AC 2007-2791: A REAL-WORLD EXPERIENCE USING LINKAGES TO TEACH DESIGN, ANALYSIS, CAD AND TECHNICAL WRITING

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A Real-World Experience using Linkages to Teach Design, Analysis, CAD and Technical Writing

Abstract

Most undergraduate students in mechanical engineering are comfortable using fundamental principles and closed-form equations to solve textbook problems that are well-defined and that have a unique answer, e.g. statics, dynamics and strength of materials. However, these same students are unsure how to apply these fundamental principles and closed-form equations the first time they are given the task of doing an engineering design of a system where the parameters are such that multiple solutions are possible. To give students a first exposure to a real-world product-development team-environment scenario, the design and analysis of linkages is used as the central topic to integrate engineering analysis, design, CAD, project management and technical writing into a semester-long design project. The students work in teams of four and take a loosely defined problem from conceptual design on paper to a virtual prototype and finally to a working prototype made in the machine shop. Each week's lecture material is reinforced with an applied hands-on lab and each weekly lab builds upon the progress of the previous labs. Weekly technical memos are submitted to document the progress of the project. Students learn how to make rational decisions as to when enough time has been spent on one aspect of the overall project and to make the decision to move on to the next step. One of the course outcomes is a one-inch thick notebook documenting the entire project, and this notebook can be used part of the student's portfolio to be shown to a prospective employer. This paper will present the structure of the course and student evaluations of how the organization of the course relates to the success in achieving the course outcomes.

Background

Engineering education has evolved from concentrating on teaching engineering science fundamentals to teaching students how to apply these fundamentals to design systems for real unstructured engineering problems. Teaching techniques should challenge, educate and promote innovative thinking from students. The lecture-based format of teaching which typically predominates in engineering education may not be the most effective manner to achieve these goals[1,2]. Constructivist learning theory asserts that knowledge is not simply transmitted from teacher to student, but must be actively constructed by the mind of the learner through real experiences[3,4]. It has been shown that students learn best with hands-on projects[5], and it is imperative that students be forced to attempt design problems where no direct, exact solution exists. Students must be allowed to experience problems that require them to formulate solutions to problems with no specific straight-line structure to the solution – they must learn how to "think outside the box"[6].

It is imperative that the students be actively involved in the entire learning process for full deeper appreciation of the material to be learned. "After two weeks, people generally remember 10% of what they read, 20% of what they hear, 30% of what they see, 50% of what they hear and see, 70% of what they say, and 90% of what they say and do."[7]. Clearly, the students need to drive the learning process and be "active" participants in their educational process.

One common approach to involve the students actively, for design classes, is to have the students do "paper designs" as a mechanism to “experience” the design process. While “paper designs” accomplish the task of integrating engineering science fundamentals into the course, these “paper designs” do not encompass the whole design process because they ignore the manufacturing step. As a result, a student can design a solution that looks good on paper, but ignores the set of problems that surface when making the product.

In most engineering classes that have design assignments, these projects are assigned like homework problems within a chapter in the textbook. An engineering topic is presented in class, and the students are assigned a design project that involves that topic. Then another chapter in the book is covered in class, and a design project is assigned for that chapter, and so on throughout the semester. While this approach of integrating fundamentals and design is better than not having any design content, many students lack the maturity to see any connection in the design assignments as the course progresses through the chapters.

At the University of Massachusetts Lowell, one mechanical design class uses an innovative approach to providing a very real engineering design scenario that includes design, fabrication, team work, reporting and scheduling all within the confines of one course to design a linkage mechanism for a specific task. This paper describes that approach.

Introduction

The first design experience that integrates mechanical engineering fundamentals occurs in the first semester of the junior year—Mechanical Design I—and is composed of a well connected set of hands-on tasks to teach the course concepts. This course uses the topic of linkages to teach students how to integrate the previously taught concepts of computer programming, mathematics, CAD, dynamics and communication skills in a semester-long design project. During the entire semester, all the lectures revolve about one major design project. The background material is discussed in the lecture portion of the class. The application of the concepts as they may be used in the "real world" is then related to the semester-long project. The students are given weekly “lab” assignments for applying the concepts to their semester design project. Each weekly design task builds upon the previous tasks, so the students can experience directly how each of the topics discussed in the lectures and applied in the project are connected to one another. The hands-on labs have been developed around the textbook[8] used in the class.

By the end of the semester, the students have developed multiple "paper designs", selected the “best” design using a decision matrix, used computer tools to analyze the design, made a set of machine-shop quality drawings, manufactured their design in the college machine shop, and bench-tested their design. The bench test verifies whether or not their final product matches the performance of the paper design, which was shown using virtual modeling to meet the performance specifications. Team building is also an important aspect of the class, and the students work in teams of four. Technical communication skills are honed as the team submits progress reports as each task is completed. A Gantt chart is used to mark the milestones along the way and introduce the students to project management. The students finish this course with a new appreciation for the many aspects of bringing a product from concept to working hardware in a preplanned time period. The class consumes on average 15 hours per week for each student to complete their respective contribution, as a result time management is another skill that is indirectly learned a result of the project.

Course Organization

The Mechanical Design I class is a 3 credit-hour class. All the students meet for two one-hour lectures each week with the course instructor. The students split into two groups and meet with a teaching assistant once a week in a two-hour lab. Each lab session has a typical enrollment of 24 students.

The weekly tasks associated with the design project are typically more than can be accomplished in a two-hour lab session, so the primary function of the time in lab with the TA is to help the students to understand the weekly assignment and to give the students guidance in successfully completing the assignment and in finishing the assignment on time. The students complete what they can in their two-hour lab and then distribute the work amongst the team members for completion on their own. The team then submits a technical report documenting the task outcomes the following week.

Project Description

Over the course of a semester, students (working in teams of four) will design a fourbar positioning linkage coupled with a fourbar Grashof driver linkage. Each team will be responsible for the design of the fourbar linkage and the selection of the fourbar Grashof driver linkage. The final design will be manufactured and tested, and each team will submit a final report describing the design and actual performance of the linkage system.

A total of nine lab reports will be written during the course of the semester. In addition to developing experience in a design project and working in a team environment, the students will develop technical communication skills.

Project Assignment

A component of the company's latest model all-terrain, all-weather, shockproof, self-priming bilge pump requires four spot welds as a final assembly operation. As shown in Fig. 1, the weld locations can be "paired up" because there are two common 2.756-in. spacings. With this pairing, two spots can be welded simultaneously, thereby reducing production time.

The unwelded component will be delivered to the welding station and automatically placed on a moving platform. The team must design this platform and its driving mechanism. Due to the cost constraints, the mechanism should be a linkage design. An example of a completed linkage design including the stationary electrode pair is shown in Fig. 2.

Requirements and Specifications:

1. The unwelded component will be placed onto the moving platform by a robotic positioner to ensure consistent and proper placement.
2. The platform will continue its motion to bring the weld locations A and B directly under the electrode pair. The platform must dwell for at least 1.5 seconds in this position to allow for the welding operation.
3. The platform will then move to bring locations C and D under the electrodes and again dwell for at least 1.5 seconds.

   Note: The two dwells need not be of exactly the same duration. The shorter one should be as close to 1.5 seconds as possible, while the other can be slightly longer.
4. The completed component is removed from the platform as it returns to its original position, where it receives the next unwelded component. The cycle repeats continuously.
5. All linkage "ground" pivot points must be located at least 2.953 in. from the electrodes (see Fig. 1).
6. The mechanism must be driven at a constant RPM from an electric motor.
7. Use the last four digits of your student ID number to determine what dimensions you should use for your individual design (see Table 1).

Table 1. Dimensions based on student ID number

SIDN1	X (in.)	SIDN2	Y (in.)	SIDN3	Z (in.)	SIDN4	θ (deg)
0-2	3.740	0-2	0.984	0-4	1.968	0-2	50
3-4	3.937	3-4	1.181	3-4	2.099	3-4	55
5-6	4.331	5-6	1.378	5-6	2.231	5-6	60
7-9	4.528	7-9	1.575	5-9	2.362	7-9	65

Each team must submit the following:

- A memorandum report for each lab. Each memo report is due by noon on the Friday of the week following the week that the lab was assigned. The lab report is to be written in MSWord and sent by email. The format and address for the email submission are described in detail on the course web site.
- A comprehensive project notebook, which is a compilation of the individual lab reports. Any technical and grammatical errors should be fixed in this project notebook. The graded reports should be placed directly behind the revised reports.
- A working prototype of your design constructed first of cardboard and finally a prototype made of aluminum with ball bearings.

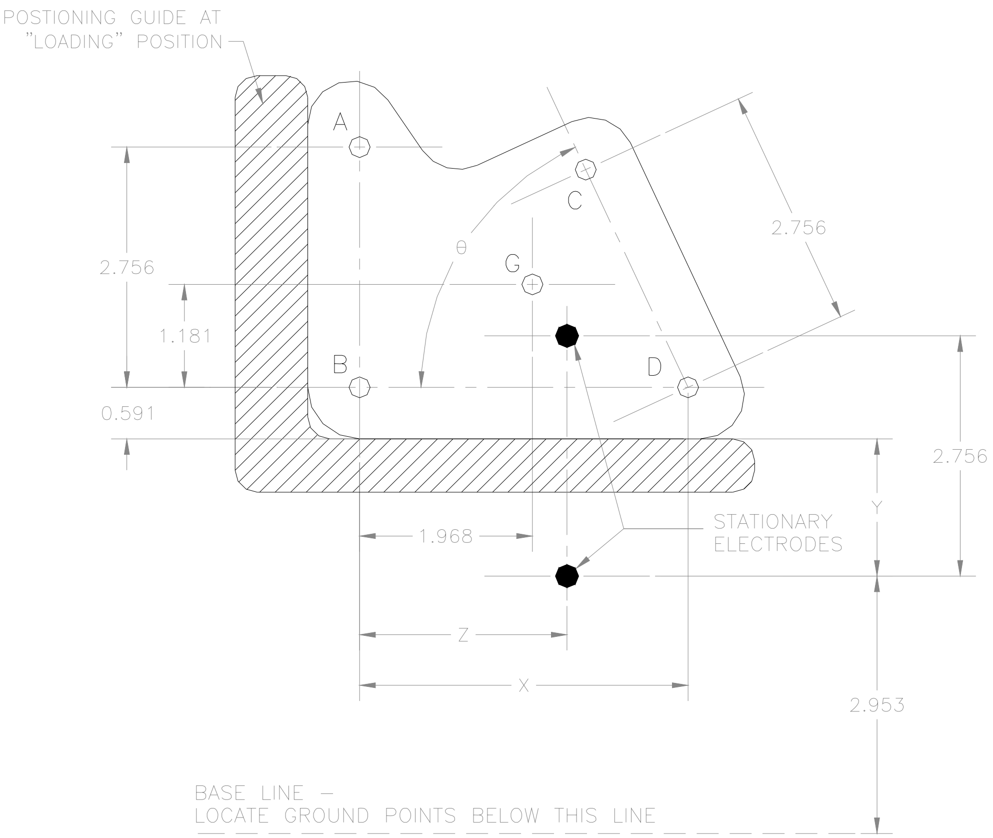


Figure 1. Project layout requirements – part is in the "loading" position (dimensions are in inches)

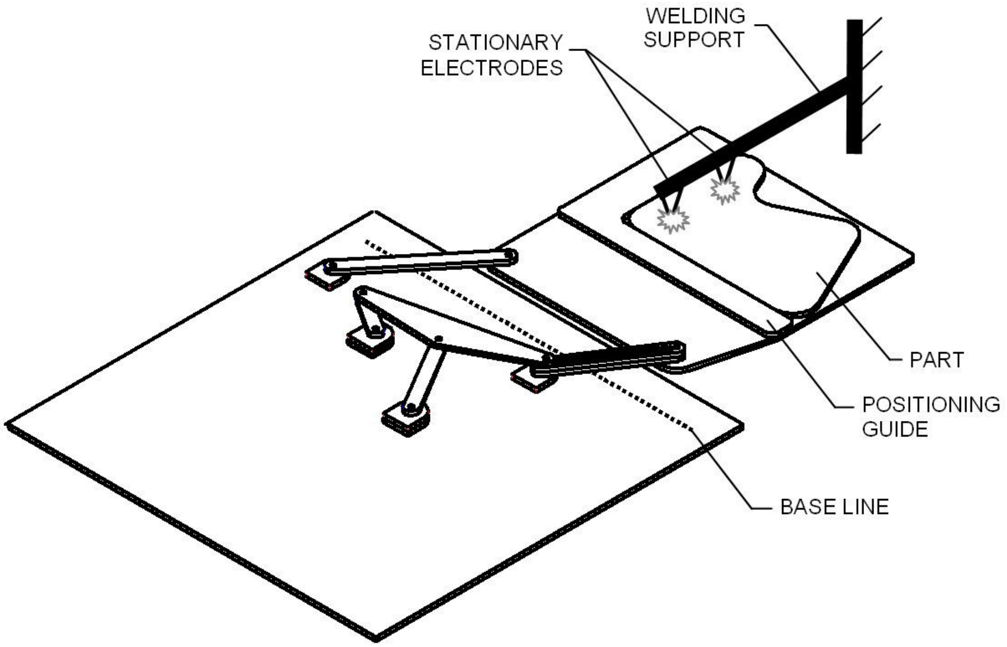


Figure 2. Complete linkage design example – part is in the first welding position

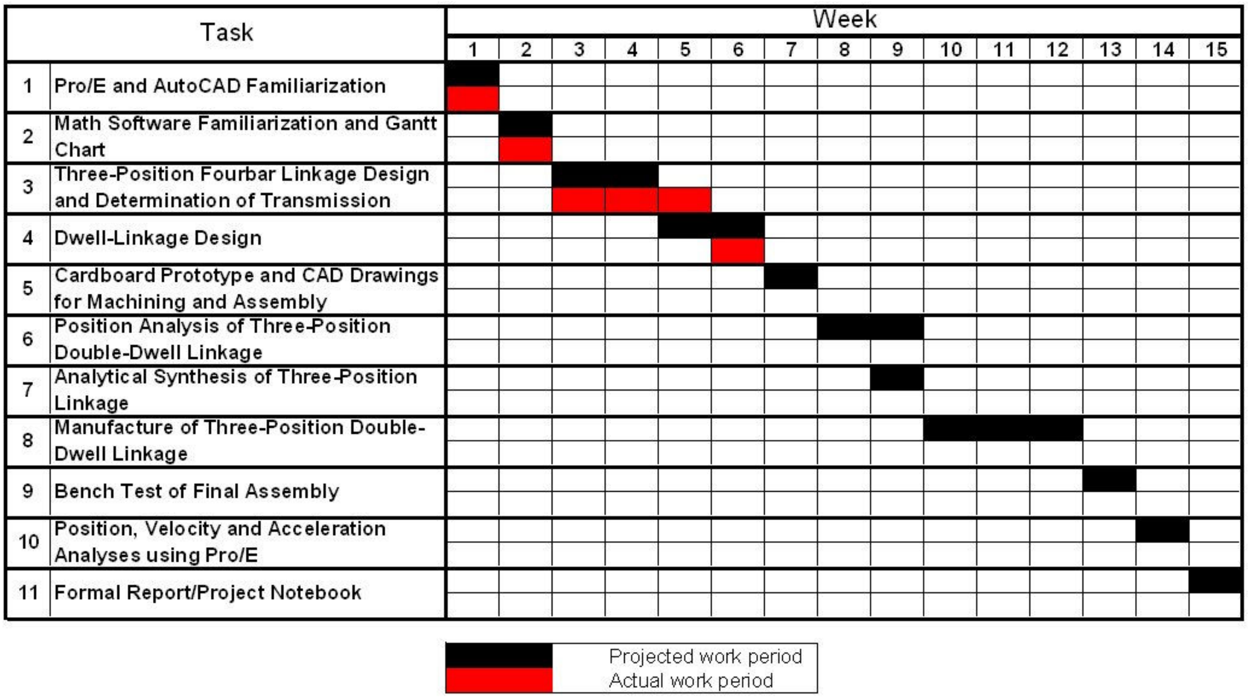
Summary of Project Tasks and Team Formation

The individual tasks required of each team are summarized in the Gantt chart shown in Fig. 3. As can be seen in the Gantt chart, the tasks associated with the design project are distributed in a continuous thread throughout the semester. Each team develops such a Gantt chart based on the dates given in the course syllabus and updates the chart as each task is completed. An updated Gantt chart is submitted as an appendix to each memo report to track the project milestones and acts as visual map to reinforce the connection of the course topics to one another. The Gantt chart also is an introduction to how to manage a project by planning tasks that need to be completed in serial and what tasks can be done in parallel to have a distributed workload over the time period while finishing the project on time.

Tasks #1 and #2 are done as individual technical reports. Students do not necessarily come to the course knowing any of the students in the class. Thus, the first two weeks is a time for the students to begin to meet others during the two-hour lab sessions and to force each student to be involved in all aspects of writing a technical memo report. Any weaknesses in technical report writing and formatting in MS Word are to be resolved in these first two labs. Furthermore, it takes essentially three weeks to cover enough material in the lectures to get the students to the point where they have enough background to start designing a linkage to satisfy the motion-generation aspect of the project. Commencing with Task #3, the memo reports are submitted as a team report, where the responsibilities of doing the technical work and the writing of the report are shared equally among the team members.

Rather than the course instructor or the TA forming the four-person teams, the students have the responsibility of forming the teams. This process of team forming gives the students the freedom to choose their coworkers for the term project and removes some of the student anxiety of having the final grade not solely in their control. This method of team forming also removes the potential for a student to rationalize their poor performance in the class on the teammates assigned to them by the instructor. Working in teams educates the students the advantages and disadvantages in having others contribute to the overall success of the project and about interpersonal dynamics. The teams approach also gives students that have felt a loose connection to their education before taking this course a sense of now being a member of a group.

Over a period of four years, team sizes of two, three and four were tried. It was found through experience that four is the optimum team size for this class. The work required to complete the tasks is more than two people can reasonably handle. While three persons on a team may be sufficient to do the work in a timely manner, this size team leads to the potential for two persons to gang up on the third person. Four people on a team makes for a practical workload for each student and for a reasonable number of reports to be graded thoroughly each week by the instructor.



Task		Week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Pro/E and AutoCAD Familiarization	■ 🟥														
2	Math Software Familiarization and Gantt Chart		■ 🟥													
3	Three-Position Fourbar Linkage Design and Determination of Transmission			■ 🟥	■ 🟥	🟥										
4	Dwell-Linkage Design					■	■ 🟥									
5	Cardboard Prototype and CAD Drawings for Machining and Assembly							■								
6	Position Analysis of Three-Position Double-Dwell Linkage								■	■						
7	Analytical Synthesis of Three-Position Linkage									■						
8	Manufacture of Three-Position Double-Dwell Linkage										■	■	■			
9	Bench Test of Final Assembly													■		
10	Position, Velocity and Acceleration Analyses using Pro/E														■	
11	Formal Report/Project Notebook															■

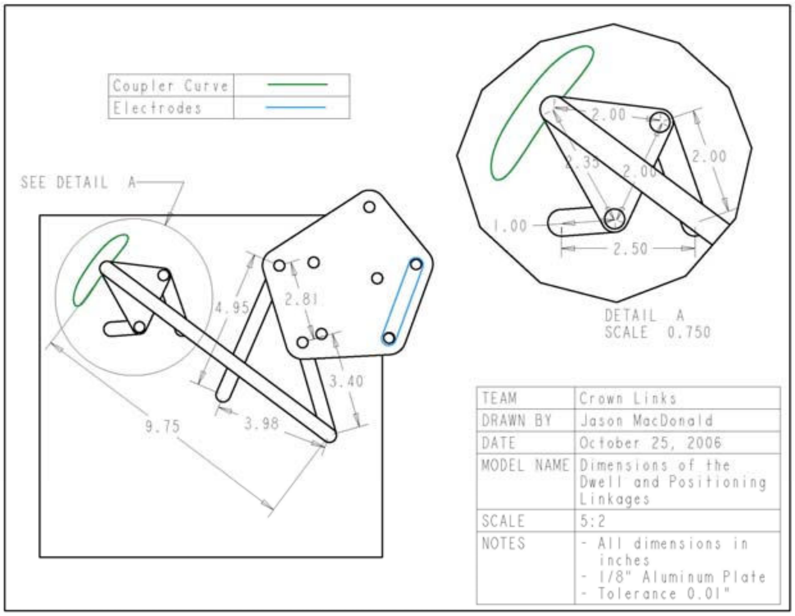
■ Projected work period
🟥 Actual work period

Figure 3. Example of a Gantt chart for semester-project tasks updated through Week #6

Graphics Usage

The application CAD tools in the design project is a major component of the course. Pro/E is the "official" CAD package for the class. The Design Lab I class, which is offered in the second year, is the course in the curriculum where students are taught how to use Pro/E. Students are welcome to use any other CAD package, e.g. AutoCAD and SolidWorks, when they feel that an alternate package is more applicable to the design task being pursued and/or if they are more comfortable using another CAD package. However, the TA is only obligated to be prepared to give help in the "official" CAD package. CAD is used:

- To create the potential designs for achieving the three positions that the bilge plate must assume as it is "loaded" onto the platform by the robot in Position 1, then moved to weld in Positions 2 and 3 in Task #3
- To add a second fourbar linkage to achieve the two dwells and to do an animated kinematic analysis of the linkage in Task #4 (Figs. 4 and 5, respectively)
- To create a set of machine-shop quality drawings for assembly (Fig. 6) and for machining (Fig. 7) in Task #5
- To do a position analysis of the angle of the output rocker in Task #6
- To do position, velocity and acceleration analyses in Task #10



TEAM	Crown Links
DRAWN BY	Jason MacDonald
DATE	October 25, 2006
MODEL NAME	Dimensions of the Dwell and Positioning Linkages
SCALE	5:2
NOTES	- All dimensions in inches - 1/8" Aluminum Plate - Tolerance 0.01"

Figure 4. CAD drawing of the positioning linkage combined with the driving linkage

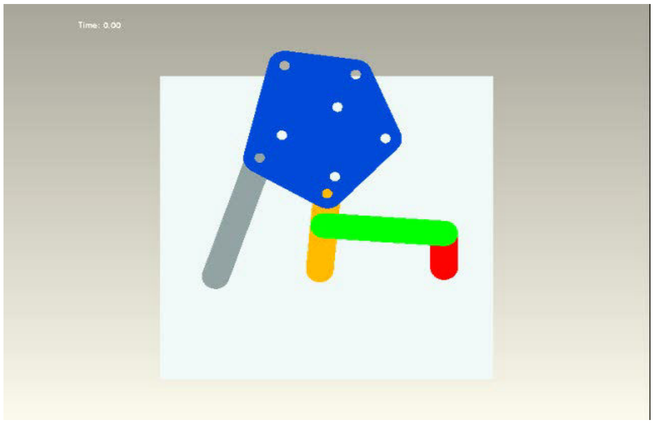


Figure 5. Screen capture of virtual animation

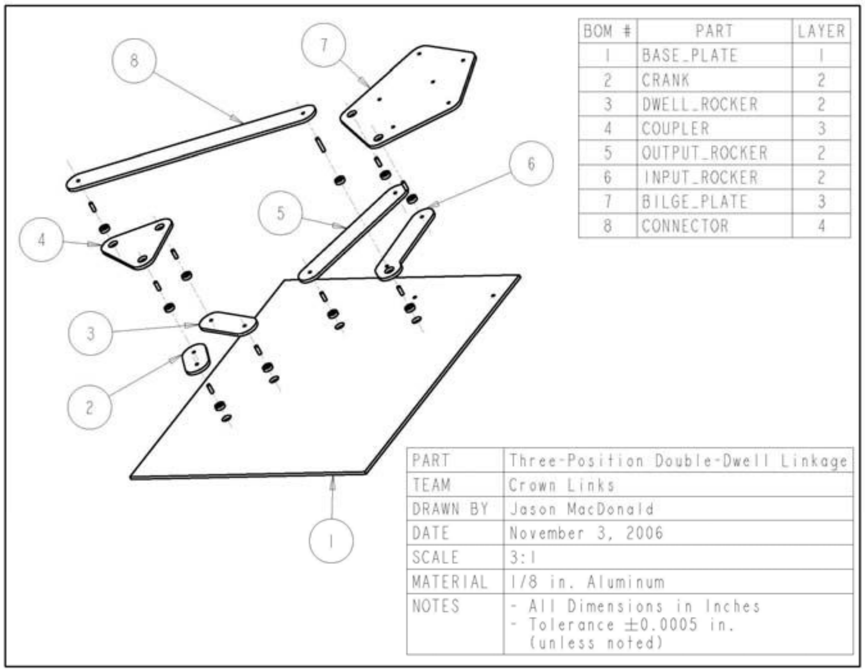


Figure 6. Exploded view of the linkage for assisting in the machine shop assembly task

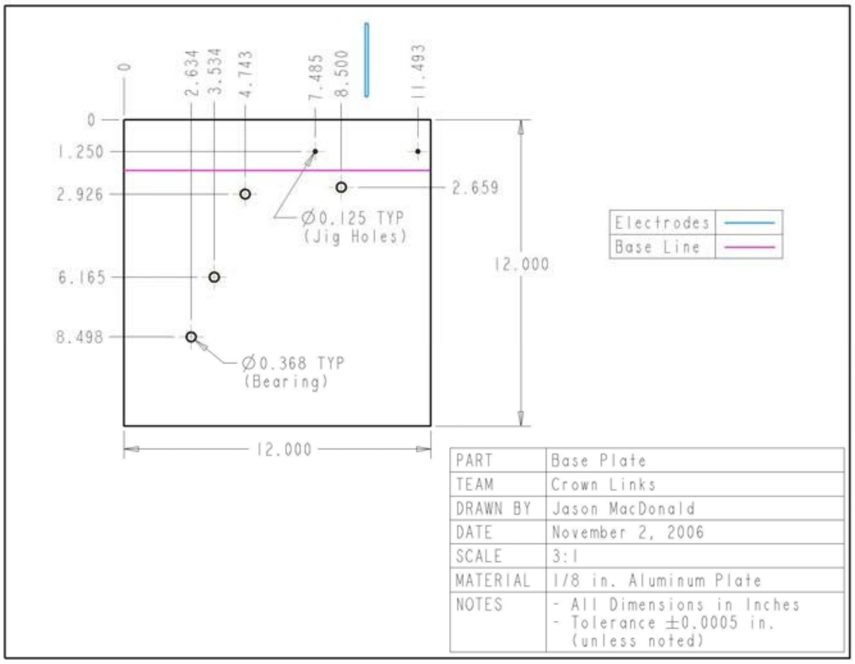


Figure 6. Base plate dimensioned for machining in milling machine

Examples of Student Designs

The matrix of dimensions given in Table 1 admits a potential of 256 different combinations of dimensions. This number of combinations gives a low probability of any two students in the class having the same design parameters or the same as a student that took the class in recent years. These 256 potential combinations along with the design constraints for the locations of the fixed pivots admit an infinity of possible designs. Fig. 4 shows 12 example linkages from the Fall 2006 offering of the class. Note that no two linkages are the same.

Fig. 4 Examples of 12 linkage designs from Fall 2006

Each student is required to design a linkage to satisfy the positioning needs based on their respective student ID number. Of the four different designs developed within each team, the team then chooses one to be used in Task #4, where a second linkage that will control the dwells is combined with the positioning linkage. Resource constraints for the purchase of materials and access to the machine shop do not admit the manufacturing of a prototype for each student. Thus, each student has to sell his design to the rest of the team. A decision matrix is used to assist in this choice.

Student Assessment

In-class "one-hour" exams can typically be used to assess student learning of the fundamentals. These exams can be a combination of true/false, short-answer and/or relatively simple calculations of closed-form solutions. Such solutions can be described as linear. In contrast, the assessing of student learning for real-world design scenarios cannot typically be packaged in "one-hour" exams because design is most often an iterative process. For this course, student learning is assessed using a combination of measures.

Progress Reports	35%
Project Notebook	15%
Midterm Exam	15%
Final Exam	15%
Homework	10%
Class Participation	10%
Total	100%

Technical Writing (Progress Reports and Project Notebook)

The assignments directly associated with the design project account for 50% of the course assessment—35% for the nine technical reports and 15% for the project notebook. The technical reports are intended to be written as memos documenting the progress of the assigned task. The reports are critically reviewed by the instructor for content, grammar, format, clarity and writing style to stress the importance of good communication skills in the work place. There is also a grade for the technical aspects of the respective reports. Typically the technical calculations in the reports are correct. However, the writing skills of the students are weak, and the attention to the formatting of tables and figures is lax. The teams are required to address all comments by the "reviewer" and revise each lab accordingly. The revised labs are then collated in a one-inch project notebook that is submitted in the last week of the semester. Revising the labs forces the students to learn from the mistakes that they made in their initial submission of the report.

The memo reports are intended to be written as though the students are working as a design team within a company, and the report is being submitted to their immediate superior, who may in turn cherry pick pieces from the report to compile his weekly progress report for his group to his superior. Because this is the first time that many of the students are being required to write reports that are critically evaluated and the students are inexperienced in knowing what to include and what not to include in the report, an itemized grading form, which is the same one used in the grading process, is made available to the students for each report. The role of the grading sheet is twofold. First, it is a tool to educate the students as to what is and is not important to report to your boss. Second, it ensures a uniform set of evaluation criteria are used by the course instructor. An example of a lab evaluation form is given in the Appendix. Each student on a team receives the same grade. A procedure has been developed to scale grades when a team has one or more members that are not shouldering their fair share of the work. This system is based on the self-voting scheme proposed by Brown[9] and also discussed by Kaufmann and Felder[10].

All reports are graded by the instructor. Graduate student TAs are typically good at grading technical aspects of the reports. However, these same TAs are not qualified to critique the technical writing or the quality of the tables, graphs and CAD drawings that are contained in the reports. Having used TAs in the past to grade the reports and now having the reports graded by the course instructor, the students get more detailed and constructive feedback from the instructor than from a TA. The students have responded very favorably to the feedback from the instructor even though it is harsher than what was given by the TA. Students understand that they are still growing their report-writing skills and want feedback on how they can improve these skills.

Midterm and Final Exams

Because a uniform mastering of the course concepts by all the students is unlikely, determining a final course grade solely on the technical reports may not be a true measure of student learning. Therefore, two two-hour exams are used to measure student learning of the course outcomes. Because the course is intended to be a simulated workplace scenario, the exams are open book—closed notes. In the real world, an engineer will most likely use their textbook as a reference, so the exams allow the students to use their books. Having access to the text during the exam removes the need to memorize equations, thereby allowing the student to concentrate their exam preparation on being able to apply course concepts. To accommodate the ABET assessment process, the questions on the exams are tied to the course outcomes.

Homework

Students tend to exercise academic triage. If a course component is not assigned a point value in the overall course grade, then the student typically elects not to do that component. Thus, homework is given sufficient weight, 10%, so as to encourage the student to do it. Problems are graded on a basis of 1 to 3 points, with 3 points for a correct solution, 2 points for a good try, and 1 point for at least rewriting the problem question. The philosophy for the 1 point is that the student should receive some credit for at least making an effort to look at the problem.

Class Participation

Without some motivator, many students will attend class and be passive participants in the learning process. Attending class is another aspect of higher education where a student will exercise academic triage. Many of the students at University of Massachusetts Lowell are the first generation in their family to attend college and many have to work 20-40 hours a week to meet their financial obligations for college and living costs. While these students have a very good work ethic, they are all too often faced with making the choice among working, sleeping and attending class. Therefore, assigning credit for class participation has been found to be a great motivator to encourage students to attend class and to participate actively in the learning process. While it is the responsibility of the course instructor to engage the students in the learning process, the first key to engaging is to get the students into the classroom. Class participation carries a 10% weight in the overall grade for the class. The grade of 0 to 10 is subjectively assigned by the course instructor as attendance is not taken daily. Attendance is only documented by the five short-answer quizzes that are given during the semester. Rather the class participation grade is based on the instructor's impression how often a student participates in the classroom discussions and how well a student answers questions that are asked during the course of the semester. Every 5 to 10 minutes, the instructor will engage the class by asking a question to one or more students. Students who appear to attend class regularly and who make an honest effort to answer a question in class and to contribute to the class discussions are typically assigned a full 10% for class participation.

Course Outcomes

After the students finish the final exam, they are asked to do an assessment of the course outcomes. The reason for administering the assessment on the day of the final is because this is the time when the students have their best understanding of the concepts that were taught and all of the items that will be used to assess the student performance in the class have been submitted. If the course outcomes were assessed during the last week of classes, the students may still be unsure of one or more topics. However, by the day of the final exam, the student should have their best grasp of the material.

Table 2 summarizes the average of the scores given by the students for Fall 2006. Except for a score of 2.9, most of the scores are well above 3.0. The student assessments reflect that they have a good grasp of how to design and analyze linkages and of the concepts associated with linkages. The lower scores are associated with the mathematical derivations presented in the class, i.e., Outcomes 7, 10, 15 and 16. Outcomes 7, 15 and 16 are not reinforced in the semester design project, and this may explain why these are not as well understood by the students. These outcomes are discussed in lecture numerous times. However, because the students are never asked to do a hands-on exercise involving these topics, they do not feel as comfortable with them as they do with the topics addressed in the semester-long project.

Outcome 10 is included in Task #7. However, to reduce the time required to complete the task, the teams are given a MathCAD program that has all of the equations programmed into the script. The teams are asked to provide the proper input information for their respective linkage design, and compare the analytical solution to the one the found in Task #3 using a graphical technique. The program may appear to be a "black box" because they do not necessarily understand how the equations work to produce a solution.

Table 2. Average scores for the Student Assessment of the Course Outcomes (Fall 2006)

1.	Calculate the Grashof condition for a linkage and explain what it means.	3.8
2.	Take a sequence of positions for a line or point in space and using graphical methods to synthesize a linkage which will generate the required sequence of events through either rocker or coupler motion.	3.7
3.	Evaluate the tasks associated with a design project from initial concept to production and develop a Gantt chart to organize these tasks and estimate a time required for each task.	3.5
4.	Explain the concept of a toggle position in a linkage and the advantages and disadvantages of toggle positions.	3.6
5.	Give an example of a linkless linkage.	3.6
6.	Design a linkage to satisfy a path, motion or function output.	3.5
7.	Write and solve sets of equations, which will define the position, velocity and acceleration of any point on a linkage.	2.9
8.	Find the Instant Centers of a fourbar linkage and explain the concept of ICs.	3.1
9.	Create a set of machine-shop quality drawings for the machining of the parts used in a linkage.	3.6
10.	Design a fourbar linkage with prescribed fixed pivots using an analytical method.	3.2
11.	Design a linkage to have one or two dwells.	3.3
12.	Write a memo report describing the project status and a completed task.	3.5
13.	Calculate the position, velocity and acceleration response of a linkage using Pro/E.	3.4
14.	Identify the normal, tangential, slip and coriolis components of acceleration.	3.5
15.	Write a vector loop for a linkage using exponential notation.	3.1
16.	Decompose an exponential notation equation into two scalar equations.	3.2
17.	Machine parts and assemble a linkage.	3.6
18.	Appreciate the need for an engineer to be able to communicate technical information to a machinist and work with the machinist.	3.8
19.	Calculate the number of degrees of freedom in a linkage system.	3.5

Conclusion

The format for using a semester-long project to teach design, analysis, CAD and technical writing and to introduce project management to third-year students in mechanical engineering was presented. The project is composed of a set well connected tasks that take a linkage design from a virtual conception to a working prototype made in the machine shop. The assessment data show the course outcomes that were included in the hands-on tasks were learned better by the students than those outcomes that were discussed in class but not directly integrated into the project, even though these nonintegrated topics were discussed in class multiple times throughout the semester.

Acknowledgements

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Appendix

Example Memo Report Grading Sheet

ME 22.321 Mechanical Design I – Fall 2006
Lab #9 – Position, Velocity and Acceleration Analyses

Overall Grade ________________/60

/2.0	Report format – proper headings
/3.0	Introduction – clearly and succinctly states the objective of the lab
/8.0	Discussion – clearly and succinctly summarizes the outcomes of the lab and reflects critical thinking about the results
/3.0	Conclusions – restate important points made in the discussion, free of editorial comments (e.g., This lab was a good). Contain no new information that was not already presented in the Discussion section of the report.
/2.0	References
/6.0	Report format – correct figure description and labels
/4.0	RPM of the motor stated with supporting calculation
/6.0	Plot position of CG bilge plate vs. time (in Discussion section of the report)
/6.0	Plot velocity of CG bilge plate vs. time (in Discussion section of the report)
/6.0	Plot acceleration of CG bilge plate vs. time (in Discussion section of the report)
/6.0	Identify maximum velocity and acceleration obtained
/4.0	Overall report presentation
/4.0	Updated Gantt Chart
/	Add/Subtract - +5% per day early / -5% per day late