The Mechanical Engineering Capstone Design Experience at Union College

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Abstract

Design of Mechanical Systems (MER-144) is a project-oriented course that provides a capstone design experience for the mechanics area of the mechanical engineering curriculum at Union College. Choosing an appropriate design project for this course, one that integrates all of the required pedagogical elements, is always a challenge. This year, students enrolled in MER-144 were asked to design a walking robot to compete in the SAE Walking Machine Challenge (part of the SAE Collegiate Design Series). This proved to be a very appropriate project vis-à-vis the course objectives and outcomes, particularly with respect to developing an ability to practice the techniques, skills, and modern engineering tools necessary for engineering practice.

By referring to specific examples from the student design projects, this paper describes how the various course objectives were successfully met. In addition, certain criteria for choosing an appropriate design problem are discussed.

Introduction

The mechanical engineering curriculum at Union favors a hands-on approach to engineering education whereby theoretical analysis is reinforced by laboratory exercises and design experiences. In fact, the program features two senior level capstone design courses. *Design of Thermo-Fluid* Systems (MER-160) applies optimization techniques and cost analysis to the design of thermal/fluid processes and systems. The second design course, *Design of Mechanical Systems* (MER-144), is a project-oriented course that provides a capstone design experience for the mechanics area of the mechanical engineering curriculum.

This paper focuses on the latter and specifically addresses the question of selecting an appropriate design project that is consistent with the course objectives and outcomes. The design project is the single most important component of the course and has a direct impact on several of the course objectives, namely:

- The ability to carefully analyze a design problem and brainstorm possible solutions.
- The ability to design, analyze (kinematics, dynamics, stress) and model an engineering system as well as the ability to apply the appropriate engineering tools including Computer-Aided Design (CAD), Finite-Element Analysis (FEA), and motion analysis.
- The ability to apply the basic principles of “Design for Manufacture and Assembly”.
- The ability to prepare a professional engineering drawing package describing a complex engineering system.

These objectives relate directly to ABET program outcome "k", i.e. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Design Requirements

This year, students enrolled in MER-144 were asked to design a walking robot to compete in the SAE Walking Machine Challenge™ (part of the SAE Collegiate Design Series). With respect to detailed design specifications, students were given a copy of the SAE Walking Machine Challenge rules which are available online at:

http://www.sae.org/students/walkrule.pdf

The only additional specifications were budgetary. Students were instructed not to exceed $2500.00 for all purchased components and raw materials. Since labor was to be supplied by the engineering machine shop at Union College, students were asked to familiarize themselves with the capabilities of the shop and design accordingly.

SAE Walking Machine Challenge™

In brief, students participating in the SAE Walking Machine Challenge™ must design a "walking" robot which competes in six events:

1. The *Dash* demonstrates the speed of the walking machine over a straight course.
2. The *Load Retrieval Event* demonstrates the walking machines' capacity for carrying a useful load of between 10 and 60 kg.
3. The *Slalom Event* is designed to assess the manoeuvrability of the walking machines through a series of tight turns and narrow gates.
4. The *Trip Wire* challenge consists of having the walking machines traverse the competition surface while stepping over and not touching two trip wires placed 15 cm above the ground and 15 cm apart.
5. The *Object Seeking Event* involves locating and picking up a wooden block which is placed somewhere on the competition surface and then returning to the starting box.
6. The final, most difficult event is the *Endurance and Obstacle Challenge* which tests the endurance and manoeuvrability of the walking machine in an unstructured environment. The precise layout of the course is determined by the organizing committee and is unknown to the participants prior to the event. As a general guideline, obstacles can not exceed 200mm in height.

For the purposes of the competition, a walking machine is defined "*as a mobile machine supported discontinuously and propelled by articulated mechanisms ("legs"). Each leg must have one or more joints or hinges by which is moves relative to ALL other legs and the frame.*" In addition, the walking machine must be capable of fitting through a one meter square opening on a flat floor and the power source must be carried onboard. The walking machines may be autonomous or teleoperated (i.e. manually controlled), however, the scoring formula heavily favours autonomous machines. A participant's score is based on an evaluation of the design by a panel of judges and by how well the machine performs in the six events described above.

Course Schedule

Union College operates on a trimester system, consequently *Design of Mechanical Systems* (MER-144) is limited to a ten week term. The lecture portion of the course concentrates on selected topics directly related to the design of mechanical systems that are either not covered elsewhere in the curriculum or that need to be reinforced. These topics include actuator selection and sizing (electric, pneumatic, hydraulic), power transmission (gears, belts, pulleys, chains), designing with standard mechanical components (bearings, bushings, shafts, keyways, fasteners), and Computer-Aided Engineering. The laboratory sessions are devoted almost exclusively to the design project.

WEEK	LECTURE TOPIC	LABORATORY EXERCISE PROJECT MILESTONE
1	Introductory Remarks, Presentation of Design Project	Presentation of Design Requirements
2	Engineering Design Tools: CAD, FEA	Preliminary Brainstorming Session and Team Selection
3	Engineering Design Tools: Motion Analysis, Animator	Preparation of Initial Concepts for First Engineering Design Review
4	Actuator Selection and Sizing: Servo and Stepper motors	**First Engineering Design Review**
5	Actuator Selection and Sizing: Fluid Power Actuators	Reorganization of Teams as a Result of Design Review
6	Drive Train Design: Gears	Detailed Design of Prototype: Kinematic, Dynamic and Stress Analysis
7	Drive Train Design: Belts, Chains	Detailed Design of Prototype: Kinematic, Dynamic and Stress Analysis
8	Analysis of Shafts, Keys and Couplings	**Second Engineering Design Review**
9	Screws and Fasteners: Bolted Connections	Finalization of Design and Preparation of Engineering Drawing Package and Final Design Report
10	Bearings, Clutches and Brakes	**Third Engineering Design Review**

Table 1: Course Schedule for MER-144

Engineering Design Reviews

As illustrated in the course schedule above, the project milestones culminate in formal engineering design reviews. These reviews serve several purposes. They help keep the students on schedule by providing deadlines at regular intervals. In addition, they provide an engineering review experience similar to what they may one day experience in engineering practice. In order to ensure this, two reviewers were recruited from local industry. Both were senior engineers who had participated in many design reviews over their careers.

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During the first class a survey was conducted to determine the skill level of each student in several relevant areas; e.g. Computer-Aided Design (CAD), Finite-Element Analysis (FEA), Manufacturing Processes, etc. The students were subsequently divided into four groups of four students each. An effort was made to ensure that the groups were balanced in terms of technical expertise. The next two weeks were spent analyzing the specifications (i.e. the rules), reviewing existing designs and brainstorming possible solutions. Each group was then asked to prepare a 5 to 10 page memorandum describing their most promising concept as well as their design philosophy (i.e. the strategy for winning the competition). These memos were distributed to the reviewers by E-mail prior to the first engineering design review.

All the submissions included a preliminary CAD model of the design. A typical example is illustrated below.

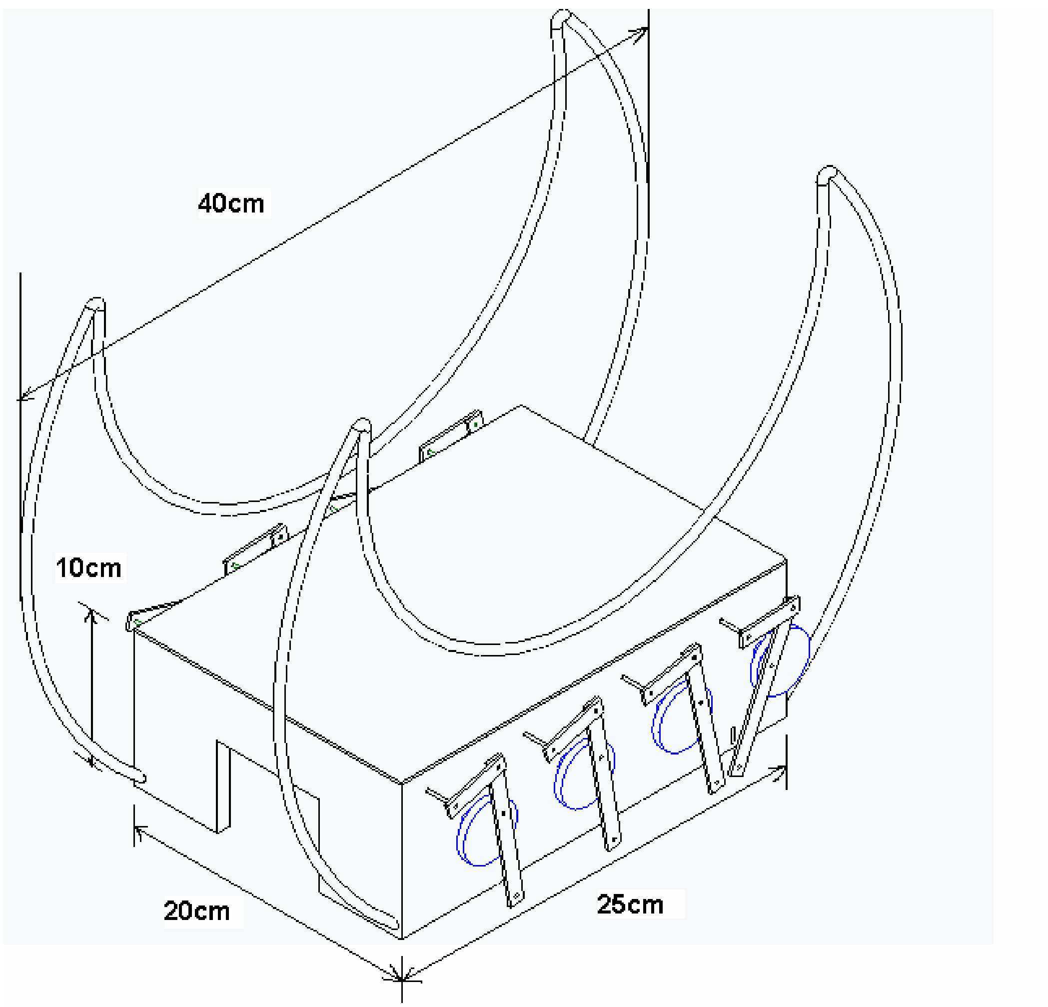

Figure 1: A typical initial concept drawing.

First Engineering Design Review

After the first design review, the mandate of the various teams was redefined based on the comments provided by the reviewers. Three of the designs employed similar "tractor" units designed exclusively for speed on flat terrain. Figure 1 illustrates a typical tractor design. Clearly the tractor unit alone is incapable of clearing obstacles. Consequently, all three teams proposed secondary systems for dealing with obstacles, e.g. rolling over obstacles, “jumping” over obstacles or carrying a light-weight bridge-like structure to lift the tractor over obstacles. In view of the similarities between the proposed tractor designs, the decision was made to have one group concentrate exclusively on the tractor design (the Tractor Group). Two groups concentrated on two different approaches to clearing obstacles (the Jumper Group and the Bridge Group). The fourth group (the Spider Group) proposed a more conventional six-legged design that was large enough to step over obstacles. They were permitted to continue work on their proposed design.

The reorganization of the various groups had an added pedagogical advantage. Since the Tractor Group was now designing a subsystem for both the Jumper Group and the Bridge Group, the required interaction between the various groups greatly increased. Regular meetings between the groups were now necessary to discuss problems related to interfacing the various subsystems.

Second Engineering Design Review

Following the reorganization of the groups, approximately four weeks were spent on detailed design and analysis through the application of a variety of engineering tools. The minimum requirements for the second design review were as follows:

1. Kinematic/dynamic analysis of the walking mechanism
2. Stress analysis of all critical components
3. Actuator selection and sizing
    - Cylinders, valves, tanks
    - Motors, batteries
4. Complete engineering drawing package
    - Detailed drawings of every manufactured part including dimensions, tolerances in accordance with standard engineering practice, section and detailed views and notes for manufacturing
    - Assembly drawings including bill of materials for both purchased and manufactured parts
    - Exploded views as required

Third Engineering Design Review

The final two weeks were spent finalizing the detailed engineering drawing package, preparing the final design report and addressing all of the concerns of the reviewers. For the third and final design review, students were expected to cover the following topics:

1. An overview of the kinematic, dynamic and stress analysis.
2. A complete performance estimate including speed, load carrying ability, walking repeatability, endurance, turning ability and an itemized weight analysis.
3. A critical design evaluation that answers the following questions:
    - Are there any manufacturing problems associated with the proposed design?
    - Is the manual control of the machine likely to be a challenge?
    - Is autonomy difficult to implement?
    - Are there any safety issues and have they been addressed?

- What is the likelihood of success in the competition?
- What were the problems encountered during the design process?

In general, there were very few uncertainties or omissions in the designs by the date of the third design review and the comments of the reviewers were overwhelmingly positive.

Integration of Modern Engineering Tools

As stated in the introduction, the primary objective of MER-144 is to develop an ability in the students to use the techniques, skills, and modern engineering tools necessary for engineering practice (i.e. ABET program outcome “k”). Solidworks® was used exclusively in the preparation of the 3D models and engineering drawings. Structural analysis based on the Finite Element Method (FEM) was realized using COSMOS/Works, a design analysis software package, while COSMOS/Motion was used for the kinematic/dynamic analysis of the various mechanisms. Both packages are fully integrated into SolidWorks and operate on the same 3D models that are used to generate the detailed engineering drawings.

This integrated approach to engineering design is becoming more prevalent in industry where engineers are increasingly responsible for much of the analysis done on their own designs[1]. Although mechanical engineering students at Union College are exposed to CAD and FEA in a number of courses throughout the undergraduate curriculum, MER-144 focuses on integrating design and analysis. If a part or assembly doesn’t meet specifications, students are expected to modify the CAD model and analyze it again to see if the changes helped. A typical example of this integrated approach to engineering design is presented below. Figure 2 is an isometric view of Team Jumper’s final design while Figure 3 illustrates the results of the finite element analysis on one of the critical components.

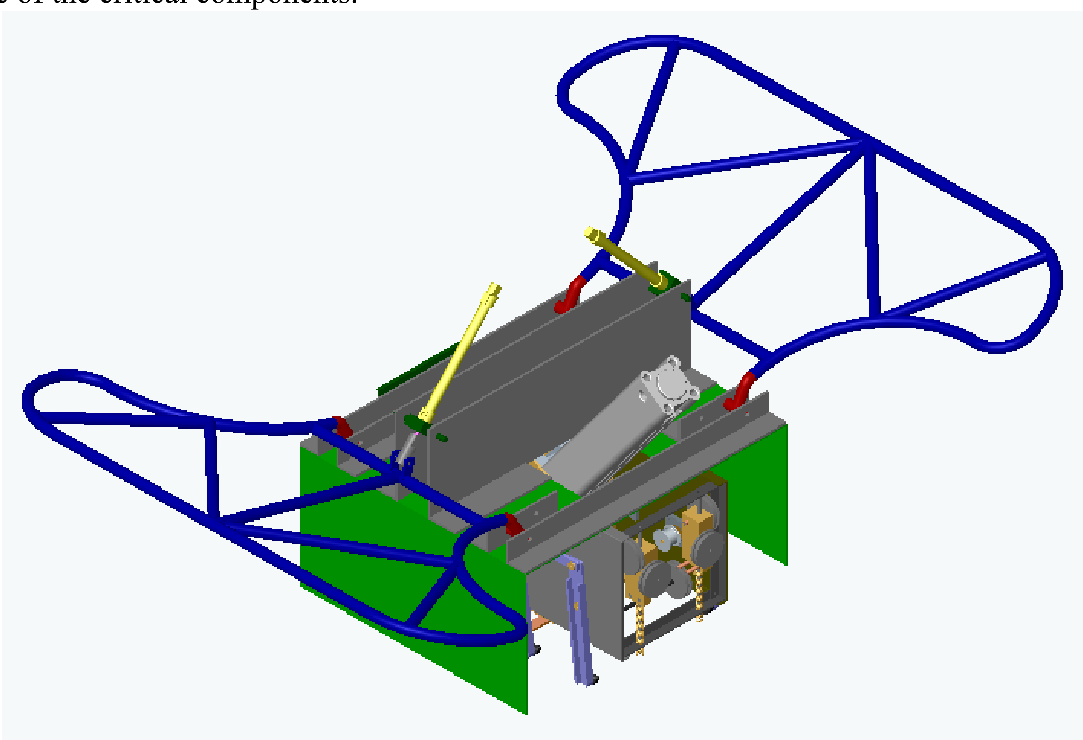

Figure 2: Isometric view of Team Jumper’s final design.

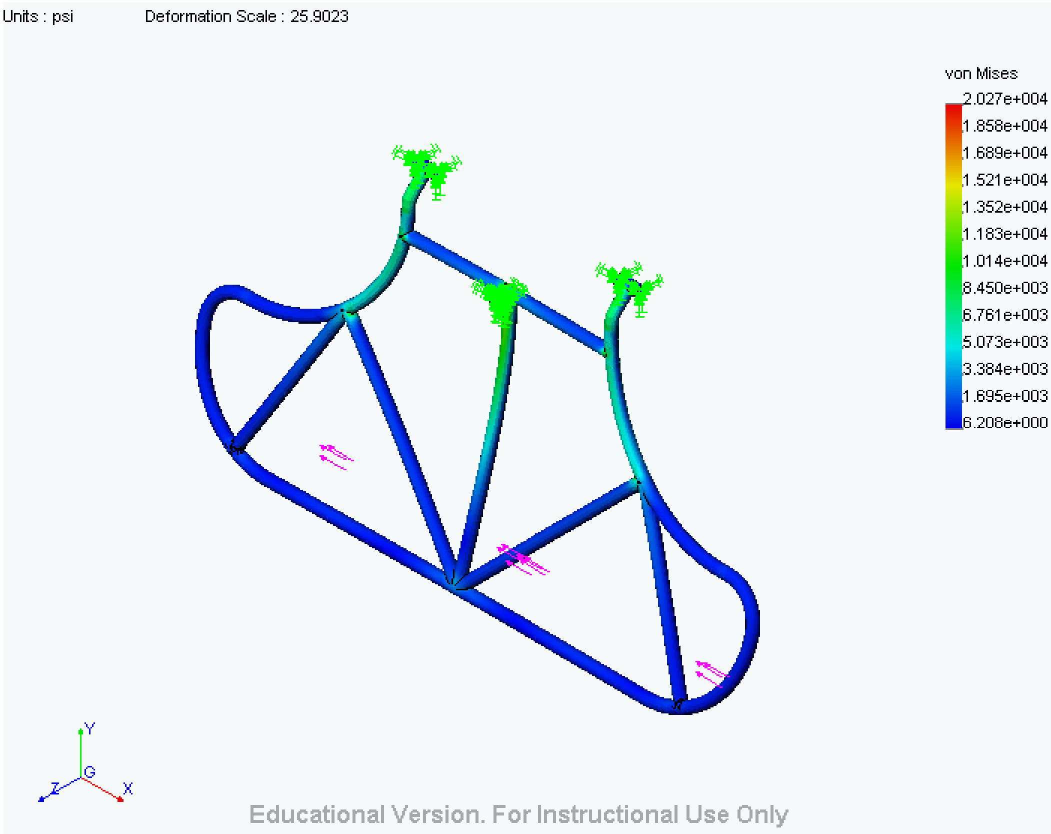

Figure 3: Finite Element Analysis of landing arm.

Lumped Parameter Modeling of Dynamic Systems

An additional engineering tool that was introduced into MER-144 was the modeling of dynamic engineering systems by means of the lumped parameter method. System models were typically solved through the use of MATLAB/SIMULINK®.

Team Jumper made extensive use of lumped parameter modeling. Their design incorporated a pneumatically actuated foot for propelling the walking machine over obstacles. The dynamics of this subsystem were modeled using MATLAB/SIMULINK and the acceleration/deceleration results were used to estimate the loading for the finite element analysis. Figure 4 illustrates a simplified block diagram of Team Jumper's lumped parameter model. Figure 5 shows the simulated trajectory of their walking machine.

Selection of an Appropriate Design Project

The design of a walking robot has proven to be a very appropriate project for *Design of Mechanical Systems* (MER-144) vis-à-vis the course objectives and outcomes.

In the majority of design competitions sponsored by the SAE (e.g. Formula SAE, Mini Baja), the top entries are very similar, i.e. there appears to be a winning formula which most teams try to adhere to. In the case of the Walking Machine Challenge, winning entries from year to year vary significantly both in size, complexity and design philosophy. Since the range of design alternatives is so large, students tend to employ greater creativity and are not as influenced by previous winning designs.

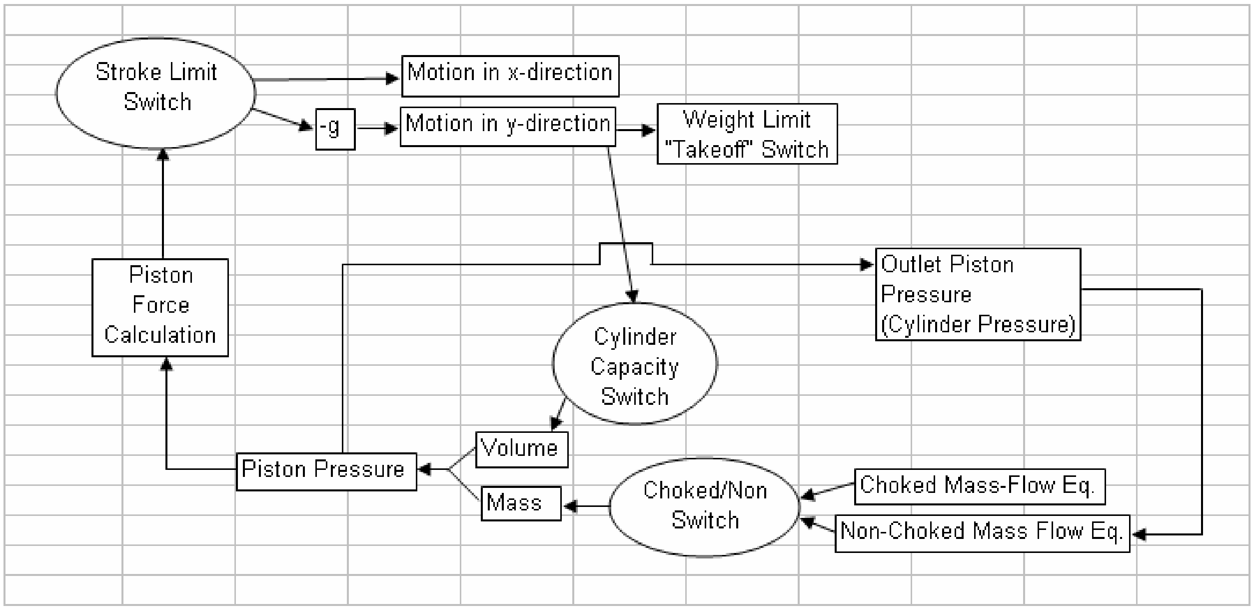

Figure 4: Simplified SIMULINK model of jumping subsystem.

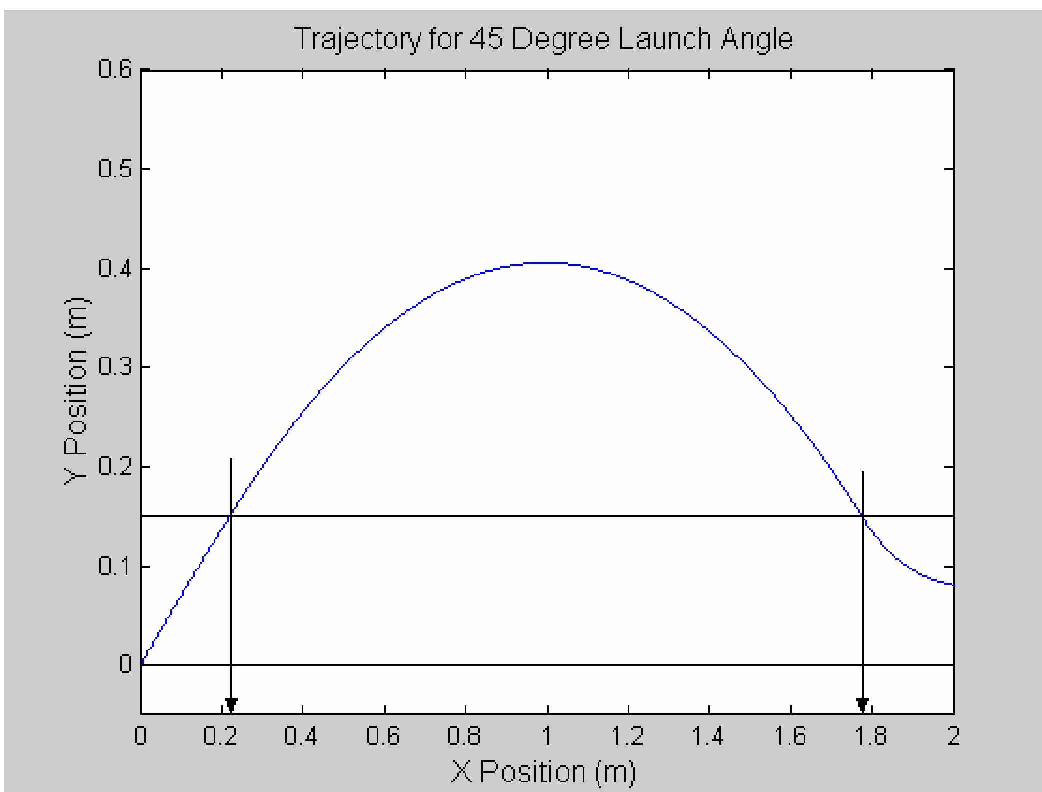

Figure 5: Simulated trajectory of Team Jumper's design.

The range of design alternatives also facilitates the integration of a variety of topics such as the selection and sizing of electrical, hydraulic and pneumatic actuators into the course curriculum. The mechatronic nature of the design experience facilitates the integration of topics including system dynamics, sensors and controls. In addition, this particular design problem is extremely well-suited to the application of contemporary engineering design and analysis tools; e.g. CAD, FEA, motion analysis.

Assessment of Course Objectives and Outcomes

In addition to the customary teaching evaluations, students were required to submit an assessment essay as part of their course portfolio at the end of the term. Specifically, the students were asked to comment on whether or not the course successfully met the course objectives and outcomes as outlined in the course syllabus. Several themes and conclusions were cited repeatedly by the students. For the sake of brevity, only a few representative comments are cited for each theme.

- Design Experience:
  - "The most important aspect of this course was that it gave me a large amount of actual design experience."
  - "The course provided a complete understanding of an entire design process. This complete overview has not been provided in any other course."

- Team Work:
  - "Just like in the real world this class required a great deal of team work and team building. The fact that five different individuals, with various opinions, are brought together caused us to make many compromises… This process taught me a lot and built upon my team working skills, which I believe will help me in the future."
  - "The design project, first and foremost, developed the most important skill, team work. With other projects completed in previous courses team work was not as important to success."

- Introduction to Engineering Practices:
  - "The format in which the project was carried out was the greatest strength of the course. Using a panel of professors and industry representatives to judge our designs was a fantastic way of introducing us to the practices used in the real world."

- Familiarization with Modern Engineering Tools:
  - "On a more technical note, I re-learned SolidWorks and Simulink. On top of that, I learned how to use Cosmos in SolidWorks to do a stress analysis. Using these programs that are used in the real world as in-depth as we did was a very useful exercise."
  - "We had to use previous knowledge from various courses combined with new material learned in the lectures to analyze certain design criteria and develop a system that would conquer the tasks of the SAE Challenge. In doing this we used various computer packages such as SolidWorks, Cosmos, and Excel to both design and test models of potential machine parts. The project called for work in stress analysis,

motor sizing, hydraulic design, motion analysis, and couplers, as well as the completion of a full drawing package that could lead to the assembly of a fully functioning device."

- New Material:
    - "The topics covered during class lecture were new to most of the class… This was the first class where the manufacturing process was discussed. This was especially beneficial."
    - "My knowledge about hydraulic systems has greatly increased. I barely hand any previous understanding on the workings of hydraulics and pneumatics."

Discussion and Conclusions

The design of a walking robot to compete in the SAE Walking Machine Challenge has proven to be a very appropriate project vis-à-vis the course objectives and outcomes of MER-144 (*Design of Mechanical Systems*). This project-oriented course provides the main capstone design experience for the mechanics area of the mechanical engineering curriculum at Union College.

The project proved particularly relevant to ABET program outcome "k" (i.e. an ability to practice the techniques, skills, and modern engineering tools necessary for engineering practice). The project has the advantage of being inherently interdisciplinary in nature, the range of design alternatives is large which promotes greater creativity among students, and the cost of implementing a successful design is relatively low.

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Bibliographic Information

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Biographical Information

NICHOLAS KROUGLICOF joined the Mechanical Engineering Department at Union College in September 2000. Previously, he was a faculty member at the École de technologie supérieure in Montreal. He has taught and developed laboratories for a number of undergraduate courses relating to system dynamics and control, mechatronics, automation, and CAD. His research interests are in the areas of machine vision, intelligent sensors, and mechatronics.