Enhancing the teaching of machine design by creating a basic hands-on environment with mechanical ‘breadboards’

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Abstract The pendulum of engineering education is swinging from an emphasis on theoretical material to a balance between theory and hands-on activities. This transformation is motivated, in part, by the different experiential background of students presently entering engineering programs in comparison with their predecessors. Instead of a tinkering background with the dissection of machines and use of tools (which was previously common for students), students are now entering with a background in computing, video games, and other ‘virtual’ experiences. This focus has left a void in the ability to relate engineering principles to real-world devices and applications. Another void is also apparent in the variety of students’ learning styles. Our course presentation should accommodate these different styles. In this paper, we introduce a new approach for filling these voids in a mechanical engineering curriculum. Through the application of ‘mechanical breadboards’, clear relationships between machine design principles and the reality of machine components are established. The introduction of hands-on devices also provides a foundation for teaching to the full spectrum of learning styles. We have seen a dramatic increase in student motivation (as measured by student course evaluations) and a tremendous increase in students’ ability to *apply* machine design concepts in subsequent design courses. Faculty have reported an initial increase in preparation workload, but have also indicated that the course is much more effective at meeting its stated objectives.

Keywords hands-on; machine design; mechanical breadboards

Introduction

Motivation

Engineering education is transforming from a strictly theoretical emphasis to a balance between applied mathematics, engineering sciences and hands-on activities. Design components in related courses are helping to provide this balance [1–6]. Instead of relegating design content to courses in the last two semesters of an engineering program, many universities are integrating the experiences across the entire 4–5-year curriculum.

An example of this distribution of design courses is shown in Fig. 1, which illustrates the spectrum of design education at the University of Texas at Austin (UT), Department of Mechanical Engineering, and the United States Air Force Academy (USAFA), Department of Engineering Mechanics, during the 1998–2002 academic years. As shown in Fig. 1, five-core courses and one graduate course (Product Design & Development) of the UT mechanical engineering curriculum include substantial design components. These begin with a freshman Introduction to Mechanical Engineering course, in which students study a range of topics, including: ‘survival

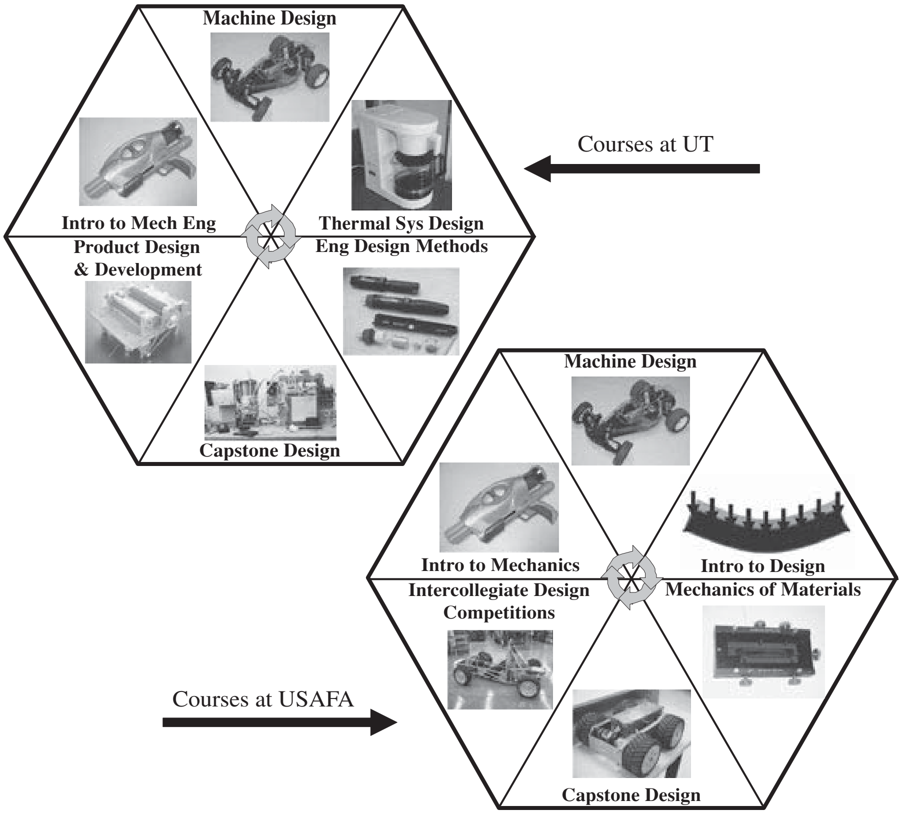


Fig. 1 *Spectrum of engineering design courses at UT and USAFA.*

skills' (using library and internet resources, e-mail, ethics, team skills, etc.); the engineering design process; engineering graphics, drawings, and solid modeling; the role of engineering analysis; and others. The topics in this course are integrated with experience of reverse engineering. Student teams choose a mechanical toy or other device (e.g., a mechanical clock), predict how the device works, dissect it, analyze the functionality and simple physical principles, predict how it was fabricated, and suggest possible redesigns and improvements.

Following the freshman year, students enroll in a number of basic and major sequence courses. Two courses, in particular, are Machine Design (or Machine Elements) and Thermal Systems Design. Both are usually taken during the second semester of the sophomore or junior years. These courses include fundamentals in machine components, solid mechanics, and thermodynamics, but they also focus on open-ended design activities, in which the course material can be applied to real systems.

The materials in these core courses are used to develop or complement design components in supporting technical electives. The design sequence at UT then closes with two courses during the senior year. The first course investigates design processes and methodology. In this, students learn fundamental product design principles and supporting techniques. They also apply the results to a more sophisticated reverse engineering and redesign project [3, 5–7]. In the second course, students complete a capstone experience on industrially sponsored design projects. Teams of three or four individuals carry a design problem from initial problem definition through to working drawings and initial prototypes. The results of the design are presented and delivered to the industrial sponsors.

The design sequence at USAFA follows a similar format. Design methodology is introduced in the freshman year Introduction to Mechanics course. During the sophomore year, a full course in design methodology is provided. Machine design is usually taken in the second semester of the junior year and the capstone design course occurs during the senior year.

These course sequence descriptions at UT and USAFA illustrate where the pendulum has swung to include more physical interaction with the theory being studied. While this illustrates a significant effort towards this goal, much more work is needed to integrate design more fully into the curriculum while still achieving a good balance between theory and hands-on application.

One of the key motivating factors behind this effort is the changing student population entering engineering programs. In the recent past, a majority of the students could be expected to enroll with a significant history of ‘tinkering’ with devices. This tinkering might include the dissection of devices just to see how they work, or the fabrication of tree houses, go-karts and so on using basic tools and materials. Today’s engineering student cannot be expected to have this background or even to have ever nailed two pieces of wood together. Our current society is much more information based, translating into significant computer and video experience on the part of the students. We are thus faced with the tinkerer’s problem: how do we ground the students in engineering fundamentals while tying these fundamentals to actual physical hardware so that they may be retained and applied? In this work, we address this problem by building on what others have done using hands-on devices to enhance their courses [8–15], by establishing a suite of hands-on techniques that will apply to a course in machine design.

Another motivating factor behind this work was the desire to teach to a variety of learning styles. The move from a strictly lecture paradigm to one that includes hands-on and project-based interaction has been shown to more fully span the spectrum of learning styles and thus became a goal of this work [16–23].

In this paper, we discuss the evolution of the machine design courses at UT and USAFA to address the issues mentioned above. As stated, these courses are normally taken during the junior year of a mechanical engineering program, and the approach includes more of a hands-on, project-oriented emphasis.

Background and issues

Most universities that teach mechanical engineering include a machine design or machine elements course as part of the curriculum. Such courses usually focus on the material covered in classical texts such as those by Spotts [24], Shigley and Mischke [25], or Juvinall and Marshek [26]. These textbooks, for the most part, cover the fundamentals of solid mechanics, factors of safety, and the analysis of discrete machine components.

At UT, undergraduate mechanical engineering students enroll in a machine design class during the early part of their junior year. This course, known as ME 338 – Fundamentals of Machine Elements, focuses on a balance between solid mechanics theory and a survey of machine elements, such as gears, bearings, and springs. At USAFA, cadets in the mechanical engineering program taken their machine design course during the second semester of their junior year. This course is referred to as ME 370 – Machine Design, and it also divides the course material into basic theory and a survey of machine elements. Thus, classically, the emphasis of machine design courses has been on solid mechanics principles applied to individual machine elements.

The emphasis of machine design courses has its roots in material from the 1950s. These roots are important and have evolved from the research in the field of mechanisms and machines. However, the classical emphasis of teaching machine design raises a number of issues in the contemporary engineering curriculum. For example, students are no longer tinkerers, by default. This characteristic results in a disconnection between the theory in the course and the reality of implementing machine elements in a device. Due to this disconnection, students are often not successful in implementing the knowledge in follow-on design courses, such as their capstone design course.

Likewise, students are not given many opportunities to make assumptions and estimates. While textbook problems may be repeated and solved by the students, they do not demonstrate an ability to apply the material to simple machines, such as mechanical toys or electromechanical kitchen appliances. The skills of taking a ‘real world’ device, dissecting and filtering the information, and simplifying the results are not emphasized in the classical approach.

A companion issue concerns the lack of a systems design approach in many machine elements courses. Quite often elements are considered singularly. Their combination and interfaces are not dealt with in terms of analysis or design. The introduction of a real-world device provides a platform for a study of systems design capability.

Different learning styles across the student body raise a complementary issue concerning the pedagogy of machine design instruction. Past student evaluations at UT and USAFA show that the interest in machine design courses is not as high as desired or expected. Since machines are fundamental to mechanical engineering, one would expect machine design to be one of the most popular courses in the curriculum. However, past student evaluations do not support this expectation. An analysis of the evaluations shows that students are seeking a more hands-on approach, one in which they experience, hypothesize, assemble, and test actual machine systems, not just the theory of how they are designed.

Further motivation for promoting hands-on activities is illustrated in Fig. 2, which shows Kolb's model of learning [19, 27–29], embodied by a cycle that begins with concrete experience, proceeds with reflective observation and conceptualization, and ends, before restarting, with active experimentation. By studying and dissecting current machines, the physical components may be directly experienced with all senses. Design methods may then be used to hypothesize current functions, and conceptualize new functions and/or solutions to the current configuration. Observation and active experimentation with the current and refined concepts may then be executed, realizing mental ideas into physical embodiments. The process may then begin again, where further iteration enhances and cements learning, as well as actual product improvements.

The Kolb model (Fig. 2) swings the pendulum of learning engineering from an emphasis on generalization and theory to a balance encompassing all modes of learning [28]. Engineering education inherits an equal focus on experiential activities. Without this approach, no concrete experience exists to ground learning and build a solid foundational understanding. The grounding in current machines helps nurture our interest in understanding the way things work and for making devices work better.

Need

Identification of these issues in traditional machine design courses led to the following statement of need: 'create a hands-on environment for ME 338 and ME 370 instruction, evolving the purely analytical focus of the past'. Supporting goals for

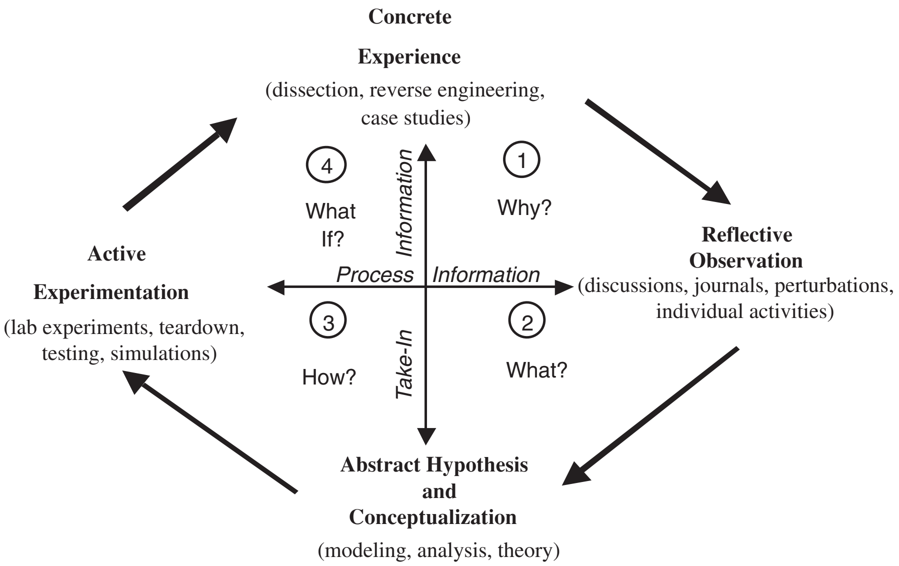


Fig. 2 *Kolb's model of learning [28].*

this need include the following: develop activities where students manipulate the components they are studying, with emphasis on familiar devices; add project-oriented design components into the course, both machine layout and analysis; add team assignments to promote active learning through peer interaction and questioning; redesign the course to better span the known space of learning styles; and implement a systems approach for studying machine design, where elements are not studied in isolation. The remainder of this paper addresses these goals as they have been implemented in our curriculum.

New course design

In this section, we present the skeletal structure of our new course design at UT and USAFA. Our fundamental premise is not to revolutionize machine design instruction; it has a long and rich history within mechanical engineering. Instead, the goal is to evolve the curriculum in machine design to address the contemporary needs of our students.

Development

The development of an evolved machine design course originated at USAFA during the fall of 1997. Three faculty members were involved in the new course design, which was carried out in the summer of 1997. Because most cadets at USAFA have a heavy course load (18–21 hours a week), and because a majority of the cadets seek to be pilots after graduation, special emphasis was placed on designing the course within the cadets' constraints. Three sections of the course were initially offered, to a total of 36 cadets.

Following implementation of the new course at USAFA in the fall of 1997, this course, with some modifications, was introduced at UT during the summer of 1998 (20 students). It replaced the Fundamentals of Machine Components course in the curriculum, and it has since been taught in each semester from the fall 1998 through the fall of 2003 (400 students) and in each summer from 1998 to 2001 (80 students). At USAFA the revised course has been taught since the spring of 1998 (300 students up to the time of writing). The following sections provide a brief description of the primary course components.

Course organization

The new course seeks to complete the full cycle of Kolb's learning model and span the spectrum of learning styles. Hands-on activities are the primary addition to the course to accomplish these goals. In addition, a systems approach to machine design is emphasized. Because of the additions and redirected focus, a portion of the content previously taught is removed from the course. The idea is to teach the covered material to interest and motivate the students, with the expectation of retention and connection to the fundamental concepts. Approximately 30% of the material was removed to make room for the new hands-on and project-oriented content. The content that was removed was a specific subset of component analysis, in addition to basic solid mechanics review topics taught in prerequisite courses. In our experience, the students often did not retain much of this material for subsequent use. To balance this hands-on approach with the removal of content, we required students to analyze components on their final project that were *not* covered in lecture. Students had to assimilate the new content and apply it to a real-world application.

Table 1 shows the new course structure. The first three lessons review critical concepts learned in previous solid mechanics courses. Subsystems of machines are then covered sequentially, beginning with the power train subsystem (shafts, bearings, gears, fatigue, and gear trains). The subsystems of fasteners (threaded connectors and welds), energy storage (springs and flywheels), energy dissipation and transfer (brakes and clutches), and motion control (mechanisms) are then presented and integrated. From these fundamentals, the end of the semester is devoted to the study of entire systems through project work.

Course features

Besides a new course structure, the following features are added to the course:

1. A defocus of repeated solid mechanics instruction; an emphasis on fundamentals and applications of machine elements as subsystems.
2. A balance between homework exercises and hands-on projects (Kolb's model); a move toward active learning through multiple, team-based projects.

TABLE 1 *Basic course syllabus*

Lesson	Topic	Lesson	Topic
1	Intro; admin; principal stresses	22	Welds
2	Principal stresses	23	Springs
3	Principal stresses; failure theory	24	Springs
4	Failure theory; shafts	25	Project time – welding
5	Fatigue	26	Project time – welding
6	Fatigue	27	Clutches and brakes
7	Journal bearings	28	Clutches and brakes
8	Journal bearings	29	Clutches and springs
9	Rolling-element bearings	30	Machine element summary
10	Spur gears	31	Exam #3 review
11	Spur gears; gear trains	32	Exam #3
12	Exam #1 review	33	Intro to mechanisms*
13	Exam #1	34	4-bar linkages
14	Project time	35	Velocity diagrams*
15	Threaded fasteners	36	Project time
16	Bolted joints	37	Inertial force analysis*
17	Bolted joints	38	Project time
18	Fastener lab	39	Project time
19	Welds	40	Project test and evaluation
20	Exam #2 review	41	Project test and evaluation
21	Exam #2	42	Wrap-up and evaluation

*These topics are replaced by a unit on corrosion in the USAFA version of the course.

3 'Show-and-tell' and product dissection activities.
4 Implementation of a mechanical breadboard to incrementally construct, analyze, and redesign machine systems.
5 A supplemental reverse engineering project.
6 Addition of motors as a topic to the course using new multimedia education software developed by Professor Sheri Sheppard's group at Stanford University (UT curse only) [30–33].

These features replace some of the extensive component survey material originally covered in the course. In the first case, homework exercises on fundamentals and machine element analysis are used to explain the basic concepts (just as in the original courses); however, team projects (two to four persons) are added to study real-world devices for each subsystem and to complete Kolb's cycle.

In conjunction with projects, students obtain hands-on experiences with machines through a 'show-and-tell' activity. In the UT version of the course, after studying each major subsystem, students are asked to bring in real-world devices from home or work. Students must predict the internal components in the devices, dissect them in front of the class, and write a short summary (less than one page) of each device, how it operates, and how the analysis from class applies to the components. A subset of the class is asked to summarize their findings to their classmates during the first 10 minutes of a lesson. In the USAFA version, the students give a preliminary design presentation prior to analysis of the components of a specific 'mechanical breadboard' system (see below). The presentation consists of establishing 'customer needs' pertaining to a redesign of the system and using them to develop a comprehensive set of redesign mission and goal statements.

This show-and-tell activity has a dramatic impact on the students. In addition to becoming familiar with the technical terminology, they are also introduced to the world of 'tinkering', using tools, and analyzing how products are constructed. They also connect classroom material directly with products they have studied.

This impact is further elaborated through the introduction of mechanical breadboards into the courses at UT and USAFA. The concept of a mechanical breadboard is analogous to breadboards in electrical engineering. Basic building-block components, such as gears, bearings, connectors, and so on are provided with a flexible support structure. These components may be configured on the support structure according to the system being emulated, prototyped, or designed.

A mechanical breadboard is used in the new course to incrementally construct a system as the subsystems are being studied. After each construction exercise, machine-component analysis is applied to the subsystem, and at the end of the course, a systems analysis is performed to redesign and improve the overall device. A mechanical breadboard, in this case, represents the final project for the course.

Many options exist for providing mechanical breadboards for a machine design course. These include Lego^{TM} or other construction kits, commercially available precision-metal breadboards, household products, or hobby kits, such as radio-controlled cars. The next section discusses our choice of mechanical breadboards at both UT and USAFA.

The remaining two features for the new course include a reverse engineering project and the study of electric motors. As a supplemental, extra-credit, or main project, students can choose a household device to dissect and reverse engineer [4]. Such devices include kitchen appliances, mechanical toys, and power tools. Students dissect the product, choose a subset of customer needs (such as durability, low weight, etc.) to study, set up the analysis for two or three subsystems, measure geometric, power flow, and material data from the product, perform the analysis relative to the customer needs, and make recommendations for redesign. This project provides a wonderful forum for exciting the senses of the student, for improving modeling and assumption skills, for closing the loop of the Kolb learning model and for spanning the spectrum of learning styles.

As a final feature for the UT version of the new course, electric motors are studied. A systems approach to machine design requires a source of power or prime mover. Electric motors are prevalent in many of the systems used by the students. To teach this new topic, an experimental multimedia tool is used from Stanford University. This tool, developed with support from the National Science Foundation, uses an interactive game to analyze the fundamentals of electric and magnetic fields. It applies these fundamentals to a systems game where students must set the parameters on a Lego™ cart, powered by an electric motor, to travel up a hill as fast as possible [30–33].

Course niche: breadboard alternatives

Considering the features added to the new machine design course, the concept of a mechanical breadboard intrigued and excited both the faculty and students. Machine design is a very difficult topic area, due to the large number of components, complex analyses, three-dimensional geometry, variety of connection methods, and required creativity. Utilizing a mechanical breadboard, as an analogy to an electrical breadboard, has the potential to overcome many of these difficult features. Students are able to connect the studied theories with actual interfacing hardware. They also have a reconfigurable medium for trying and testing their ideas.

A number of options exist for implementing the concept of a mechanical breadboard. Five options are considered below, balancing the tradeoffs of cost, complexity, and utility.

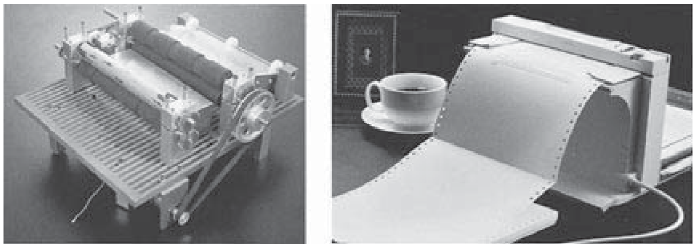


Fig. 3 *Mechanical breadboard prototype printer. (Courtesy of Product Genesis Inc., Boston, MA.)*

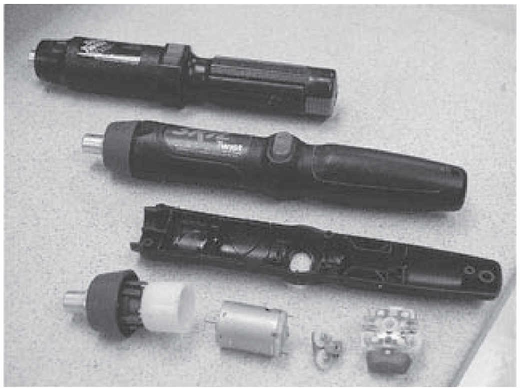


Fig. 4 *Consumer product example (cordless screwdriver).*

Precision mechanical breadboard kits

A number of suppliers sell high-end mechanical breadboards [34–36]. These breadboards include precision metal components and actuators that attach to configurable structures with slot-set-screw connectors. Many kits are available from the vendors, and the kits can be used to architect a variety of machine layouts. For a set of 10 *basic* kits, the cost would be over $20,000. Fig. 3 shows the application of a mechanical breadboard as a prototype for a printer product.

Household consumer products

Consumer products are a possible option for a mechanical breadboard [6, 7]. Products, such as power tools, lawnmowers, mechanical toys, and kitchen appliances, may be dissected and distributed to students in kits. These kits may then be assembled in part or in whole from complete or partial assembly diagrams. Such kits would not be easily reconfigurable, and the cost would range between $10 and $100, depending on the products chosen. Fig. 4 shows an example of a consumer product that could be used in this exercise.

Children's construction kits

One of the key ways that students can challenge and improve their mechanical intuition (and for instructors to assess student understanding) is through creation of a model to mimic a product's functions. The recent Lego–Robolab kits prove to be a successful medium for modeling as it is both familiar to most students and flexible enough to capture a significant range of electromechanical functions. These kits include a range of Lego elements, from structural blocks to actuators and sensors, and a control system, including a microprocessor and National Instruments' Robolab software. Using this system, students can explore machine design both at the detailed level of component geometry and materials, and at the functional level, achieved by a system of components. A major contribution to developing intuition in these areas is to 'tinker' with existing commercial products.

A potential project using this system begins with the following scenario: 'Imagine you are working for a company that wants to produce a competing product to an existing design, and you are trying to discover how the competing products were designed'. Working in groups of three, the students set out to discover how electromechanical functions are accomplished in their chosen product, how components were designed to avoid failures, and how the engineers balanced tradeoffs in the design process (for example, how cost was reduced at the expense of component quality). The project follows four states, as shown in Fig. 5, and culminates in the construction of a similar working prototype made from the Lego-Robolab kits (see example in Fig. 6).

The new kits, which include actuators and sensors, also provide the ability to design controllers and dynamic subsystems. The costs of these kits range between \$25 and \$500. Note, however, that many of these kits have a severe limitation in the ability to apply many of the solid mechanics analyses (due to the plastic material properties and methods for fastening).

Remote-controlled car kits

Another option is to purchase commercially available remote-controlled (RC) vehicle kits. These kits are available for many types of vehicle, such as cars (road racers, formula, and trucks), helicopters, and airplanes. Such kits provide scale ver-

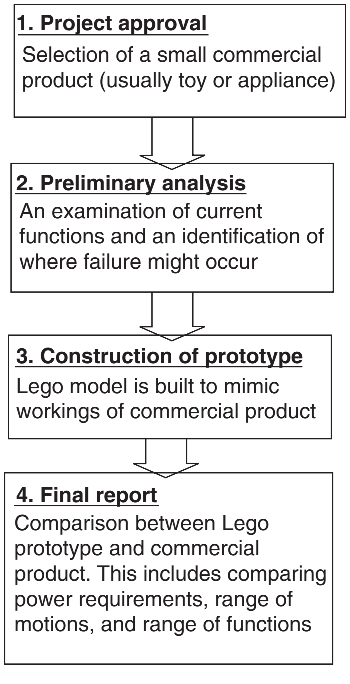


Fig. 5 *Project tasks in the Lego reverse engineering project.*

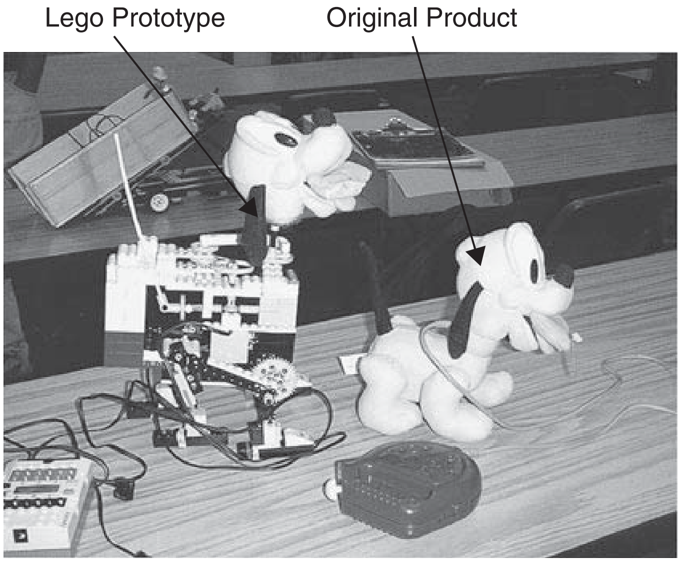


Fig. 6 *Comparison of walking dog prototype and its commercial counterpart.*

sions of actual vehicles. They also provide the capability for the use of tools, the study of a wide variety of components and mechanisms, testing, and limited reconfigurability. The cost of these kits ranges from $150 to $1,000. Fig. 7 shows an example RC car.

Automobile/aircraft subsystems

Automobile and aircraft subsystems are also an option for the concept of a mechanical breadboard. Example subsystems include suspensions, doors and hoods, steering and motors. Such subsystems can be dissected and reassembled (but with significant effort). They also provide good cases for solid mechanics analyses, and relate significantly to the future job market for both USAFA and UT graduates. The cost for such subsystems range from $500 to $4,000. However, reconfigurability is greatly limited, and they are difficult to transport and use in the classroom because of their size and weight.

As an alternative to automobile and aircraft subsystems, go-kart kits may be purchased. These kits provide small-scale on-road or ATV vehicles with 5–10 Hp motors. The cost ranges from $750 to $2,500 per kit, and the kits provide limited reconfigurability.

Choice/compromise

For the UT and USAFA courses, the final choice among these options is the combination of RC car kits or Lego–Robolab kits with in-class product examples, show-and-tell product examples, and supplemental reverse engineering projects of consumer products. This choice represents a good compromise in cost, scale, viability of measurements, and viability of analyses. This choice also satisfies the hands-

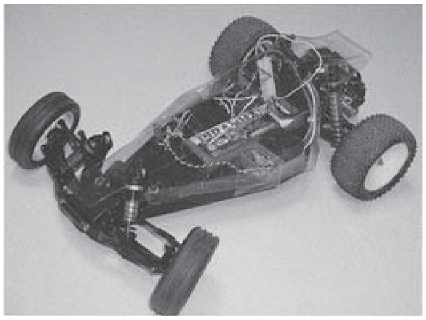


Fig. 7 *Remote-controlled car.*

on requirements of the new courses, in addition to the variety of components and the possibility to make design modifications. RC car kits have the potential to be great fun and introduce a potential for motivational racing competitions at the end of the semester. Likewise, they use state-of-the-art materials, and they are challenging, in that they are open ended, no obvious answer exists by inspections, and uncertainties exist in performance. The primary disadvantages of this choice include their limitations in reconfigurability (not completely analogous to electrical breadboards), the need for replacement parts, and the use of limited energy supplies (batteries or nitro fuel).

Example applications and exercises with the RC car breadboard and supplemental projects

The study of machine design and/or machine elements can be difficult for students as it is often presented as a series of independent concepts with the only common thread being the general principles of mechanics and kinematics. The use of mechanical breadboards offers them the opportunity to integrate more effectively the knowledge of the design of machine elements and offers hands-on experiments, which reinforce the theoretical knowledge base. In addition, the experience with a simple but integrated system also better prepares the students for their follow-on design courses. Machine design courses normally cover the analysis of common mechanical components, such as shafts, gears, bearings, springs, and clutches, but fall short of synthesizing the components into a working system.

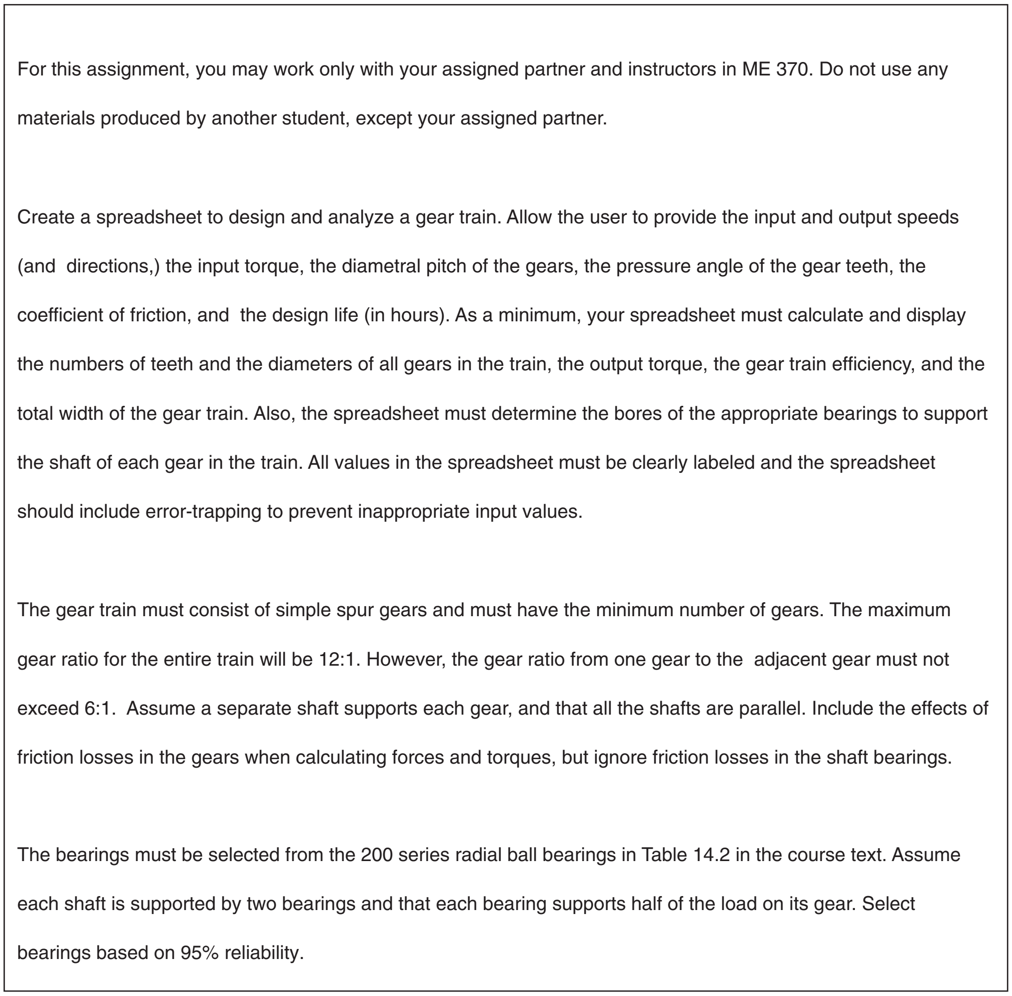
The incorporation of a RC car to use as a mechanical breadboard allows the student to experience many of the commonly studied machine elements in a single system. The RC car allows basic analysis and design of the following systems and components:

- Transmission – gears, bearings, shafts, fasteners
- Drive train – motors, clutches, shafts, belts
- Suspension – spring variations (e.g. length, stiffness, diameter)
- Steering – motors, levers, linkages, fasteners

This section describes a selection of projects introduced in the course specifically to allow the students an opportunity to both analyze and design, in an integrated system, different components of the RC car. These projects were supplemented with additional homework problems used to reinforce basic theoretical concepts.

Engineering design

Early in the course the students are introduced to the topic of power train subsystems, including the subtopics of bearings (both journal and rolling-element), followed by an introduction to gears and shafts. To supplement their understanding of the design aspects of these components, as well as their interdependence, the project shown in Fig. 8 was assigned.



For this assignment, you may work only with your assigned partner and instructors in ME 370. Do not use any materials produced by another student, except your assigned partner.

Create a spreadsheet to design and analyze a gear train. Allow the user to provide the input and output speeds (and directions,) the input torque, the diametral pitch of the gears, the pressure angle of the gear teeth, the coefficient of friction, and the design life (in hours). As a minimum, your spreadsheet must calculate and display the numbers of teeth and the diameters of all gears in the train, the output torque, the gear train efficiency, and the total width of the gear train. Also, the spreadsheet must determine the bores of the appropriate bearings to support the shaft of each gear in the train. All values in the spreadsheet must be clearly labeled and the spreadsheet should include error-trapping to prevent inappropriate input values.

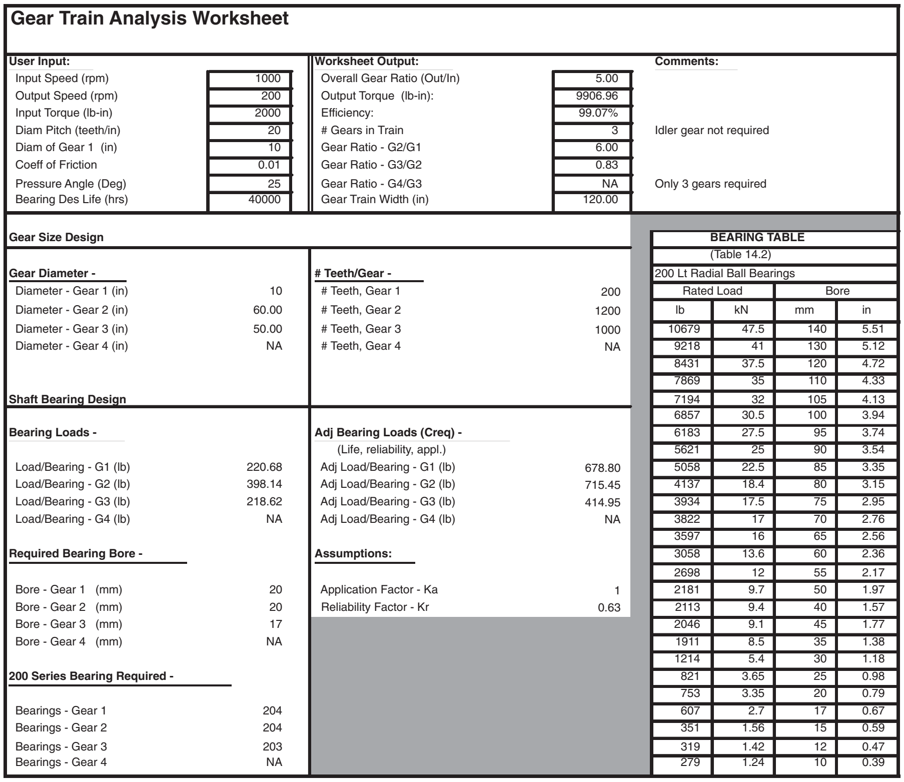
The gear train must consist of simple spur gears and must have the minimum number of gears. The maximum gear ratio for the entire train will be 12:1. However, the gear ratio from one gear to the adjacent gear must not exceed 6:1. Assume a separate shaft supports each gear, and that all the shafts are parallel. Include the effects of friction losses in the gears when calculating forces and torques, but ignore friction losses in the shaft bearings.

The bearings must be selected from the 200 series radial ball bearings in Table 14.2 in the course text. Assume each shaft is supported by two bearings and that each bearing supports half of the load on its gear. Select bearings based on 95% reliability.

Fig. 8 *Gear train design project.*

The intent of this project, globally, is to provide a realistic experience where students must use a computational tool to model a real-world problem. In particular, this project enabled the students to perform parametric design of various gear train combinations and observe the effects of frictional losses, gear ratios, power transmission, and gear train efficiencies. The result of this effort becomes a tool for subsequent design and analysis of the RC car transmission. Fig. 9 shows a representative solution for this project.

Spring elements also play an important part in machine design and are a major component in the suspension system of the RC car. The class project shown in Fig. 10 offered the students the opportunity to design springs for their RC car based on design criteria derived from operating conditions and geometrical constraints from the car structure. The students then compared their results with the front and rear springs provided with the car kit and also with experimentally determined spring stiffness (rate) coefficients. Fig. 11 provides a representative solution for this project.



Gear Train Analysis Worksheet

User Input:		**Worksheet Output:**		**Comments:**
Input Speed (rpm)	1000	Overall Gear Ratio (Out/In)	5.00	
Output Speed (rpm)	200	Output Torque (lb-in):	9906.96	
Input Torque (lb-in)	2000	Efficiency:	99.07%	
Diam Pitch (teeth/in)	20	# Gears in Train	3	Idler gear not required
Diam of Gear 1 (in)	10	Gear Ratio - G2/G1	6.00	
Coeff of Friction	0.01	Gear Ratio - G3/G2	0.83	
Pressure Angle (Deg)	25	Gear Ratio - G4/G3	NA	Only 3 gears required
Bearing Des Life (hrs)	40000	Gear Train Width (in)	120.00	

Gear Size Design

Gear Diameter -		**# Teeth/Gear -**	
Diameter - Gear 1 (in)	10	# Teeth, Gear 1	200
Diameter - Gear 2 (in)	60.00	# Teeth, Gear 2	1200
Diameter - Gear 3 (in)	50.00	# Teeth, Gear 3	1000
Diameter - Gear 4 (in)	NA	# Teeth, Gear 4	NA

Shaft Bearing Design

Bearing Loads -		**Adj Bearing Loads (Creq) -** (Life, reliability, appl.)	
Load/Bearing - G1 (lb)	220.68	Adj Load/Bearing - G1 (lb)	678.80
Load/Bearing - G2 (lb)	398.14	Adj Load/Bearing - G2 (lb)	715.45
Load/Bearing - G3 (lb)	218.62	Adj Load/Bearing - G3 (lb)	414.95
Load/Bearing - G4 (lb)	NA	Adj Load/Bearing - G4 (lb)	NA
Required Bearing Bore -		**Assumptions:**	
Bore - Gear 1 (mm)	20	Application Factor - Ka	1
Bore - Gear 2 (mm)	20	Reliability Factor - Kr	0.63
Bore - Gear 3 (mm)	17		
Bore - Gear 4 (mm)	NA		
200 Series Bearing Required -			
Bearings - Gear 1	204		
Bearings - Gear 2	204		
Bearings - Gear 3	203		
Bearings - Gear 4	NA		

BEARING TABLE

(Table 14.2)

200 Lt Radial Ball Bearings

Rated Load		Bore	
lb	kN	mm	in
10679	47.5	140	5.51
9218	41	130	5.12
8431	37.5	120	4.72
7869	35	110	4.33
7194	32	105	4.13
6857	30.5	100	3.94
6183	27.5	95	3.74
5621	25	90	3.54
5058	22.5	85	3.35
4137	18.4	80	3.15
3934	17.5	75	2.95
3822	17	70	2.76
3597	16	65	2.56
3058	13.6	60	2.36
2698	12	55	2.17
2181	9.7	50	1.97
2113	9.4	40	1.57
2046	9.1	45	1.77
1911	8.5	35	1.38
1214	5.4	30	1.18
821	3.65	25	0.98
753	3.35	20	0.79
607	2.7	17	0.67
351	1.56	15	0.59
319	1.42	12	0.47
279	1.24	10	0.39

Fig. 9 *Example solution to the gear train design project.*

We wish to design the rear shock springs for the RC-10B2 Sport Car. Our design will consider fatigue-loading conditions,where the off-road impact load varies from 8.88 N to 35.52 N on each rear spring. Given D = 14.23 mm, and δ = 57 mm (unloaded to fully loaded), assume that steel spring wire (ASTM A227) with shot peening (Fig.12.16) is to be used.

(a) Choose appropriate values of d and N for your spring design. Compare your calculated values to the actual rear springs in the car.

(b) Calculate the spring rate for the design, and compare to the experimental values below:

RC Car Problem: Spring Design

Measured Spring Constants:

Silver
Deflection (in.)

Mass (g)	Spr1	Spr2
0	0	0
500	0.344	0.406
1000	0.844	0.876
1200	1.063	1.094
1300	1.173	1.203
1500	1.298	1.329

Green

Mass (g)	Spr1	Spr2
0	0	0
500	0.297	0.25
600	0.359	0.375
700	0.422	0.406
800	0.484	0.469
1000	0.609	0.594

(N/mm)

k_s1	k_s2	k_g1	k_g2
0.561367	0.475641	0.650203	0.772441
0.457607	0.441395	0.645494	0.617953
0.435997	0.423642	0.64065	0.665897
0.428402	0.417362	0.638381	0.658798
0.446326	0.435915	0.634188	0.650203
Avg. 0.46594	0.438791	0.641784	0.673058

Grand Mean (N/mm):
0.452365 0.657421

(c) Check for buckling and spring surge for your design (assume that the car encounters bumps every 100 mm at a speed of 25 mph during off-road driving). Draw conclusions about the results.

Fig. 10 *Suspension spring design project.*

Rear Spring					Front Spring				
User Input:					***User Input:***				
Given Values			*Design Parameters*		*Given Values*			*Design Parameters*	
Car Weight (N)	15.0		G (Pa)	7.9E+10	Car Weight (N)/(lb)	15.0		G (Pa)	4.1E+10
Force/spring (N)	5.4		D (m)	1.4E-02	Force/spring (N)/(lb)	2.1		D (m)	1.3E-02
delta (δ) (m)	5.0E-03		d (m)	1.4E-03	delta (m)	2.0E-02		d (m)	1.1E-03
delta_max (δ) (m)	5.0E-02		N	12.2	delta_max (m)	2.5E-02		N	27.2
Spring Constant (k) calculation using 2 methods:					Spring Constant (k) calculation using 2 methods:				
k = F/d (N/m)	1075.4				k = F/d (N/m)	104.3			
k = d^4G/8D^3N (N/m)	1075.4				k = d^4G/8D^3N (N/m)	104.3			
Constraints:					Constraints:				
C = (D/d)	1.02E+01				C = (D/d)	1.2E+01			
Length_Free (m)	7.5E-02				Length_Free (m)	3.0E-02			
Length_Solid (m)	2.0E-02				Length_Solid (m)	2.1E-03			

Fig. 11 *Example solution to the suspension spring design project.*

Engineering analysis

Mechanical breadboards offer students the ability to perform an array of engineering analyses using a combination of hands-on experiments with analytical tools to reinforce concepts such as: torque/speed relationships, shaft and bearing load, failure, fatigue, gear tooth stress and strength, steering system kinematics (four-bar linkages), and fastener stress and strength.

The RC car affords a unique opportunity for students to experiment with a simple, single friction disk clutch. The tension on the clutch disk can be adjusted by means of a single screw and allows for analysis of the axial force on the disk and resulting slippage of the drive mechanism. The class project shown in Fig. 12 was accomplished in parallel with class lectures on clutch and brake machine components.

During assembly of the RC car kit's transmission components, the students were asked to analyze the power flow through the system and determine the stresses in the gear teeth using the project described in Fig. 13. The assembly task involved the installation of gears, shafts, and bearings in the transmission housing and enabled the students to see and feel the interactions between the components as they analyzed the system.

The next system in the RC car drive train is the drive shaft, which delivers power from the transmission to the wheels. The analysis problem in Fig. 14 was introduced to demonstrate relationships between the most basic kinematic concepts (distance versus time) and advanced concepts of beam deflections, critical speeds, stress concentrations and factors of safety with respect to shear stress.

The project also served to complete the flow of power in the form of torque from the electric motor to the wheels. A sample analytical solution to this problem is provided in Fig. 15.

Fun competition

From the day the course project was introduced, the students knew the day would come when they would put their RC cars, complete with modified clutches, sus-

Specifications for the RC10-B2's Reedy Firehawk electric motor indicate a maximum output of 0.25 hp at 15,000 rpm. This power is transferred through a pinion and drive gear to the car's clutch mechanism, which is a single molded Rulon disc with a coefficient of dynamic friction of 0.36.

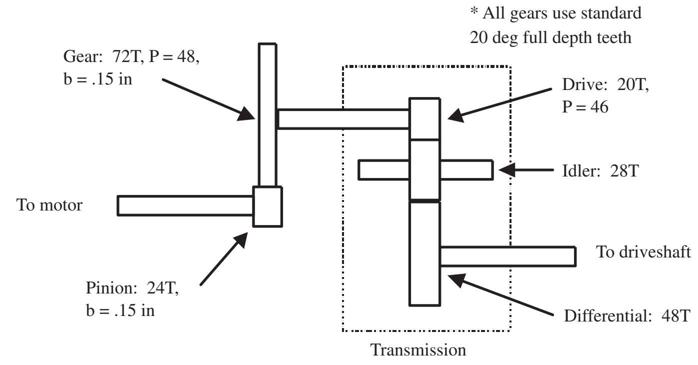
(a) Determine the initial (i.e new) axial force setting required by the clutch's spring using a factor of safety of 1.0 with respect to clutch slippage.

(b) After the clutch has been 'broken in', what adjustment will be required to the axial spring force to provide the same torque and factor of safety with respect to clutch slippage?

(c) Is the clutch disk designed for maximum torque transfer? Why or why not?

Fig. 12 *Clutch system analysis project.*

1. Preliminary tests of our Associated RC110-B2 Sport resulted in an output torque at the rear driveshaft 1.28 in-lb at an angular velocity of 3,000 rpm. The efficiencies of both the pinion-gear set and the transmission are 98%.



a) Calculate the motor horsepower required to drive the pinion based on the above diagram and specifications.

b) Determine the highest gear tooth stress, between the pinion and the gear, based on bending fatigue. Assume there is no load sharing between the gear teeth, and let $K_v = 2.5$, $K_o = 1.5$, and $K_m = 1.6$.

Fig. 13 *Transmission analysis project.*

pensions, gear ratios, lubrication, and so on, to the final test. Shown in Fig. 16 is the final course project. The intent of this project was twofold. First, the project tasked the students to analyze the performance of the car with respect to the steering system, the suspension system, and the drive train system. In each case the students were asked to state any and all assumptions in their analysis and also to explain their results, and comment specifically where their results differed from the current design of the car.

Secondly, the project introduced the final phase in the design and analysis effort – the end-of-course competition. As part of this effort, the students were tasked with documenting any modifications made to their car's components to increase performance, including complete engineering analysis to support the changes. At this point in the course, the students had a significant knowledge base and an array of analytical tools developed throughout the course with which to use to fine tune their cars for the competition.

Course assessment

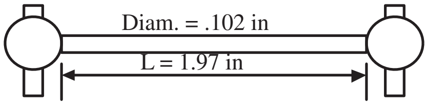
To assess our new machine design course, two instruments are employed: course ratings and the evaluation of specific course advancements according to the personality types of the students [21]. Tables 2 and 3 list the results of the course ratings by students. Table 2 shows the results from UT during the first five semesters of

A preliminary speed test of the EM470 RC10-B2 Sport radio-controlled car produced the following results:

Time (s)	Distance (ft)
1.85	28
3.1	56
4.2	84
5.25	112
6.3	140
7.35	168

The mass of the car was measured to be 1.53 kg and the tires have a diameter of 3.0 inches. The driveshaft properties and geometry are shown below.

Driveshaft
1020 HR Alloy Steel
Mass = 2.16 gr.



a. Determine the maximum lateral and angular deflections of one of the vehicle's driveshafts. State all assumptions made in your analysis.

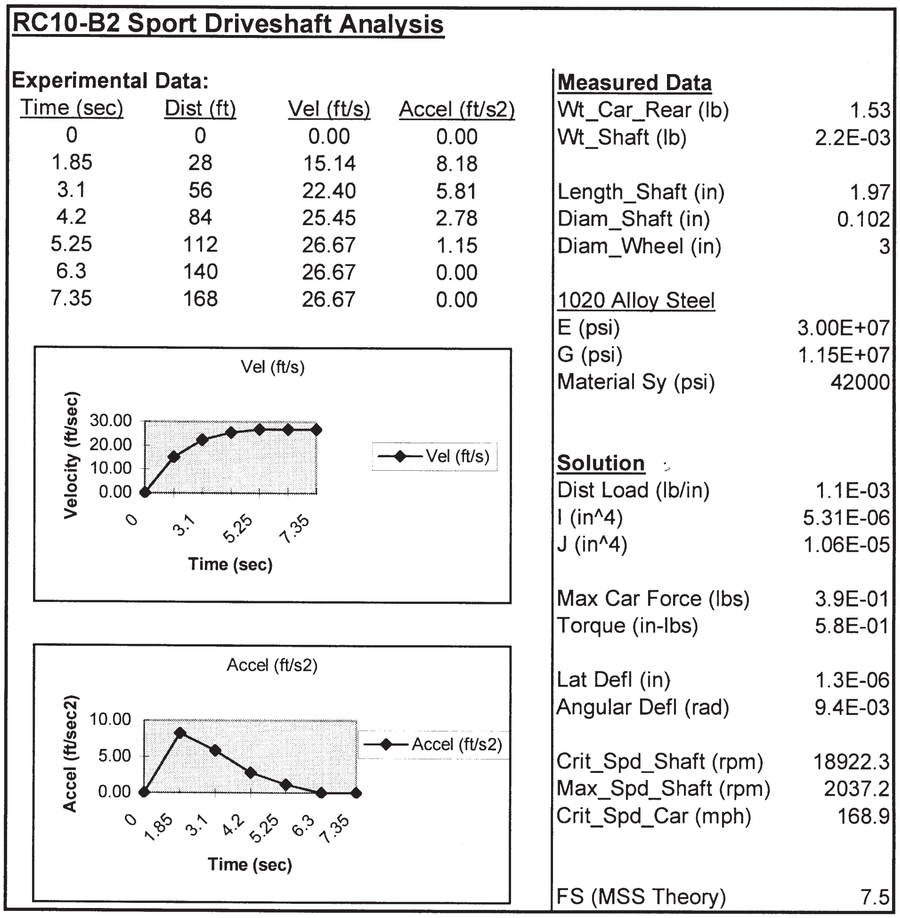
b. Determine the critical speed of the driveshaft. In the test above, was the driveshaft anywhere near the resonant speed? What would be the speed of the vehicle at the resonant speed of the driveshaft?

c. Assuming the driveshaft is experiencing torsion only, determine the factor of safety in the design based on the theory of maximum shear stress.

Fig. 14 *Kinematic analysis of drive shaft.*

implementing the new course, with a sample size of 100 students. It also shows the average ratings of the course (0–5-point scale) from 1995 through the spring of 1998, before the course changes were implemented. This average is across eight faculty members. Table 3 shows the course ratings for USAFA during the inaugural semester of the new course, fall 1997. It also shows the immediate previous semesters (1995–96) and the subsequent semesters where the material, hands-on activities, and design projects were further refined.

The results from the course ratings at both UT and USAFA are very encouraging. The trends show an increase in reception by the students, especially regarding the ability to reason independently and the relevance and usefulness of the course content. In the UT case, the course material was evaluated as very difficult and chal-



RC10-B2 Sport Driveshaft Analysis

Experimental Data:

Time (sec)	Dist (ft)	Vel (ft/s)	Accel (ft/s2)
0	0	0.00	0.00
1.85	28	15.14	8.18
3.1	56	22.40	5.81
4.2	84	25.45	2.78
5.25	112	26.67	1.15
6.3	140	26.67	0.00
7.35	168	26.67	0.00

Measured Data	
Wt_Car_Rear (lb)	1.53
Wt_Shaft (lb)	2.2E-03
Length_Shaft (in)	1.97
Diam_Shaft (in)	0.102
Diam_Wheel (in)	3
1020 Alloy Steel	
E (psi)	3.00E+07
G (psi)	1.15E+07
Material Sy (psi)	42000
Solution	
Dist Load (lb/in)	1.1E-03
I (in^4)	5.31E-06
J (in^4)	1.06E-05
Max Car Force (lbs)	3.9E-01
Torque (in-lbs)	5.8E-01
Lat Defl (in)	1.3E-06
Angular Defl (rad)	9.4E-03
Crit_Spd_Shaft (rpm)	18922.3
Max_Spd_Shaft (rpm)	2037.2
Crit_Spd_Car (mph)	168.9
FS (MSS Theory)	7.5

Fig. 15 *Example solution of drive shaft analysis.*

lenging, yet the students perceived that an active and project learning forum greatly added to their ability to understand and retain the material. The long-term implications at USAFA have also been positive. For the four years following the reformulation the student feedback shows a 14% increase in 'Instructor's ability to provide clear, well organized instruction' and also a 14% increase in 'Instructor's effectiveness in facilitating my learning'. During this same four-year period, students' responses show only a 2% increase in 'Instructor's enthusiasm'. This is important, as it indicates that the 14% increases do *not* stem simply from more enthusiastic instructors.

Beyond the immediate impact, faculty in follow-on courses were interviewed to determined the retention of the material by the students. Faculty in these courses observed improved abilities in the students to analyze electromechanical devices, especially from a systems approach. The design faculty, in particular, observed

Part 1 [150 points]: Model the RC10-B2 Sport's steering mechanism using Working Model (R:\WM303). All necessary dimensions are to be measured directly from your car. Specifications for the steering servo are as follows: Torque = 2.78 in-lb, Speed = 0.72 rev/s, Angular Displmt = +/–37°

A. Turning Radius and Ackerman Angle –
  (1) Calculate the minimum turning radii *R* using the δ_i determined from the working model. Investigate both left and right turning.
  (2) Calculate the minimum turning radii *R* based on the measured values of g_i for your car. How do these values compare to the radii determined in part 1 above? Explain any differences.
  (3) Measure the minimum turning radii of your car. How do these values compare to the radii determined in part 2 above? Explain any differences.
  (4) Is your car's steering system designed with the correct Ackerman angle? Explain your answer.

B. Steering Velocity –
  (1) Using the working model, determine the angular velocity with which the wheels steer, assuming maximum servo input and initial straight-line motion of the car.
  (2) Using a velocity vector diagram, repeat the analysis in part 1 above. Compare the results and explain any differences.
  (3) Determine the mechanical advantage gained or lost between the steering servo and the wheels and explain its importance in the design.

Part 2 [50 points]: RC Car Traction and Speed Design

A. Off-road RC10-B2 cars must maintain front-wheel traction to turn on varying terrains. Many parameters exist to adjust front- and rear-wheel traction. Two important parameters are the heights of the front and rear suspensions. These heights may be adjusted by setting the shock travel, or by choosing appropriate spring constants. Your task is to design new springs (i.e., spring constants) to maximize front-wheel traction. State all assumptions, where you need not verify the static or fatigue stress in the springs.

B. For the sets of pinion and spur gears provided with your car kits, calculate the maximum *ideal*, straight-line speed, based on a motor speed of 20,000 rpm. Assuming the drive-train is not ideal, estimate a new maximum speed for gear-mesh losses only. Measure the actual maximum speed of the car, compare these measurements to your two estimates, and explain the differences.

Part 3 [100 points]: RC Car Race Competition

During lessons 40 and 41, we will be holding intra-class race competitions. Each team should complete the construction and testing of their car before these lessons. It may be assumed that we will be competing on an oval track, a hill climb, and/or an obstacle course. The competitions will be organized by random draw and single elimination, where winners will receive 10 bonus points.

Each team will be expected to 'tune' and adjust their cars for the best possible performance. Adjustments (besides maintenance, repair, and battery charging) will not be allowed after the beginning of lesson 40. Teams must document their adjustments and provide justification for their choices in car configuration. No non-stock parts or permanent modifications may be used/made to the car or any of its components, except for the car body.

Fig. 16 *Final course project.*

TABLE 2 *UT course ratings (0–5-point scale)*

Item rated	Mean rating 1995–98 (old course)	Fall 1998	Summer 1998	Spring 1999	Spring 2000	Spring 2001	Mean for new course
Course well organized	*3.3*	4.5	4.8	4.5	4.5	4.1	**4.5**
Communicated information effectively	*2.8*	4.8	4.9	4.7	4.5	4.0	**4.6**
Helped to think, reason, and evaluate	*3.2*	4.8	4.7	4.6	4.4	4.3	**4.6**
Overall instructor rating	*2.9*	4.8	4.8	4.7	4.5	4.0	**4.6**
Overall course rating	*2.9*	4.5	4.9	4.4	4.5	4.3	**4.5**

TABLE 3 *USAFA course ratings (0–6-point scale)*

Item rated	Mean rating 1995–96 (old course)	Fall 1997	Fall 1998	Fall 1999	Spring 2000	Spring 2001	Mean for new course
Course well organized	*4.1*	4.2	4.7	4.3	4.2	4.3	**4.3**
Information communicated effectively	*4.2*	4.5	5.3	4.5	4.6	4.7	**4.7**
Intellectual challenge and independent thought	*4.5*	4.5	5.4	4.4	5.1	4.7	**4.8**
Relevance and Usefulness of content	*4.6*	5.0	5.2	4.6	5.1	5.1	**5.0**
Overall course rating	*4.0*	4.1	4.8	4.2	4.3	4.6	**4.4**

improvements in the students' ability to generate and use machine design concepts. While the overall course ratings for UT are impressive, the ratings for USAFA are less significant. We hypothesize that this is due in part to the emphasis placed on the curriculum by cadets who anticipate flying versus engineering to be their primary focus following graduation.

Discussion and conclusions

The move from the traditional lecture format to a more active learning environment has met with tremendous success at both USAFA and UT. The incorporation of mechanical breadboard projects like the RC car have enhanced the students' ability to design and analyze mechanical systems, resulting in students being better prepared to enter their senior capstone design course(s). Although the transition does not come without cost, the reduction in course content and initial increased investment in faculty time and department resources have resulted in a significant increase in student interest and motivation, and ultimately an improved retention of the course material.

The course description, objectives and syllabus as well as all of the projects and analytical exercises we have developed are available electronically by contacting one of the authors.

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References

[1] D. D. Jensen and M. Bowe, 'Hands-on experiences to enhance learning of design: effectiveness in a reverse engineering/redesign context when correlated with MBTI and VARK types', *Proceedings of the ASEE Annual Conference and Exposition*, Charlotte, NC, June 1999.

[2] D. Lefever and K. L. Wood, 'Design for assembly techniques in reverse engineering and redesign', *Proceedings of the ASME Design Engineering Technical Conference, DETC96/DTM*, Irvine, CA 1996.

[3] K. Otto and K. L. Wood, 'A reverse engineering and redesign methodology for product evolution', *ASME Design Theory and Methodology Conference*, Irvine, CA, Vol. Paper No. DETC/DTM-1523, 1996.

[4] K. Otto, K. L. Wood, M. D. Murphy and D. D. Jensen, 'Building better mousetrap builders: courses to incrementally and systematically teach design', *Proceedings of the ASEE Annual Conference and Exposition*, Seattle, WA, June 1998.

[5] K. Otto and K. L. Wood, *Product Design: Techniques in Reverse Engineering and New Product Development* (Prentice Hall, Upper Saddle River, NJ, 2001).

[6] K. L. Wood, D. D. Jensen, J. Bezdek and K. Otto, 'Reverse engineering and redesign: courses to incrementally and systematically teach design', *Journal of Engineering Education* **90**(3) (2001), 363–374.

[7] K. Otto and K. L. Wood, 'A reverse engineering and redesign methodology', *Research in Engineering Design*, **10**(4) (1998), 226–243.

[8] H. A. Aglan and S. F. Ali, 'Hands-on experiences: an integral part of engineering curriculum reform', *Journal of Engineering Education* **85**(4) (1996), 327–330.

[9] C. C. Bonwell, 'Active learning and learning styles', *Active Learning Workshops Conference*, 1998. Content available at http://www.active-learning-site.com/vark.htm

[10] R. Borchert, D. D. Jensen and D. Yates, 'Hands-on and visualization modules for enhancement of learning in mechanics: development and assessment in the context of Myers Briggs types and VARK learning styles', *Proceedings of the ASEE Annual Conference and Exposition*. Charlotte, NC, June 1999.

[11] L. E. Carlson, 'First year engineering projects: an interdisciplinary, hands-on introduction to engineering', *Proceedings of the ASEE Annual Conference and Exposition*, Anaheim, CA (1995), 2039–2043.

[12] G. D. Catalano and K. L. Tonso, 'The Sunrayce '95 idea: adding hands-on design to an engineering curriculum', *Journal of Engineering Education* **85**(3) (1996), 193–199.

[13] S. M. Kresta, 'Hands-on demonstrations: an alternative to full scale lab experiments', *Journal of Engineering Education* **87**(1) (1998), 7–9.

[14] M. Regan and S. Sheppard, 'Interactive multimedia courseware and the hands-on learning experience: an assessment', *Journal of Engineering Education* **85**(2) (1996), 123–131.

[15] S. Shakerin and D. D. Jensen, 'Enhancement of mechanics education by means of photoelasticity and the finite element method', *International Journal of Mechanical Engineering Education* **29**(4) (2001), 307–320.

[16] R. Dunn and K. Dunn, *Teaching Students Through Their Individual Learning Styles: A Practical Approach* (Prentice Hall, Virginia, 1978).

[17] W. E. Eder, 'Comparisons – learning theories, design theory, science', *Journal of Engineering Education* **83**(2) (1994), 111–119.

[18] J. M. Feland and D. D. Jensen, 'A simple approach for using Myers Briggs type indicator data to enhance engineering education', *Proceedings of the ASEE Southwest Regional Conference*, Golden, CO, March 2000.

[19] R. M. Felder, 'Matters of style', *ASEE Prism* (1996), 18–23.

[20] R. M. Felder and L. K. Silverman, 'Learning and teaching styles in engineering education', *Engineering Education* (1988), 674–681.

[21] D. D. Jensen, M. D. Murphy and K. L. Wood, 'Evaluation and refinement of a restructured introduction to engineering design course using student surveys and MBTI data', *Proceedings of the ASEE Annual Conference and Exposition*, Seattle, WA, June 1998.

[22] D. D. Jensen and K. L. Wood, 'Incorporating learning styles to enhance mechanical engineering curricula by restructuring courses, increasing hands-on activities, & improving team dynamics', *ASME Publication and Presentation for the Award for the Most Innovative Curriculum for the Year 2000, Presented at the ASME Annual Conference*, Orlando, FL, November 2000. Details available at http://www.asme.org/education/enged/awards/cia00/jensen.pdf

[23] M. Lumsdaine and E. Lumsdaine, 'Thinking preferences of engineering students: implications for curriculum restructuring', *Journal of Engineering Education* **84**(2) (1995), 193–204.

[24] M. Spotts, *Design of Machine Elements*, 7th edn (Prentice-Hall, Upper Saddle River, NJ, 1998).

[25] J. E. Shigley and C. R. Mischke, *Mechanical Engineering Design*, 5th edn (McGraw-Hill, New York, 1989).

[26] R. Juvinall and K. Marshek, *Fundamentals of Machine Component Design*, 2nd edn (John Wiley & Sons, New York, 1991).

[27] D. A. Kolb, *Experimental Learning: Experience as the Source of Learning and Development* (Prentice Hall, Englewood Cliffs, NJ, 1984).

[28] J. E. Stice, 'Using Kolb's learning cycle to improve student learning', *Engineering Education* (1987), 291–296.

[29] R. E. Terry and J. N. Harb, 'Kolb, bloom, creativity, and engineering design', *Proceedings of the ASEE Annual Conference and Exposition* (1993), 1594–1600. University of Illinois-Urbana/Champaign.

[30] D. Reamon and S. D. Sheppard, 'Analytic problem solving methodology', *Proceedings from the 1996 IEEE Frontiers in Education Conference* (UT, Salt Lake City, 1996), vol. 1, pp. 484–488.

[31] D. Reamon and S. D. Sheppard, 'The role of simulation software in an ideal learning environment', *Proceedings of the ASME Design Theory and Methodology Conference*, Sacramento, CA, 14–17 September 1997.

[32] D. Reamon and S. D. Sheppard, ‘Motor workshop: the role of interactivity in promoting learning’, *Proceedings from the 1998 IEEE Frontiers in Education Conference*, Tempe, AZ, 4–7 November 1998.

[33] S. D. Sheppard, D. Reamon, L. Friedlander, C. Kerns, L. Leifer, M. Marincovich and G. Toye, ‘Assessment of technology-assisted learning in higher education: it requires new thinking by universities and colleges’, *Proceedings from the 1998 IEEE Frontiers in Education Conference*, Tempe, AZ, 4–7 November 1998.

[34] W. M. Berg, 499 Ocean Avenue, East Rockaway, NY 11518, USA. http://www.wmberg.com/prbreadboard.html, 2001.

[35] PIC Design, 86 Benson Road, PO Box 1004, Middlebury, CT 06762, USA. http://www.pic-design.com/products/data1.htm, 2001.

[36] EnduraTEC Systems Corporation, 5610 Rowland Road, Minnetonka, MN 55343, USA. http://www.enduratec.com, 2001.