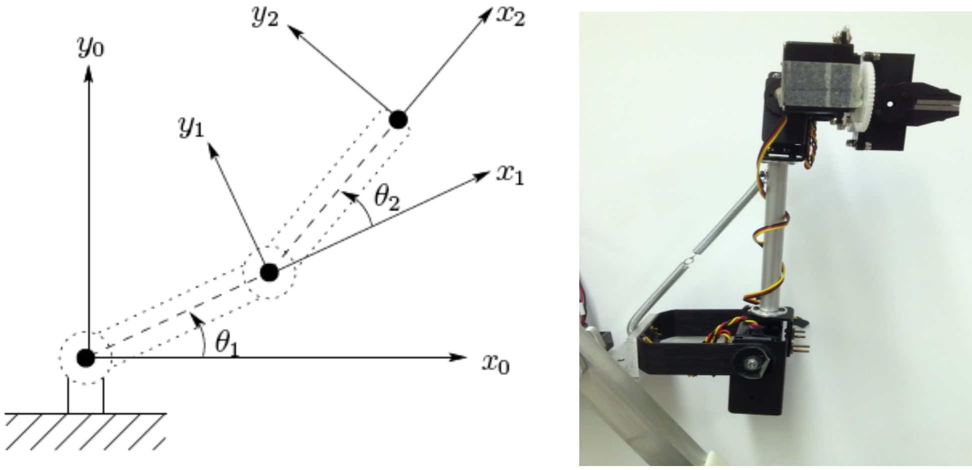

Figure 2. The Modified ALD5 Lynxmotion Robotic Arm

Lab Project 2: Gears and Gear Trains used in the Design of Planar Robotic Arms
The goal of this lab is to give the students an insight of the actuation of the planar three-degree of freedom robotic arm, analyzed in Lab Project 1. For this lab students are exposed to conducting experiments related to finding the actual speed for the servo-motors of the robotic arm. Datasheet of the robotic arm servos provides the no load maximum speed; however, servos are more likely to spin in different speeds with respect to loading within safe limitations.

Lab Project 3: Mechanical Design of a Passive Suspension for a Small Rover, based on Given Constraints
The goal of this project is to propose a design for a passive suspension for a small rover, capable of moving over rough terrains. For this lab, the students are asked to design a multi-bar linkage used for a passive suspension of a small rover. The wheel diameter and the approximate body size are given. It is also assumed that the multi-bar suspension consists of two four bar linkages, rigidly connected to each other, as shown in the two examples in Figure 3.

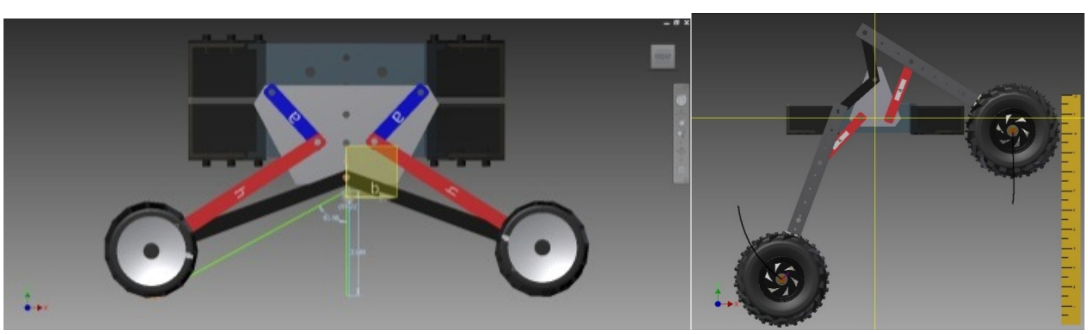
Figure 3. Two examples of multi-bar linkage suspension designs. For both examples the four bar linkage on the right hand side had been designed and then a mirror image of that design had been connected to it

The constraints for the passive suspension design include an obstacle climbing ability of more than 1.5 times the wheel diameter, vertical motion of the center of the front wheel as close to linear as possible, in order to decrease overturn moment and thus increase the stability. The students are asked to use cardboard and snaps to construct the chassis, the attached suspension linkage and front wheel. They are also asked to submit CAD drawings, demonstrating their design results, specifically:

1. The chosen location of the fixed frame, the locations of the fixed pivots of the passive suspension with respect to a fixed frame, as well as the link lengths.
2. The obstacle climbing ability of the designed suspension, as well as the maximum linear range of motion, by obtaining the path of the front wheel center (see Figure 4).
3. Analyze the designed linkage and present a table of results (input angle, output angle, coupler angle, input and output velocities, as well as the Mechanical Advantage of the proposed design in different configurations).
4. Comment on the performance of the passive suspension design.

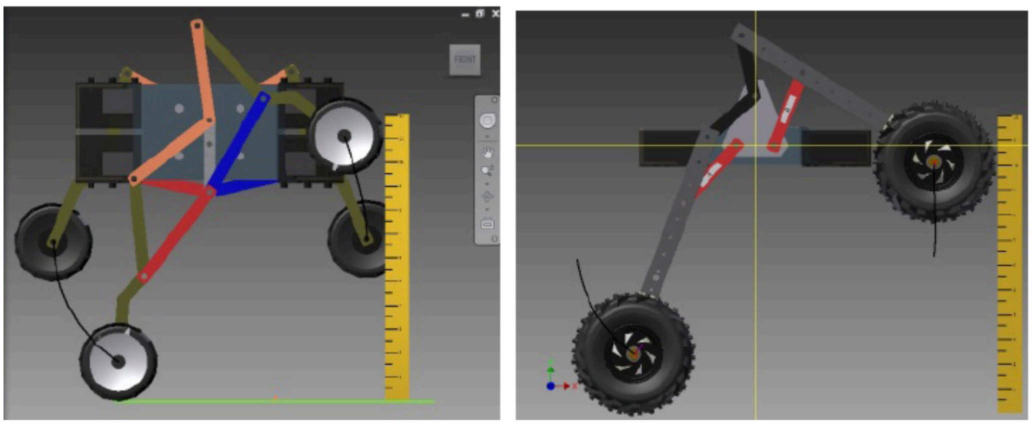

Figure 4. Climbing ability of two different passive suspension designs

Lab Project 4: Building a Passive Suspension for a Small Rover using Four Bar Linkages

The goal of this project is to assemble a passive suspension for a small rover, capable of moving over rough terrains, using the ASEP tool-kit, developed at XXXX University. Part of the tutorial for assembling and building the ASEP rover is given in Figure 5.

Figure 5. Part of the tutorial for assembling and building the ASEP rover platform

Lab project 5: Assembling the Rover-Arm System ASEPS

The goal of this lab is for the students to attach the arm to the rover platform, thus assembling the entire rover-arm system. As mentioned above, the ALD5 Lynxmotion Robotic Arm is modified to be compatible with the ASEP unit and attached to the front of the rover (see Figure 6).

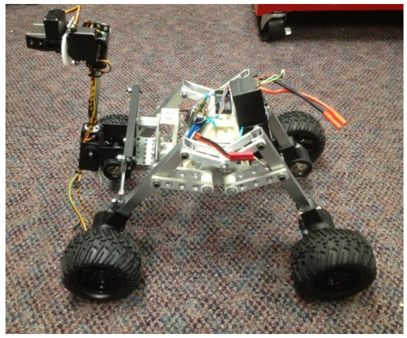

Figure 6. The ALD5 Lynxmotion robotic arm, modified to be compatible with the ASEP unit and attached to the front of the rover.

Lab Project 6: Arm-Rover System Center of Gravity and Stability

The goal of this lab is to give the students a general insight about calculating the center of gravity and to test the stability of the ASEPS system. The lab includes comparison of the system stability for two different designs. The maximum slope or gradeability, is broken into two perspectives for two different designs, shown in Figure 7.

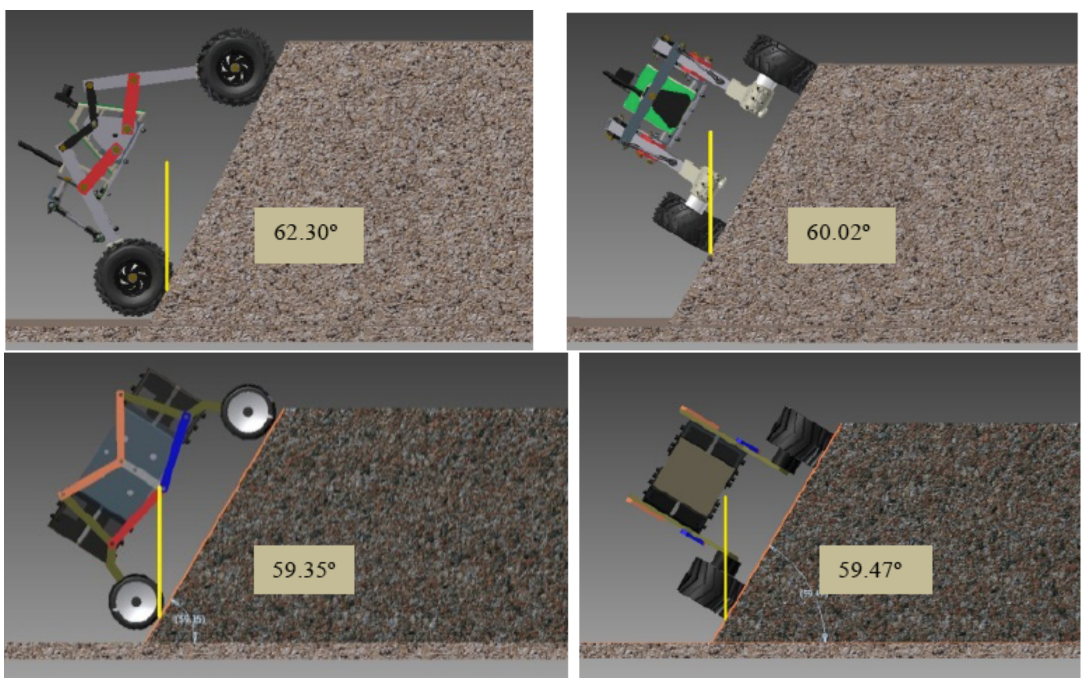

Figure 7. Center of gravity location and gradeability for two passive suspension designs

Both designs require a rear linkage set, shown in Figure 8, which adds stability by relating the movement of the right and left linkage chains.

Figure 8. The rear linkage set, adding stability by relating the movement of the right and left linkage chains

Lab Project 7: Dynamic Force Analysis of the Rover Suspension
The goal of this lab is to provide students with techniques for determining the magnitude, direction and location of forces as well as assess them. Specifically, the students are asked to derive the forward kinematics of the passive linkage suspension to find all the unknown angles, angular velocities and angular accelerations. As a next step, they need to model the links as free bodies and find a matrix representation of the suspension system dynamics. Finally, the students are asked to calculate the values of the bearing forces in the joints, as well as the input torque for a given range of the input angle.

Lab Project 8: Dynamic Force Analysis of the Robotic Arm
The goal and the steps that the students need to follow to perform this lab are similar to the steps, described in *Lab Project 7*.

Lab Project 9: Platform Motor Controller and RC Control of the ASEPS
The goal of this lab is for the students to understand the functions of the motor controller that is used to control the rover four motors and the capability of technical datasheet of the motor controller. Wiring and connecting the motors, RC receiver, and the battery have to be done under a great caution of technical, mechanical, and electrical conditions for both human and system safety. Programming the motor controller is implemented via the software provided by the motor driver's company (see Figure 9). The RC transmitter and receiver are chosen to remotely control the ASEPS.

Figure 9. Motor Controller RC Components

Lab Project 10: Assembling the Motor Controller and the Batteries into the ASEPS
The goal of this lab is for the students to get familiar with mounting and fitting the different components into the limited space of the rover platform, with the main goals of (1) minimizing vibration of these components, while the platform is moving over rough terrains, as well as (2) electrical safety issues. The motor controller has to be mounted with paying a great attention to the electrical safety concepts. Plastic is used as isolable underneath the motor controller to protect it from vibrations and electrical damage. Special rubber bands are used to hold the battery to reduce the mechanical shocks while the ASEPS is climbing over an obstacle or moving through rough terrains. Connections and wiring are done according to the control approach, implemented to operate the functions of the ASEPS tasks (see Figure 10).

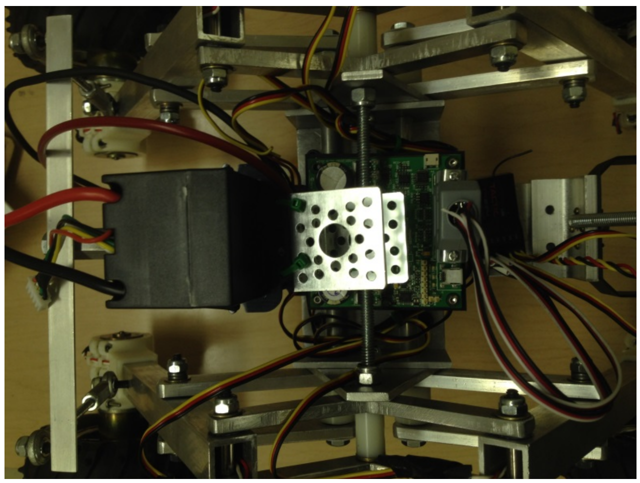

Figure 10. Assembling the motor controller and the batteries into ASEPS

Lab Project 11: Testing the Rover-Arm System in the Physical Environment "Planet Mars"
The goal of this laboratory is for the students to learn how to prepare test plans and how to test the functionality of the ASEPS on a Mars-like terrain. This environment is available in our Human Interactive Robotics Lab at California State University, Fullerton (see Figure 11).

Figure 11. Testing the rover platform on "Planet Mars" environment

Lab Project 12: Joint Failure Analysis and Plans for Recovery of the Robotic Arm-Rover System
The last part of the lab sequence is closely related to the faculty on-going research on developing novel techniques for the failure recovery of rover arm systems, i.e. how to continue the mission if a particular joint actuator of the robotic arm fails [17-18]. The goal of this lab is to present to the students a recovery strategy for an arm mounted on a mobile platform to achieve its mission in the face of an actuator failure. This strategy reconfigures the arm-platform system using degrees of freedom that exist in the system but are locked during arm movement. These degrees of freedom are the position of the base of the arm achieved by moving the rover, and the position of the wrist of the end-effector relative to the tool frame, which is fixed by the grasp location. By obtaining different recovery strategies for the different actuator failures, the students are expected to derive results and show that it is possible to identify base and grasp locations such that the failed robot can achieve the specified task, despite the failed joint.

Preliminary Results on the Effectiveness of the Learning Environment

The first eight Lab Projects were presented to the class during Fall 2013 semester, in the form of two major team activities: Mechanism Analysis, covering main parts of Lab Project 1 through Lab Project 4 and Design Challenge, covering Lab Project 5 through Lab Project 8. The students had to work in small teams of maximum three. As part of the learning process the students were notified that they should work without direct faculty assistance.

Anonymous survey questions (see Appendix A and Appendix B), based on the project specific goals, outlined in the beginning of the paper, were performed. The questions were related to the effectiveness of the two activities, based on students' perspective. Forty-eight students completed the survey. Table 1 shows the average learning outcomes from the two activities, based on student perception on a scale from 1 (poor) to 5 (excellent). As expected, the student learning outcomes were higher at 4.38 out of 5 for the Design Challenge, versus 4.1 out of 5 for the Mechanism Analysis (see Table 1). This is obviously because the Design Challenge, although more complicated, was specifically designed to build up on the first activity, giving the students the opportunity to explore and learn more. Table 1 also shows the top and bottom three scored questions, based on student perception. The Mechanism Analysis project revealed areas that the students did not feel comfortable with, such as "ability to take decisions and defend them". However, this area appears to be among the top scored questions for the Design Challenge activity, which implies the faculty's efforts in emphasizing critical thinking and intellectual growth throughout the semester. The top scored question for the Mechanism Analysis was "make gains in hands-on activity in analyzing a real-world mechanism", while the lowest scored question for the Design Challenge was "ability to design a real-world mechanism". We hypothesize that the more students learn about analysis and design and the deeper they get into the material, the more they understand how much more knowledge they need to be able to solve the problem. It is not quite easy to make any conclusion as to which of the project labs revealed more positive qualities. However, the results in the last column of Table 1 show clearly that the two different activities complement each other and bring to successful results. The faculty assumes that in future, when the students are presented with the rest of the lab series, this pattern will continue.

Table 1. Learning Outcomes, Based on Students' Perception: Preliminary Results

Major Activity	Top Scored Question	Lowest Scored Question	Average Learning Outcomes (from 1 to 5)
Mechanism Analysis: Lab Project 1 to 4	Make gains in hands-on activity in analyzing a real world mechanism	Ability to take decisions and defend them	4.1
Design Challenge: Lab Project 5 to 8	Ability to take decisions and defend them	Ability to design a real mechanism	4.38

The next step was to assess the desired student learning outcomes, from the faculty viewpoint, outlined in the beginning of the paper. In an effort to get some ideas on enhancing the projects in future, as a part of the survey, the students were asked to identify three questions (see Appendix A and Appendix B) that they were asking themselves, while working on each project [19]. Next, the students' questions were classified into three major groups, according to the three desired outcomes: *critical thinking, responsibility for one's own learning* and *intellectual growth*.

The *critical thinking*, was assessed by the number of students' questions with regard to their interest in analyzing data, evaluating alternative solutions, taking critical decisions, and communicating design ideas. Examples of the student question from this category are: *How does geometry affect the wheel travel?, How can we minimize overall mass and keep the rover stable?, How can we increase the range of motion of the suspension?, Can shock absorbers be implemented into the design?, At what point would too much range of motion of the rover create instability?*

The comparison in *students' responsibility for their own learning* was assessed by the number of student's questions regarding their desire to learn more, be successful and look for additional sources, out of the class. Examples of the student question from this category are: *Is there any way I can improve my skills, i.e. read more on-line, books, etc. to be able to do successfully my project?, How can I make sure that I am following the right procedure to solve the problem?, Where can I find additional sources to help me better understand the project?*

The *intellectual growth* was assessed by the number of student questions regarding their ability/desire to propose improvements to a design, to find out the relationships between different concepts and defend their design decisions. Examples of the student question from this category are: *How may I get a good performance out of my design?, How will our model compare to real world models that are constructed to achieve similar design constraints?, How can I make my design better?, How do I layout my design and what alternatives do I have?, How can I maximize the climbing ability of the rover?* The results are shown in Table 2.

Table 2. Comparison in Critical Thinking, Responsibility for One's Own Learning and Intellectual Growth between the Two Projects, based on Student's Questions: Preliminary Results

Major Activities	Number of Questions, related to *critical thinking*	Number of Questions, related to *responsibility to ones' own learning*	Number of Questions related to *intellectual growth*
Mechanism Analysis: Lab Project 1 and Lab Project 2	29	7	21
Design Challenge: Lab Project 3 and Lab Project 4	41	26	35

Given the difficulty of carrying out a clean and conclusive comparative study, the best we could do is to look at the results to see if any robust generalizations can be inferred. Forty-eight students participated in the Survey. From the 144 students' questions, 57 questions from the Mechanism Analysis and 102 questions from the Design Challenge projects seemed to comply with the three desired outcomes. Most of the students' questions (70) were related to critical thinking, fifty-six to intellectual growth and only thirty to responsibility to one's own learning. A simple comparison between the two projects shows that responsibility for one's own learning was the category that improved the most. Based on comparison between the average students' grades and the average learning outcomes, for each project, Table 3 reveals a certain *transfer of knowledge* from the first to the second series of projects. For the short period of about a month and a half (between the end of the first and the end of the second project), the students' grades on project content and presentation increased from 94.59 to 95.85 out of 100. Therefore, it seems that inductive methods are efficient not only *for learning new tasks*, but also in *transferring learned skills to tasks of greater difficulty.*

Table 3. Learning Outcomes, from both Projects Reveal Transfer of Knowledge: Preliminary Results

Major Activity	Average Learning Outcomes (from 1 to 5)	Students' Grades on Project Content and Presentation (out of 100)
Mechanism Analysis	4.1	94.59
Design Challenge	4.38	95.85

Finally, Table 4 compares the instructional demands imposed by the proposed lab project approach and the conventional teaching approach (combined lectures and small projects) from the faculty viewpoint, on a scale from 1 (small), 2 (moderate), 3 (major). Table 4 shows that preparing and performing the outlined lab projects, require a heavier commitment in faculty time and resources in comparison to the conventional teaching techniques. The instructor's involvement in the lab development is major. Moreover, the lab projects, which have a direct relation to the class curriculum, are based on faculty on-going research and have been developed such that each of them builds upon the previous. Most importantly, the last column of Table 4 related to student resistance, which was notified by the faculty simply from the students' interest and involvement in the projects, shows that the students enjoy working on hands-on real world problems. Ultimately, isn't producing graduates with enhanced critical thinking, responsibility for their own learning and intellectual growth, capable of analyzing and designing real world products the main goal of engineering education?

Table 4. Instructional Demands Imposed by the Proposed Lab Project and the Conventional Teaching Approach, based on the Faculty Viewpoint

Method	Resources Available to Stud.	Planning Time	Instructor's Involvement	Direct Relation of the Project to the Class Curric.	Student Resist.
Proposed Lab Projects (one lecture, one lab project per week)	Real-world devices	Major	Major	Major	Small
Conventional (lectures, homework and small projects)	Internet	Moderate	Moderate	Moderate	Moderate

Impacts and Future Directions

There has not been a great deal of research done on the effectiveness of research in undergraduate engineering classes and labs in particular. The challenges provided by inductive methods and, specifically, incorporating faculty on-going research in education are a great way to motivate students, encourage them to adopt a deep approach to learning and serve as precursors to intellectual development.

The lab projects, presented in this paper are developed specifically for mechanical engineering students, but could be easily transferred to multidisciplinary teams of electrical and mechanical engineering students. The labs aim to take the study of engineering design to the next level by incorporating faculty on-going research into the educational process, to motivate the undergraduates with research and applications to real-world problems thus prepare them for their senior capstone design class. The students work in multidisciplinary environments, take the theoretical ideas and implement them. As a result, the students are expected to not only understand the main challenges in mechanical design and analysis, but also to comprehend how the ASEPS units are assembled, what types of functions can be done by these rover-arm platforms and propose possible innovative ideas. Our preliminary results show that presenting a number of different projects, which complement each other, brings to successful results. For the limited time of one semester, the results show students' improved critical thinking, taking more responsibility for their own learning, as well as intellectual maturity.

It is important to note that the lab-based alternative to other undergraduate research engagements is novel and provides interesting experiences for the students. Despite the fact that the lab sequence was specifically concentrated on design and control of a rover-arm platform, our future plans involve incorporating the current model to the development of a Human-Robot Interaction laboratory sequence based on faculty research, where students will be presented to experimental work with motion capture systems and other sensor-based devices to obtain human biomechanics data and then use it in the design and control of different assistive devices.

Acknowledgements

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Appendix A: Survey Questions

As a result from the Mechanism Analysis (MA) activities in what extent did you make gains in:
1. Hands-on activity in analyzing a real world mechanism
2. Ability to clearly describe the device and its operation
3. Ability to describe the science and engineering principles
4. Ability to present data, calculations and results from the analysis
5. Ability to asses the design and propose possible ideas for improvements
6. Ability to identify additional work that is needed to refine the results
7. Ability to take decisions and defend them
8. Ability to analyze a real world mechanism
9. Share at least three questions that you were asking yourself while working on the MA activities
10. Additional Comments

Appendix B: Survey Questions

As a result from the Design Challenge (DC) activities to what extent did you make gains in:
1. Solving real world problems without direct assistance
2. Working efficiently with others
3. Ability to think through a problem with specific constraints
4. Ability to develop models which help you to communicate and better understand your ideas
5. Ability to asses the performance of your design, based on task objectives
6. Ability to identify additional work that is needed to refine your results
7. Ability to take decisions and defend them
8. Ability to design a real world mechanism
9. Share at least three questions that you were asking yourself while working on the DC activities
10. Additional Comments