

# MECHATRONICS IN UNIVERSITY AND PROFESSIONAL EDUCATION: IS THERE ANYTHING REALLY NEW HERE ?

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## ABSTRACT

*Mechatronics* is the *synergistic* combination of mechanical engineering, electronics, control systems and computers. The key element in mechatronics is the *integration* of these areas through the design process. The essential characteristic of a mechatronics engineer and the key to success in mechatronics is a *balance* between two sets of skills: modeling / analysis skills and experimentation / hardware implementation skills. Synergism and integration in design set a *mechatronic system* apart from a traditional, multidisciplinary system. So the answer is YES! There is something new here - in the way mechanical engineers are expected to design and in the way professors must now teach design!

This paper describes the undergraduate program in mechatronics at Rensselaer, i.e., two senior-elective courses, *Mechatronics* (fall semester) and *Mechatronic System Design* (spring semester), and in particular, the integration of the theory covered in lectures with the laboratory exercises. The hardware systems used in both courses are described. Also discussed are observations from conducting professional training in mechatronics both in industry and for the ASME Professional Development Program.

## INTRODUCTION

Today, cost-effective electronics, microcomputers, and digital signal processors have brought space-age technology to appliances and consumer products. Systems with hearts of precision sensors and actuators have increased performance by orders of magnitude over what was once possible. What sets these new, highly reliable, cost-effective, high-performance systems and devices apart from those of the past? Is it more than just technological advancement? There are many designs where electronics and control are combined with mechanical components, but with little synergy and poor integration they become just a marginally useful, error-prone, expensive conglomeration. Synergism and integration in design set a

*mechatronic system* apart from a traditional, multidisciplinary system. So the answer is YES! There is something new here - in the way mechanical engineers are expected to design and in the way professors must now teach design!

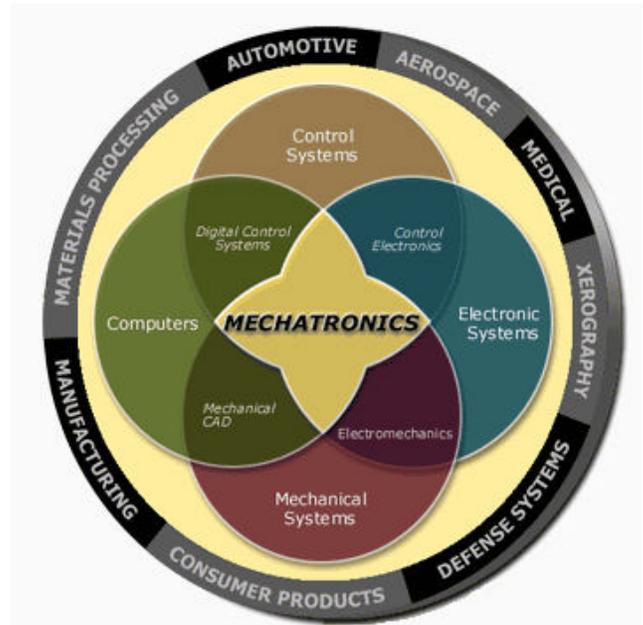


Figure 1. Mechatronics: Synergism and Integration through Design

As Figure 1 illustrates, *mechatronics* is the *synergistic* combination of mechanical engineering, electronics, control systems, and computers. The key element in mechatronics is the *integration* of these areas through the design process. In order to design and build quality precision consumer products in a timely manner, the present-day mechanical engineer must be knowledgeable (both analytically



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## MECHATRONICS AT RENSSELAER

Rensselaer Polytechnic Institute is a private, coeducational university serving approximately 4400 undergraduate and 1600 graduate students with more than 110 programs in the Schools of Architecture, Engineering, Humanities and Social Sciences, Management, and Science. The underlying goal of these programs is to develop broadly-educated women and men who will be able to exert leadership in society and contribute to human welfare. With 2600 students, Rensselaer's Engineering School offers one of the largest undergraduate engineering programs of any private university in the country. In addition, Rensselaer in recent years has been consistently ranked among the top 20 engineering research universities in the United States.

Undergraduate engineering education at Rensselaer consists of two phases: an interdisciplinary core curriculum, with instructors from various departments, followed by the disciplinary curriculum implemented by an individual department. The Department of Mechanical Engineering, Aeronautical Engineering & Mechanics at Rensselaer offers bachelors, masters, and doctoral degrees in the three disciplines represented in the name. The department awards over 200 bachelor, 80 master, and 20 doctoral degrees per year, the major portion of which are mechanical engineering degrees.

In the Department of Mechanical Engineering, Aeronautical Engineering & Mechanics there are two senior-elective courses in the field of mechatronics, which are also open to graduate students: *Mechatronics*, offered in the fall semester, and *Mechatronic System Design*, offered in the spring semester. In both courses, emphasis is placed on physical understanding rather than on mathematical formalities. The key mechatronic areas of study covered in both courses are:

- Mechatronic system design principles
- Modeling, analysis, and control of dynamic physical systems
- Selection and interfacing of sensors, actuators, and microcontrollers
- Analog and digital control electronics
- Real-time programming for control

*Mechatronics* covers the fundamentals in these areas through integrated lectures and laboratory exercises, while *Mechatronic System Design* focuses on the application and extension of the fundamentals, e.g., more in-depth coverage of digital control, as well as some advanced topics, e.g., fuzzy logic control, smart sensors and actuators.

Throughout the coverage, the focus is kept on the role of these key mechatronic areas of study in the overall design process and how these key areas are integrated into a successful mechatronic system design. A premium is placed on interactive learning through:

- student-team formation in the lectures and the discussion of design-related issues
- hands-on laboratory exercises, both in class and lab, involving industrial, off-the-shelf hardware
- computer-aided design involving the latest electronics simulation and control-design software, e.g., Matlab, Electronics Workbench
- the encouragement of critical thinking throughout the courses

Student testing is based on understanding fundamentals, not on memorization. Fundamentals are constant or slowly changing with time, while the computer tools and industrial applications are rapidly changing with time. Balance in coverage is the key, with the emphasis on the fundamentals. Some details about the two courses are given below.

### *Mechatronics*

- Studio environment, i.e., small class size (36 maximum per section, with two sections and same instructor), two-person lab/computer stations, multimedia equipment
- 4 hours lecture per week plus a 2-hour lab per week (10 of 14 weeks); lectures and labs are integrated throughout the course
- Average enrollment: 60 (80% seniors and 20% graduate students), almost all ME students
- Prerequisite topics:
  - Electronics and Instrumentation
  - Modeling and Analysis of Dynamic Systems
  - Feedback Control of Dynamic Systems
- Lab Exercises:
  - Analog Electronics (Weeks 3 & 4)
  - Digital Electronics, A/D and D/A Converters, Microcontrollers (Weeks 5 & 6)
  - Stepper Motor Control (Week 7)
  - Thermal System Closed-Loop Control (Week 9)
  - Pneumatic Servomechanism (Week 10)
  - DC Motor Closed-Loop Control (Week 11)
  - Magnetic Levitation System (Weeks 12 & 13)

### *Mechatronic System Design*

- Studio environment, i.e., small class size, two-person lab/computer stations, multimedia equipment
- 4 hours lecture per week, unlimited open lab hours
- Limited enrollment: 36 (typical enrollment 25-30)
- Prerequisite: *Mechatronics*
- Typical Projects: Students work in 4-person teams
  1. Reverse engineering of a successful mechatronic device involving actual hardware, followed by a written and oral presentation
  2. Design, build, and test project similar in scope to the mechatronic systems studied in *Mechatronics*, followed by a written and oral presentation

In both of these courses, control design, both analog and digital, and implementation is emphasized, as is the ability to work in both the time domain and frequency domain. Everything needs controls and most control systems today are digital. While there is certainly a need for controls experts and advanced control techniques, most control designs used in industry today are of the classical lead-lag type, and mechanical engineers need to know how to design and implement these as an integral part of their design and not as after-thought additions. Along with this is a need to know about various analog and digital sensors, actuators and electronics and real-time programming to make it all work. Indeed, all mechanical engineers need to become mechatronics engineers!

### MECHATRONICS LABORATORY EXERCISES

Figure 3 shows the two-person mechatronics laboratory work station consisting of:

- Pentium computer with Matlab and Electronics Workbench
- Function Generator
- Digital Oscilloscope
- Multimeter
- Powered Protoboard
- Microcontroller
- Assorted analog / digital sensors, actuators, components



Figure 3. Two-Person Mechatronics Laboratory Station

Analog and digital electronics are covered in the first four laboratory periods to review and extend the student's knowledge and experience. Topics covered include: passive and active filters, passive and active lead/lag controllers, relation between time domain and frequency domain, loading effects, input and output impedance, digital logic, and A/D and D/A converters.

For each of the five mechatronic systems studied, i.e., stepper motor, thermal, pneumatic, DC motor, and magnetic levitation, the students perform a complete dynamic system investigation:

- Understand the physical system, develop a physical model on which to base analysis and design, and experimentally determine and/or validate model parameter values
- Develop a mathematical model of the system, analyze the system and predict the dynamic response, and compare the results of the analysis to experimental measurements
- Design a feedback control system to meet performance specifications set by the designer
- Implement the control system (analog or digital) and experimentally validate its predicted performance

The stepper motor system, shown in Figure 4, consists of:

- stepper motor
- optical encoder
- 8-bit, 12 MHz microcontroller
- electronics to interface the microcontroller to the step motor and optical encoder
- full-step and half-step operation
- control via a Quad-Darlington IC
- control via a Step-Motor-Driver IC
- programming in Basic or C

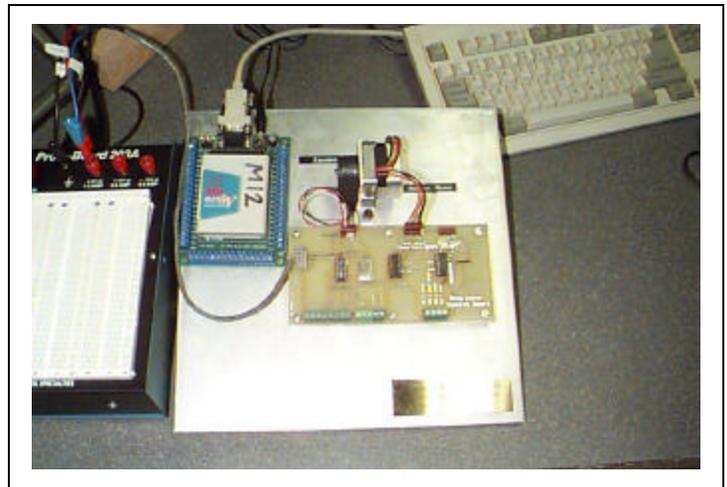


Figure 4. Stepper Motor Open-Loop and Closed-Loop Control

The thermal system, shown in Figure 5, consists of:

- aluminum plate 2" x 2" x 1/32"
- thin-film resistive heater
- ceramic insulation
- conduction and convection heat transfer
- AD590 temperature sensor
- 8-bit, 12 MHz microcontroller
- on-off closed-loop control with relay
- support analog electronics

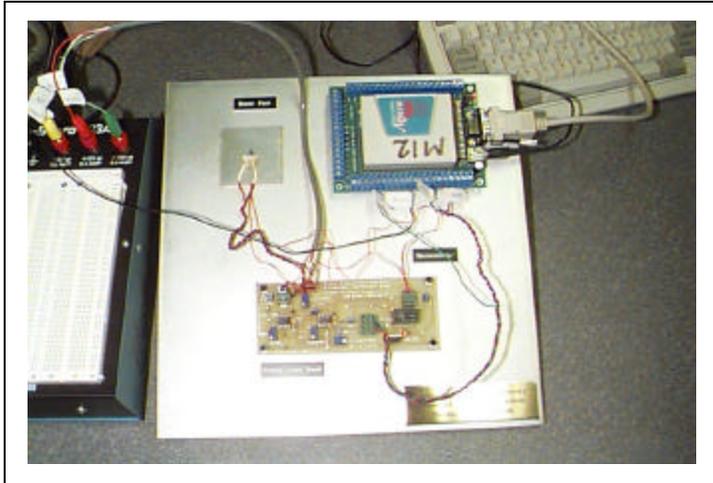


Figure 5. Thermal System Closed-Loop Temperature Control

The DC motor system, shown in Figure 6, consists of:

- permanent-magnet brushed DC motor
- integral analog tachometer
- aluminum disk load inertia
- PWM power amplifier
- 24-volt, 4-amp power supply
- analog control design and implementation: lead, lag, lead-lag
- digital control design and implementation
- 8-bit, 12 MHz microcontroller

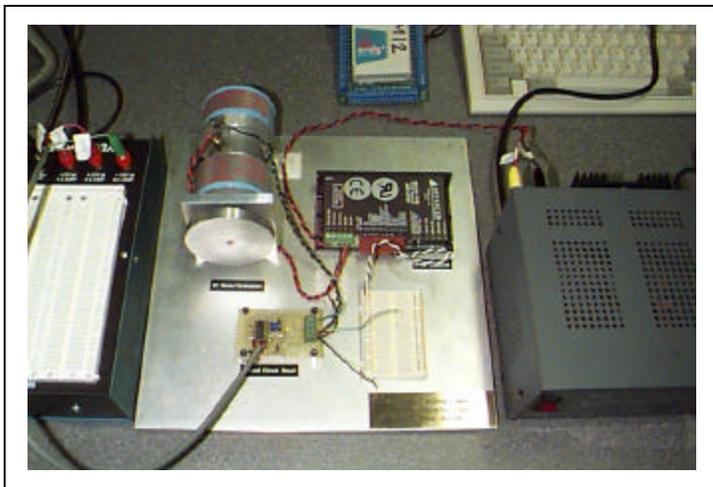


Figure 6. DC Motor Closed-Loop Speed Control

The magnetic levitation system, shown in Figure 7, consists of:

- magnetically-levitated 1/2"-diameter steel ball
- electromagnet actuator: 1/4" steel screw with 3000 turns of 26-gauge wire
- gap sensor: infra-red diode (emitter) and phototransistor (detector)
- TIP-31, NPN, bipolar transistor as a current amplifier
- $\pm 15$  volt, +5 volt power supply

- analog lead controller design and implementation

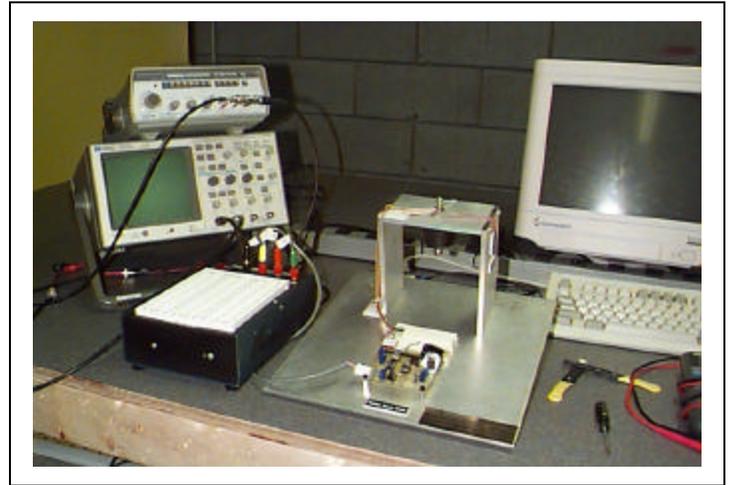


Figure 7. Magnetic Levitation System

The pneumatic system, shown in Figure 8, consists of:

- 3/4" bore, double-acting, non-rotating air cylinder
- linear potentiometer to measure output position of mass
- 30 psig air supply
- two flow-control valves
- two 1/8" ported, 3-way, spring-return, two-position solenoid valves
- Darlington switches to energize solenoids
- microcontroller
- on-off, modified on-off, PWM closed-loop control

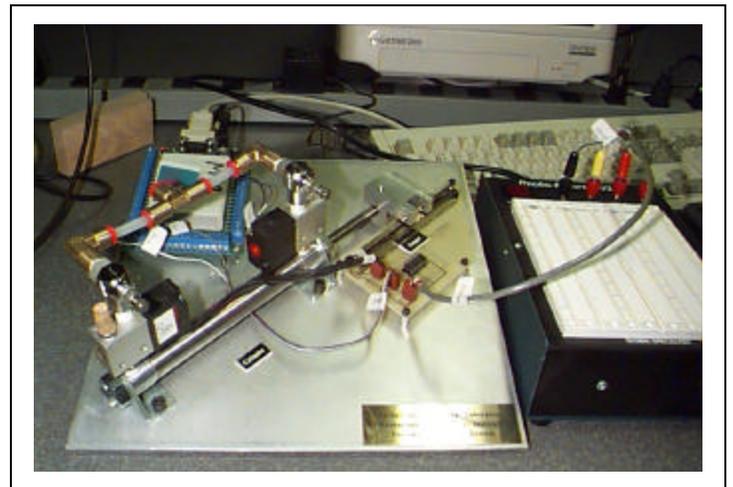


Figure 8. Pneumatic Closed-Loop Position Control

## MECHATRONIC SYSTEM DESIGN PROJECTS (Spring 1999)

### Ball-on-Beam Balancing System

The ball-on-beam balancing system is an important and common mechatronic system. This system consists of a ball which rolls on a centrally-hinged beam and the goal is to position the ball at some point on the beam. This is an open-loop-unstable system, which poses a challenging control problem. Multiple sensors are used to perform two tasks: sensing the position of the ball on the beam and sensing the angular position of the beam. The different sensor readings are used to compare the relative advantages and disadvantages of the sensors and bring forth key implementation issues. Different control schemes, such as classical, state-space, and fuzzy logic, are implemented in a MatLab / Simulink / dSpace real-time control environment to control the position of the ball. The ball-on-beam physical system is shown in Figure 9. The beam is made of acrylic and is centrally hinged. Three different sensors are used to detect the position of the ball on the beam. An ultrasonic transducer is mounted at one end of the beam. The transducer emits a chirp signal at regular intervals, and the position of the ball is determined by the time it takes for the signal to echo off the ball and return to the emitter. The beam is also instrumented with an array of 47 phototransistors spaced 1/2-inch apart in holes along the center of the beam. As the ball travels along the beam, it blocks the light over at least one phototransistor at any time. An R-2R ladder circuit is used to connect the phototransistors and determine which phototransistor(s) is covered by the ball. Also along each side of the beam is a length of Nichrome wire (wire of relatively high resistivity) inserted in a groove. The ball rides on those wires, so there is always contact between the ball and the wires as the ball travels along the beam. A voltage is applied across the ends of the Nichrome wires and the ball closes the circuit between the two wires. The ball and Nichrome wires thus operate as a linear potentiometer. A brushed DC motor is connected to the bearing-supported beam shaft through gearing. The motor is driven by a PWM servo amplifier. Two different sensors are used to measure the angular position of the beam. A rotary potentiometer is mounted on the beam shaft and an incremental optical encoder is mounted on the motor shaft.

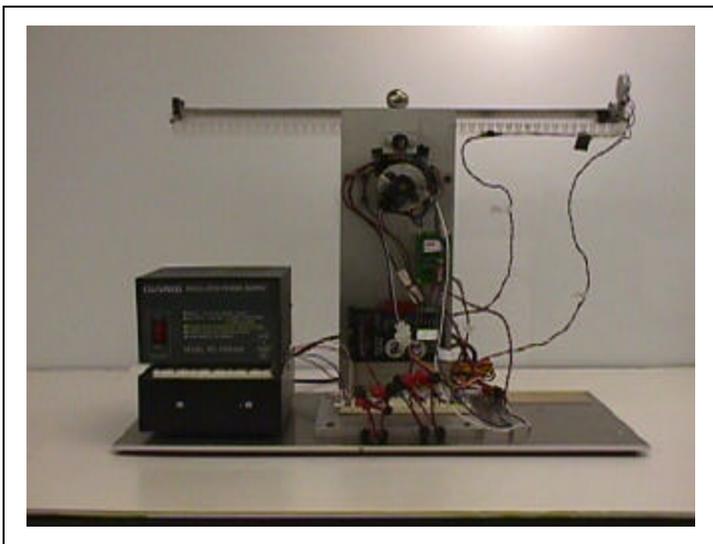


Figure 9. Ball-on-Beam Balancing System

### Ball-on-Plate Balancing System

The ball-on-plate balancing system is a popular mechatronic application. The physical system, shown in Figure 10, is mounted on an acrylic base, and is supported by four aluminum beams. The beams provide shape and support to the system, as well as provide a location where the motors can be mounted. Each motor drives one axis of rotation for the plate, and is connected to the plate via a system of linkages. A horizontal link is attached directly to the motor and drives the motion of a vertical link. The links are connected by ball joints. The motor shaft angles are measured by rotary potentiometers. The vertical links are connected to a horizontal support beam, which is in turn connected to the mounting on the acrylic plate. The center of the plate is connected to ground by a U-joint. The horizontal support beam, that the links are affixed to, is offset from the top of the plate so the U-joint will have a full range of motion. The acrylic plate is a base upon which is mounted a resistive, computer touch-screen, ball-position sensor. The 1.25" diameter brass ball rolls on the touch-screen, and the force from its weight causes the touch-screen to output voltages based on the ball's position on the plate. This information is transmitted to the controller, which sends voltage signals to our motors. A MatLab / Simulink / dSpace real-time control system is used for this application. The motors actuate and rotate the plate such that the ball rolls toward the desired location on the plate. Once the ball reaches the desired location, the plate maintains the horizontal position.

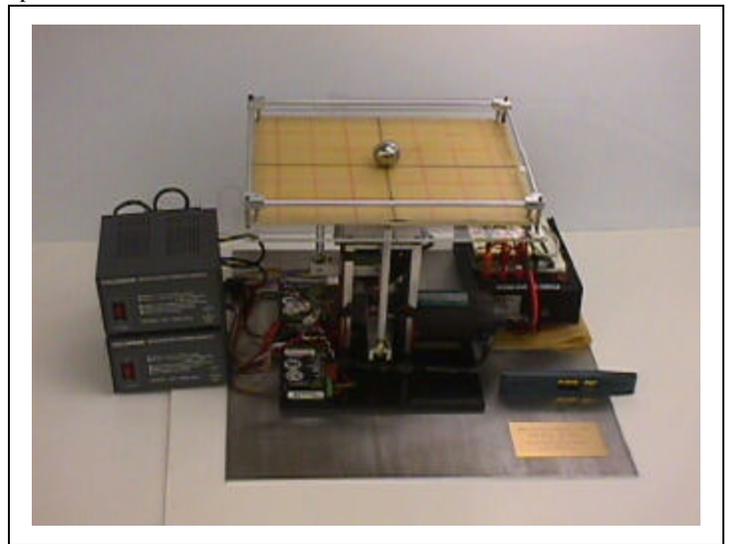


Figure 10. Ball-on-Plate Balancing System

### Inverted Pendulum Systems: Rotary and Arm-Driven

The inverted pendulum is a popular mechatronic application that exists in many different forms. The common thread among these systems is their goal: to balance a link on end using feedback control. This can be a formidable problem, depending on the configuration in question. Two rather challenging inverted pendulum systems are the rotational and the arm-driven systems. These use a link rotating about an axis to balance a second link on end. In the rotary (horizontal) configuration, the first link, driven by a motor, rotates in the horizontal plane to balance a pendulum link, which rotates freely in the vertical plane. The arm-driven (vertical) or "stick-on-a-stick" configuration uses a

driven link rotating in the vertical plane to balance the pendulum link, which also rotates in the vertical plane. The inverted pendulum system, shown in Figure 11, is unique in that it can be transformed from the horizontal to vertical configuration by replacing the links and setting the base on its side. The system uses a brushed DC motor powered by a pulse-width-modulated amplifier to actuate the first link. The command to the amplifier is provided by a MatLab / Simulink / dSPACE real-time control system. Feedback to the control system is provided by two optical encoders that provide position and velocity data for both links. Two separate control schemes are used for each configuration. The first control scheme is for swing-up control of the system. The goal of this is to swing the pendulum link up into the vertical position. Once the pendulum link is near vertical with minimal angular velocity, the second control scheme balances the link in an upright vertical position. Additional constraints can be added to further complicate the problem. These include a minimum number of movements for swing-up control and holding the driven link at a specified position while balancing the pendulum link.

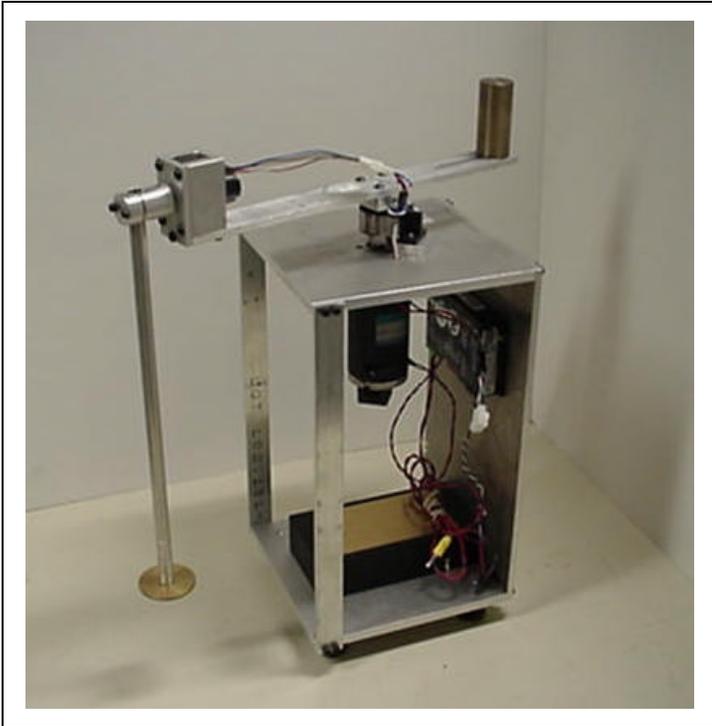


Figure 11. Inverted Pendulum Systems: Rotary and Arm-Driven

### Hydraulically-Balanced Beam System

The hydraulically-balanced beam system concept was developed by Professor D. Auslander at the University of California at Berkeley for use in mechatronics and controls courses. The physical system (shown in Figure 12) consists of a slotted, U-shaped aluminum beam (26 inches long, 5.5 inches high, 5.5 inches wide) that rotates with a shaft supported by bearings that are mounted in support stands. A water reservoir is located at each end of the beam and two gear pumps, powered with PWM servo amplifiers, are used to create a biased flow between the reservoirs. The pumps are positioned inside the aluminum beam and are connected in parallel to provide pumping between the two reservoirs without a dead zone. The amplifiers are

mounted externally to the beam on the base plate. Two pressure sensors, mounted inside the aluminum beam, are connected to the bottom of the reservoirs and are used to determine the mass of liquid in each tank. A potentiometer is used to measure the angular displacement of the beam. All system components are mounted symmetrically in the aluminum beam about the pivot shaft and there is a fine-adjustment mechanism to ensure that the beam system is balanced. The slot in the beam is used to vary the location of the system's fixed axis of rotation relative to the location of the system's fixed center of gravity (without fluid in the tanks). This allows one to change the system from an open-loop stable configuration to an open-loop unstable configuration. The system control effort is accomplished by continuously pumping water between the two reservoirs, creating a moment due to weight imbalance. The goal of tracking a velocity / position angle profile by pumping water between the two tanks is accomplished in a MatLab / Simulink / dSpace real-time control environment.

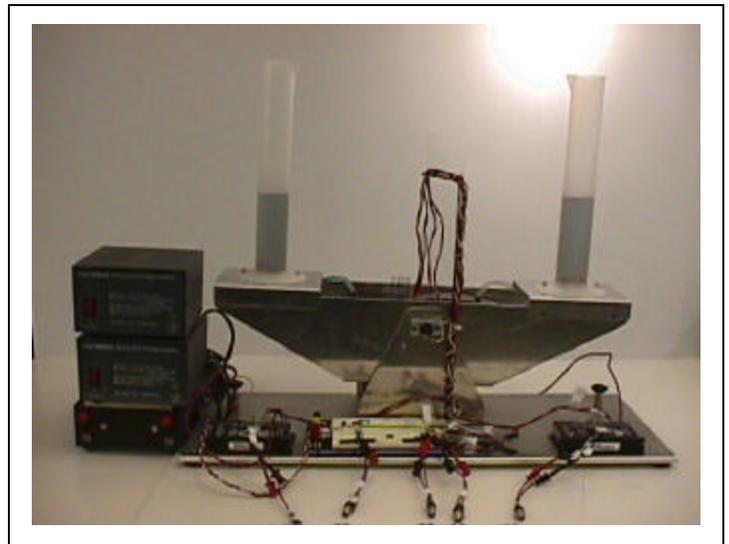


Figure 12. Hydraulically-Balanced Beam System

### PROFESSIONAL TRAINING IN MECHATRONICS

As a result of conducting 3-day mechatronics workshops, primarily for practicing engineers, over the past several years as part of the ASME Professional Development Program and also conducting hands-on mechatronics workshops for industry engineers, the following general observations are presented. These are not meant as criticisms but as issues that need to be immediately addressed by both university educators and practicing engineers.

1. *Control design and implementation is still the domain of the specialist.* Most mechanical engineers have never had practice designing and implementing a control system as part of a design. This grave deficiency can be traced back to their undergraduate engineering training where controls is taught very late in the

curriculum, if at all, as a mathematical exercise with hardly any design and little implementation.

2. *Very few engineers perform any kind of physical and mathematical modeling.* The standard procedure in industrial design is to build and test each design concept. Engineers are under such pressure to deliver hardware, they are not given the time to model and develop physical insight. This is true even if it can be shown that much money and time can be saved when problems arise or improvements need to be made if modeling were performed early in the design process. Even if engineers are given the time to model, physical modeling is a subject neglected in undergraduate engineering education since, in most instances, the problem presented starts not with the actual system, but with a physical model, and the problem ends with computer simulation results and no comparison to the actual system behavior. Also, to teach modeling requires experience with actual physical systems – something that is lacking in many faculty members.
3. *Mathematics is a subject that is not viewed as enhancing one's engineering skills but as an obstacle to avoid.* At the upper undergraduate levels in engineering, professors do not emphasize enough the importance of mathematics in engineering – the build and test mentality starts there. Also, the computer programs so widely used are often used without any understanding of the underlying physical and mathematical principles involved. This is related to the avoidance of physical and mathematical modeling, as often any modeling that is done is viewed as not being very useful, as it is often done by engineers with no hardware experience. Mathematics and modeling are essential tools in every mechatronics engineer's toolbox.
4. *Very few engineers have the balance between analysis and hardware essential for success.* Our engineering education system does not emphasize this enough. This trend will worsen as engineering schools continue to cut costs and rely more and more on computers to perform virtual experiments. How often have we heard someone say that the experiment must be wrong since the experimental results don't match the simulation results? That is very scary indeed!

These observations are most relevant to the field of mechatronics as physical and mathematical modeling skills, analysis skills, control design and implementation skills, and experimentation and hardware implementation skills are essential to success in mechatronic system design.

## CONCLUSIONS

YES! There is something new here! All mechanical engineers must become mechatronics engineers, regardless of their concentration. Mechanical engineering professors teaching design must teach an integrated approach to design – mechanical, electronic, controls, and computers – and so must become proficient in these areas. There is more of a need now than ever before for professors to balance modeling and analysis with hardware implementation in their

teaching. And students must learn how to design and implement analog and digital control systems before they graduate, as they most likely will need those skills immediately if they begin work as mechatronic engineers.

Industry wants and needs these skills in our mechanical engineering graduates and professors must meet this challenge head on.