Design of Machine Systems - a Technical Elective

David G. Tomer
ASEE/Rochester Institute of Technology

Abstract
The author has proposed, developed, piloted and now teaches a course at Rochester Institute of Technology entitled Design of Machine Systems. Over the past two years, it has been successfully offered as a technical elective to 4th and 5th year students in RIT's 5-year, co-op based, BS in Mechanical Engineering program. It is nominally a follow-up to the classical Machine Design course, but the focus is quite different, concentrating on system design as opposed to component design. The course is intended to teach the student the basics of properly selecting and integrating nominally off-the-shelf components, such as mechanical drive components [belts, chains, bearings, etc.], fluid power devices, motors, and even electronic control components, into sequential and time-based machine systems. One could easily dismiss the course as attempting to teach and promote catalog engineering design. While that is certainly a part of the course, it is much more. It is indeed an engineering design challenge to properly integrate standard and custom-designed components into a successful automatic machine. The author would also argue that much design in industry is done that way, and we are remiss if we do not offer the rudiments of that process to our engineering students. A very important component of the course is an attempt to give the Mechanical Engineering student a conversational knowledge of related fields, especially Electrical Engineering and controls, which is necessary in today's environment. In that context, this course is similar to a course in Mechantronics, but, based on the content of texts that have been reviewed, differs in emphasis and breadth of coverage.

Introduction
We, as engineering educators, currently strive to introduce ever-increasing design content into our courses. In attempting that, we sometimes teach the students to reinvent and redesign the wheel, and not teach that which we really should be teaching. Mechanical Engineering students choose elective courses which interest them, and will hopefully ease their transition into industry. Most, however, do significant learning after arriving at their place of employment: On-the-Job-Training is an important part of an engineer's continuing education. It has been my experience that one area, which typically relies almost completely on OJT, is automated equipment design, or, to use the course name, Design of Machine Systems. By this I mean the integration of mechanical, electrical, pneumatic, hydraulic, etc. components into a device, subsystem or machine system which accomplishes the desired motion or other function, performs it reliably, within the required time, with a satisfactory level of quality, and with a satisfactory operator interface. This field typically does not involve the detailed analysis and design of all of the individual components, but rather the selection of "pre-engineered" components which are

integrated with custom-designed components into a subsystem or machine system. It also often involves design work across disciplines, which creates additional obstacles to overcome. [Some of those can be seen in the classroom in a course such as this -- see the section Lack of Interest in EE/Controls.]

It is not unusual for such equipment to be built in small quantities, even singly. The design of this equipment results in the need to select pre-engineered components where possible. Conversely, components are typically selected with substantial safety factors, and with a lessened regard for component cost, as the quantities do not justify the engineering time required to optimize a design *at the component level*. Rather, the design must be optimized at the *system level*. As a result of issues like these, the focus of the engineering analysis is usually on factors such as function and component availability, rather than on optimum performance and minimum cost. In other words, the focus of the engineering effort during the design of such equipment is usually on the interrelationship of components rather than the design of each component. I often use this example with incoming ME Freshman to illustrate the difference between these two areas of design: An automotive engineer may spend a year or two analyzing, designing, testing, redesigning and retesting a component or subsystem. In that same year or two, an automated equipment design engineer will have designed, built, debugged and put into production a complete machine system. With an admitted bias, based on an enjoyable career in automated equipment design, I argue that neither is better than the other, merely different.

The typical college course in "Machine Design" is focused on component design. Whether it be failure theories, or the design of springs, gears, shafts, clutches and other power transmission components, the focus is on the analysis/design of those components rather than the selection of pre-engineered - also read "off-the-shelf" - components, based at least partly on component manufacturer's ratings and design procedures. By focusing on the system as opposed to the components, this course differs from Machine Design.

Background

The catalyst for the creation of this course was, in fact, a written report of a co-op work experience by a student. The comment was to the effect that the employer expected her to be knowledgeable about machine systems design, but that she had no training, and, in fact, RIT had no course that would have given her that knowledge. The author had thought about the desirability, or need, for such a course based on his experiences in a 26-year career in the field of automated equipment design with Eastman Kodak, but had not acted on it. The student's report provided encouragement to do that. With the cooperation of the Mechanical Engineering Department and Faculty, the course described here was formulated, successfully piloted, and subsequently approved as a regular Technical Elective at RIT.

Course Outline

The major topics covered in this course, and the approximate per cent of time spent on the topic, are listed below, along with some comments based on my experience teaching this material.

1. Kinematics/Kinetics/Design of Drive Systems & Components 25% - A thorough knowledge of the principles of Kinematics and Kinetics as they apply to drive systems and components is

required for this course. The necessary concepts are covered in standard Statics and Dynamics courses, but often focus on problems involving individual rigid bodies. Consequently, I find most students have difficulty applying those concepts to machine systems. One stumbling block seems to be the fact that drive systems have multiple rigid bodies, sometimes connected by flexible elements. The students want to treat the drive system as a single rigid body. Also, the concept of trading off speed for torque requires some learning on their part. Introduce efficiency, and some students have real difficulty.

After this review/extension of the basics, I utilize the Browning Catalog (see Text(s) section - many others would be equally appropriate) to expose the students to the actual selection of drive components. Included are V-belts, timing belts, chains, gears and gear reducers, and the kinematic speed ratios involved with all of these. To many of the students, the amount of detail required to completely specify a drive system, or even one of the components, is a surprise. For example, for a simple timing belt speed reduction, one must determine and specify: size class, numbers of teeth, width (of pulleys and belts), shaft sizes, mounting adapters (taper-style bushings, keyways and keys, set screws, etc.), belt length (based on center distance), materials, flanged/unflanged, etc. All of this must, of course, be consistent with the overall speed and torque requirements of the drive system. The situation is similar to what I often experience in Graphics/CAD: students find it somehow hard to grasp that *every* part detail drawing needs to specify (even if by a default) the tolerances for every dimension, the part material, and the surface finish.

Another area, which causes some difficulty, is the lack of a unique solution for, or an exact match to, the stated requirements. Sometimes specific components follow from the design procedure, but often there are several possible choices. Also, meeting all of the requirements exactly often is not possible, and compromises must be made. Though the heart of design, students are still typically uncomfortable having to make choices like this, as they are accustomed to getting single, exact solutions in many of their prior courses. When an exact match to the requirements isn't apparent, I challenge the students to re-examine the requirements and decide whether they can be modified, or if a more complex, but exact, solution is required. A typical example of this type of trade off would be choosing among the following: 1) an inexpensive V-belt drive, which does not provide an exact, synchronous nor consistent, drive ratio; 2) a timing belt drive, which is exact and synchronous, but perhaps is large due to availability of standard belts and pulleys; and 3) a small, exact chain drive that requires lubrication and may be noisy.

Bearings are covered, extending the coverage from our Machine Design course. The emphasis is on the types, uses and advantages and disadvantages of rolling and sliding contact bearings, and the methods used to size and select them. Pre-mounted bearings, like pillow blocks, flange cartridges and others, are covered. Linear bearings are also mentioned.

2. <u>Pneumatic Systems</u> 10% - I introduce the basic concepts of fluid systems, primarily pneumatic, with a discussion of advantages and disadvantages of fluid power, including hydraulic versus pneumatic. Basic valves, actuators and control/sensing devices are discussed and shown. Finally, simple pneumatic circuits are introduced, using the standard symbols used

with fluid power systems. The concept of flow coefficients (C_v) and component sizing is mentioned, but time is not usually available for the students to gain proficiency.

This is an area, which is completely new to the typical student, but is one, which they will immediately encounter in the field of automatic machine systems. It provides something of a transition to the concepts covered in control logic later in the course, but without the "threat" introduced by electrical components. An exception is the solenoid actuator, and its use in solenoid valves. This electromechanical device is, of necessity, discussed here. Pneumatic circuit diagrams also present somewhat of a transition to electrical control logic diagrams. Timing diagrams are discussed at this point as a convenient way to represent the actions and motions, as a function of time, involved with a machine system. This introduces the concept of sequential operation, permits the discussion of sequential versus time-based controls, and leads to a discussion of the concept of *energizing an actuator* resulting in *motion of the actuator and attached devices* allowing *sensing of operation complete* allowing *energizing the next actuator*.

As mentioned elsewhere, guest speakers are used in this course. This is one of the primary teaching techniques used in this area. An applications engineer, by showing numerous examples of fluid power devices, rapidly builds the student's understanding of this field. By using everyday examples, using hardware that the student understands, the connection is made among the motions, the components, and the pneumatic logic diagram.

3. <u>Actuators, including motors, linear motion, specialized motion</u> 20% - This section of the course is an overview of the many actuators which are used in automatic machine systems. Motors are presented as the fundamental, modern-day devices to produce motion, and AC motors as the workhorse prime movers. They are covered with qualitative emphasis on their performance characteristics. The concepts of synchronous speed, speed as a function of frequency, no-load speed, rated speed, slip, starting torque, breakdown torque, and finally, variable frequency drives are all presented. DC motors are similarly presented as inherently variable speed, variable torque devices, controlled by varying the voltage. They are presented in the context that they were used extensively to meet varying speed requirements until the advent of (reasonably priced) variable frequency AC drives. Stepper motors, servomotors, and similar devices are discussed briefly in the context of specialized, often high-speed, motion generators.

The pneumatic devices covered earlier are, of course, restated as important sources of motion, primarily cylinders to produce limited stroke, straight-line motion, but also rotary actuators and air motors as specialized rotary motion generators.

Many other types of actuators are discussed, with an emphasis on converting the readily obtained rotary motion produced by electric motors into linear or other motions. Cams, indexing drives, oscillators, etc. are discussed. Cams are presented as the underlying device utilized in many of these actuators, and the basic terminology of cam profiles, cam followers and cam design/manufacture is covered.

The primary method of teaching this material, like the pneumatic systems material, is to show by example: present devices as pictures and schematics, show real life examples, relate these to everyday usage (particularly automotive examples), utilize videos and demonstrate the analytical techniques used in selection and application.

4. Sensors, including switches, photocells, proximity sensors 10% - The many sensing devices are presented, and the way they fit into a modern control system, whether open loop or closed loop, is discussed.

The emphasis is on presence-sensing devices as opposed to strictly analog devices used in closed loop systems. This is done for several reasons, including the fact that some of the students have not taken a System Dynamics course, so they barely understand what a closed loop system is. Another reason is that presence sensing is probably the most commonly used sensing technique in automatic machine systems. Many feel that robust design demands knowing the position of all actuators at all times (except when actually traversing). For example, sensors are often used to make sure that an action has gone to completion. Cylinder switches are an example of sensors commonly used in that application, though some insist on actually sensing the operation being performed (did the part actually move, for example) rather than relying on a piston position accurately representing the end action. I believe that, for this course, a discussion of photocells, limit switches, proximity sensors and the like is the most appropriate emphasis.

The teaching method is as above, with particular emphasis on real-life examples to attempt to bridge the gap into electrical components. See also the section Lack of Interest in EE/Controls.

5. System Control & Integration, including open loop, closed loop, synchronous, asynchronous, logic 20% - The fundamental difference between open loop and closed loop systems is discussed, as is the difference between synchronous and asynchronous systems. I point out that many automatic machine systems are a combination of these types of systems. In fact, systems using the position sensing described in the previous section do employ “feedback” in the sense of initiating an action based on the (verification of the) completion of a previous action.

The basics of logic are discussed: Gate, AND, OR, NOR, NAND, flip-flop, timer, shift register, other memory devices, etc., are among the concepts discussed. Computers and Programmable Logic Controllers (PLCs) are discussed as the brains of automatic machine systems. I do not present any detail about their internal operation except to say that they are microprocessor based, that PLCs are nothing but special purpose, “disguised” computers, and that they typically use inputs and outputs (I/O) as the way that they communicate with and buffer to input/output devices. Relay logic diagrams are presented as one of the common ways of programming and documenting control system logic used with PLCs. I also explain why relay logic was popular, and why pure PC programming is now playing an increasingly important role. I explain the concept of and importance of scan time, and why it must be considered when developing a control scheme.

Lastly, I emphasize the importance of fault detection and recovery, start-up/shut down, and safety concerns in the overall machine control concept. In my experience, this can easily account for 1/3 to 1/2 of the overall logic content for an automatic machine system.

As stated previously, it is a conversational knowledge of these concepts and devices that I am striving to give to the students. By that I mean the ability to *communicate* with electrical engineers on the project team, or with electrical suppliers, to insure that the controls being designed are appropriate and will satisfy the requirements. Not many of the students taking this course will be fully responsible for the detailed design of controls for automated equipment, but most will work with an EE who is! There certainly will be instances where the Mechanical or Manufacturing Engineer is responsible for the whole control package; this course cannot hope to meet those requirements, so the coverage is perhaps superficial, but, I maintain, useful.

6. Tours of local firms designing or utilizing automated equipment 10% - On-site tours are used to show the students actual examples of the systems they have been studying. I attempt to provide tours, which show the systems being designed and built, as well as in use.

I like to start with a visit to a local design-build shop where the students can see automated equipment systems being designed and built. The owner of McKenzie Automation, Mr. Joseph McKenzie, has hosted my students all three times that the course has been taught, and has provided an overview of custom equipment building projects, including receipt of requirements, quoting of a conceptual proposal and specification of the proposed solution, and (if successful) the design, build, debug and qualification of the machine. His company typically builds machines that are synchronous dials or asynchronous pallet/conveyor systems, both using mechanical, pneumatic and electrical components. This tour is, for most students, their first experience to the competitive world of custom equipment design. I might add that Mr. McKenzie has been one of the biggest boosters of this course, providing much needed encouragement in addition to the tours.

With my personal experience at Kodak, I am usually able to arrange a tour in what Kodak calls the Film Finishing area. This is the area in which light-sensitive photographic film is put into metal and/or plastic containers, and then packaged for shipment to distributors and then final customers. The equipment is typically state-of-the-art, involving both “standard” equipment, like packaging, injection molding, metal forming, etc., but also involving equipment unique to photographic film companies and, in this case, built or contracted by Kodak.

The third tour is to a food distribution center, in this case, frozen foods. Wegmans Food Markets is a leader in the retail food industry in the western New York area, and maintains a modern facility. While not very high tech on the surface, this high speed sorting, storage (AS/RS) and distribution center clearly shows the key role that sensors, bar code scanners and the associated logic controls play in an otherwise straightforward conveyor system.

7. Tests 5% - The exams are fairly conventional, with a mix of problems and factual information. It tends to become less problem oriented and more fact oriented as the course progresses due to the overview nature of much of the “electrical” material.

Text(s)

In order to cover all of the topics, and cover them in the way desired, I have found it necessary to utilize several resources as texts. Since Mechanical Engineering Design, Shigley & Mischke[1], is used in RIT's Machine Design course, I use topics covered in that text that are not covered in our Machine Design course. Along with that, the Browning Catalog (Drive Components/Design Guide)[2], Dodge Catalog set[3] or equivalent is used to cover the selection of drive components. This includes instruction in both the use of the design guides and the subsequent selection of the specific components. Industrial Electronics, Simpson[4], is used to cover all of the electrical and electronic related topics, as well as pneumatics. It contains much material that is not covered in the course, but the level for the topics that are covered is basic and understandable. I suggest it to the students as a valuable reference for a ME expecting to work on electromechanical projects. I also suggest Marks' Standard Handbook for Mechanical Engineers[5] (or equivalent) as a valuable reference. All of the above are supplemented by numerous handouts from various equipment suppliers.

Even a cursory reading of the above paragraph will likely leave one with the impression that the text for a course such as this is a problem. While I think that an appropriate text could be produced, and may even exist without my knowledge, the use of multiple sources of information is excellent training for the world that a student taking this course is likely to experience. With much design data available in catalogs, CD ROMs and now the Internet, the student will find information and solutions in many and varied places. The single texts that come closest to meeting the needs for this course are those in Mechatronics, but I generally find them less suitable than the combination listed above.

I would be remiss, in addressing textbooks, to leave the subject without mentioning the out-of-print text that I used the first time I taught this course, Mechanical System Components by Dr. James F. Thorpe[6]. The focus of that text, and the course for which it was used, is somewhat different from that of this course, but in terms of topical coverage, it is the most complete that I have discovered. Dr. Thorpe was kind enough to provide a copy of his text for my use, and to give his permission for me to copy whatever sections of the book that I wanted to use for student use. When I became aware of the Industrial Electronics text, I chose to use it instead of Thorpe's book because of the more complete coverage of the electrical topics as well as eliminating the out-of-print problem. That text, nevertheless, was a valuable building block for this course as it exists today.

Guest Speakers

I have found it worthwhile to invite guest speakers from the industrial community to speak on certain topics. This provides several valuable features: deeper knowledge of topics on which I am weak; show-and-tell of devices; first-hand application experience; up-to-date knowledge of the state-of-the art in the field; exposure to the field of application/sales engineering; etc.

My experience has been that these speakers, and local industries as a whole, have been extremely supportive of this course. Samples, materials, software, videos and the like, in addition to the time that the speakers provide (free, of course!), are usually mine for the asking. This has been a most rewarding aspect of this course - the positive reinforcement provided by practicing engineers, often with a comment to the effect of 'I wish I could have taken your course when I was in college'.

Project
As with most modern day design courses, a team project is required of students in this course. I usually require that the students produce a "proposal" for a machine to solve a problem presented in the form of a set of requirements. I ask them to pretend that they are an equipment supplier, quoting a machine concept in response to my requirements. They should convince me that they have a workable concept, that they have done the analyses necessary to prove concept feasibility, and that their concept is the one that I should chose and why. I do not require that any equipment be built, as that is one of the key elements of RIT's Capstone Design Course. In addition, time constraints require that I limit the scope of the project work required, so I do not require further detailed analysis or design. [See also my comments in the Closure section.] On the other hand, I do require that they address operator controls and interface, and make that a part of their proposal.

One of the real problems with requiring a project in this course is one of timing. Much of the material on sensors and controls is very new to the students, and not covered until late in the course. Incorporating that knowledge into the project solution in a timely way is difficult for the students. Hence, I usually require merely a conceptual outline of the controls concept and hardware.

An example of a project assignment was to propose a machine to check batteries and accept or reject them based on terminal voltage under load. This was a simplified version of a Capstone Senior Design Project carried out the previous year.

Lack of Interest in EE/Controls
One of my goals in this course is to convince the mechanical engineering student that they need to have that *conversational knowledge* of electrical engineering and controls if they are to be successful in the present-day world of automated equipment design. And it is a very hard sell! Many, if not most, of the students that I encounter resist learning any electrical engineering beyond that required in Physics and the typical survey course(s) in EE required of ME students. I make the analogy to EE students who are required to take courses in Statics and Dynamics. For the most part, they dislike the courses intensely and want only to get through them. I wish I could report that I found a magic way to ignite the ME's interest in electronics, but I have not. I attempt to use as many everyday examples as possible to illustrate the extent to which electronics fill our lives today, and the basic principles and devices which are the foundation of the designs. It is only those students who have significant work experience, only occasionally obtained in a co-op work block, who realize the necessity of the MEs and EEs working together on project teams *understanding* each other. Not doing each other's work, but understanding what the other is doing and, perhaps more importantly, *saying*.

I usually make the point that the project engineer for a project team, very often a *mechanical* or *manufacturing* engineer, has the overall technical responsibility for the project. Consequently, she/he must understand enough about the work that engineers of other disciplines are doing to make a sound judgment about that work. Is it appropriate? Will it meet the requirements? Is the design sound? Trust and knowledge of the individuals and their work is, of course, important, but without an ability to communicate with each other, those judgments cannot be made intelligently. My goal is to introduce the topics discussed earlier and provide the beginnings of this communication ability. This is desirable in many areas in which mechanical engineers practice, but is particularly desirable in the area of automated equipment design.

Closure

A very legitimate criticism of what I have just described is that the course can't hope to thoroughly cover all of the topics listed in a 4 (quarter) hour course! I accept that criticism. The course could easily be a two-quarter course, and include a lab, and not have a single topic added. That is not readily doable, or even desirable, in the elective course structure at RIT. Consequently, I have consciously made the choice to go for breadth instead of depth. Not all would agree with this decision, but it is based primarily on my design experience. A student never knows exactly what skills will be required to accomplish an upcoming project in a career that is still unfolding. Therefore, I chose to touch on as many (related) topics as I reasonably could, covering those that I consider important in the field of automated equipment design, and knowing that the new engineer will have much to do to become fully proficient in a given area. I used the words *conversational knowledge* several times, and contrast that to the working, in-depth, knowledge that we usually strive to provide. This course does not pretend to impart working knowledge on all of the new topics introduced in it. However, the student completing the course should be well positioned to pursue any of the topics in more depth.

The process of developing and implementing this course has been very rewarding. The course has been offered three times, to over 50 students (total) with a typical class size of 20 or less. The response from most students has been positive (70% rated the course 4 or 5 - Very Good or Excellent – on a 1-5 scale), and the word among the students regarding the course appears to be positive. Feedback from companies has been extremely positive and encouraging. Current plans are to continue offering the course as a technical elective each year.

The course would be relatively straightforward to implement at another institution. The major barrier, in the author's view, is establishing the cooperative relationships with local suppliers in order to secure guest speakers, handouts, videos, etc. The course would be best taught by faculty with experience in the field of automated equipment design, since a significant portion of the learning is by way of real-life examples. That has often been a comment in students' end-of-course evaluations.

Acknowledgments

The author would like to acknowledge the following individuals and companies who have been guest speakers, provided their time, hosted tours, provided samples, catalogs, design materials, videos, etc., and, perhaps most importantly of all, provided and continue to provide sincere encouragement that this course is worthwhile and appreciated by industry:

Paul Harrison, H. M. Cross & Sons, Inc.; Joseph McKenzie, McKenzie Automation Systems, Inc.; Don Davis & Robert Leopard, Empire Air Systems; Joseph Foster, B&B Motors & Control Corp.; Matthew Fraser, Richard Nedwidek and others, Eastman Kodak Co.; John Link, Wegmans Food Markets; Marty Blakely, John M. Forster Co.; Dan Shaunessy, Zeller Electric; Power Drives Inc.; Hughes Industrial Products.

I would also like to acknowledge Stacy Kalisz, the RIT student whose co-op work report provided the catalyst and inspiration to put this course together.

Catalog Description

This is an applied course in the selection of components, and integration of those components into electro-pneumatic-mechanical devices and systems. Topics involve all aspects of machine design, including drive components and systems, motion generation and control, and electrical control hardware and strategy. This course is intended for those students interested in pursuing the design of machines, machine components and devices (as opposed, for example, to the design of products), or expecting to be dealing with such equipment. The focus of the course material is on the selection, application and integration of pre-engineered components and devices, as opposed to the fundamental design of those devices. This course is intended for 4th and 5th year (Junior and Senior) students.

Prerequisites by Topic:

1. Statics, Dynamics, Strength of Materials, Machine Design
2. Computer Aided Design
3. Familiarity with the basics of electricity, circuits, electrical devices

Bibliographic Information

[1] Shigley, Joseph Edward, & Mischke, Charles R.; Mechanical Engineering Design; McGraw-Hill © 1989

[2] Browning Catalog; Browning Manufacturing, Emerson Power Transmission Corp., Maysville KY, © 1991

[3] Dodge Components, Gearing and Bearing Catalogs; Dodge, Reliance Electric Co., P.O. Box 499, 6040 Ponders Court, Greenville, SC © 1996

[4] Simpson, Colin D.; Industrial Electronics; Prentice-Hall © 1996

[5] Avallone, Eugene A. & Baumeister, Theodore III; Marks' Standard Handbook for Mechanical Engineers, 9th Edition; McGraw-Hill ©1987 & prior

[6] Thorpe, James F., Mechanical System Components, Allyn and Bacon ©1989

Biographic Information

DAVID G. TOMER – BSME, MEngEMch, The Pennsylvania State University. He joined Eastman Kodak Co. as a Machine Design Engineer in 1965, and worked in various in-house equipment design groups for most of a 26-year career there, leaving in 1991. He then joined Rochester Institute of Technology as an Adjunct Faculty member, and has held the position of Senior Lecturer there since 1993. His primary responsibility is teaching.

Design of machine components, surfaces, and assemblies using parametric and feature-based design principles and advanced design tools. Prereq: 3670, or Grad standing in Engineering, or permission of instructor. MECHENG 5682.01.Â Technical elective in Engineering Thermodynamics including energy analysis, non-reacting and reacting gas mixtures, combustion, psychrometrics, chemical and phase equilibrium, thermoeconomics and applications. Prereq: 3501 or 3502, or equiv. MECHENG 5530.