MECHATRONICS CURRICULUM DEMONSTRATOR - AN EDUCATIONAL EXPERIENCE

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Abstract:

The University of Hartford mechatronic curriculum incorporates a language-neutral teaching approach for mechatronics system design courses that links the educational experience more closely with the processes and projects found in industry. Mechatronics education at the University of Hartford focuses on four categories; components (sensors and actuators), computer interfacing electronics, systems (modeling, analysis, simulation, and control), and language-neutral visual programming environments for implementation. The last category is especially important when one considers the extent of general software knowledge in mechanical engineering and the complexity of the language based software development process for developing real time embedded applications. The goals of this paper are to describe (1) the University of Hartford mechatronic curriculum, (2) the language-neutral teaching approach for mechatronics, and (3) a low cost technology demonstrator, developed and refined by the authors, which is suitable for studying the key elements of mechatronics including system dynamics, sensors, actuators, and computer interfacing.

1. INTRODUCTION

Mechatronics is a methodology used to achieve an optimal design of an electromechanical product. As a design philosophy, mechatronics serves as an integrating approach to engineering design. A mechatronically designed product relies heavily on system and component modeling and simulation to establish the optimal design tradeoffs between electronic and mechanical disciplines when subject to specific cost and performance constraints. The ideas and techniques developed during the interdisciplinary simulation process provide the ideal conditions to raise synergy and provide a catalytic effect for discovering new and simpler solutions to traditionally complex problems.

An important characteristic of a mechatronic system is its built-in or embedded intelligence. This intelligence, a result of the interdisciplinary simulation process, is implemented through embedded software that orchestrates a combination of precision mechanical and electrical components. There is a synergy in the integration of mechanical, electrical, and computer systems with information systems for the design and manufacture of products and processes. The synergy can be generated by the right combination of parameters, that is, the final product can be better than just the sum of its parts. Mechatronic products exhibit performance characteristics that were previously difficult to achieve without this synergistic combination.

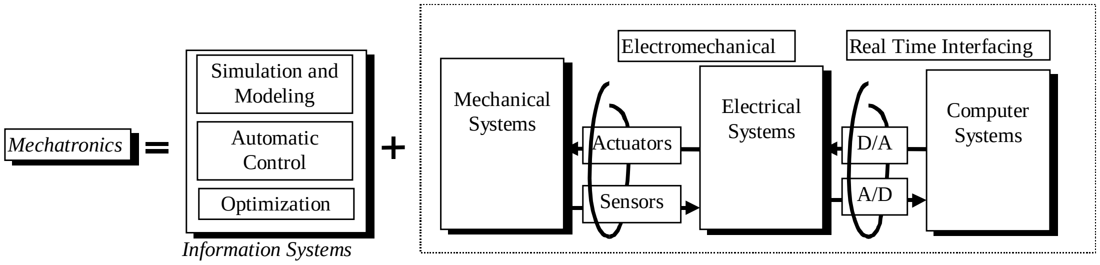

Fig. 1. Key Mechatronic Elements

The key elements of the mechatronics approach are presented in *Figure 1* (Shetty and Kolk, 1998). Mechatronics is the result of applying information systems to physical systems. The physical system, the rightmost dotted block, consists of mechanical, electrical, and computer (electronic) systems as well as actuators, sensors, and real time interfacing. Sensors and actuators are used to transduce energy from high power, usually the mechanical side, to low power, the electrical and computer or electronic side. The block labeled mechanical systems frequently consists of more than just mechanical components and may include fluid, pneumatic, thermal, acoustic, chemical, and other disciplines as well.

New developments in sensing technologies have emerged in response to the ever-increasing demand for solutions of specific monitoring applications. They have produced faster, more sensitive and precise measuring devices. Sensors are being miniaturized and implemented in solid-state form so that several sensors can be integrated and their functions combined. Irrespective of the application; industrial control, manufacturing, testing, or military, new developments in sensing technology are constantly emerging.

Fig. 2 Lockheed F22 fighter

The F-22 fighter, pictured in *Figure 2,* jointly developed by Lockheed and Boeing, is an example of mechatronic technology in action. The design metrics emphasize reliability, maintainability, and performance. Multi-disciplinary functionality such as the integrated flight-propulsion control system and thrust-vectored engine nozzles, make point-and-shoot maneuvers that defy conventional aerodynamic control possible.

Starting with the basic system design phase and progressing through the manufacturing phase, the mechatronic process optimizes the system parameters at each phase to produce a high quality multi-disciplinary integrated product in a short cycle time. Mechatronics employs control systems to provide a coherent framework for component interactions and their analysis. Integration within a mechatronic system is performed through the combination of hardware components and software, including information processing. Hardware integration results from designing the mechatronic system as an overall system which includes the sensors, actuators and embedded computer as well. Software integration is based on control functions and algorithms to be performed.

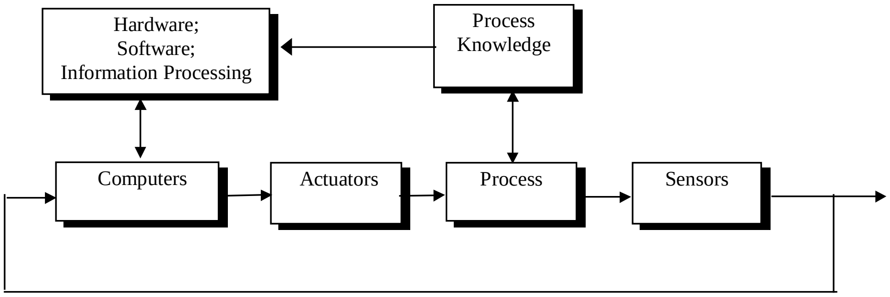

Fig.3 General Scheme of Hardware and Software Integration

Figure 3 illustrates how the hardware and software integration takes place. It also illustrates how additional process knowledge, as it becomes available, is utilized to improve the system design.

The benefits of the mechatronic design approach are greater productivity (shorter development cycles and faster time to market), higher quality, and lower cost products. They also provide additional influence through the acquisition of knowledge information from the process. A mechatronic product can achieve impressive results if it is effectively integrated with the concurrent engineering management strategy.

2. UNIVERSITY OF HARTFORD'S MECHATRONIC CURRICULUM

The mechatronics sequence at the University of Hartford provides a valuable addition for students pursuing a mechanical engineering degree. The sequence, consisting of four courses, was not only easily developed but also easily incorporated because three of the four courses were currently being taught in mechanical and electrical engineering programs. The fourth course, Mechatronics System Design I, was the only new course that had to be developed. Adapting this same sequence to other universities would likely be just as easy.

Of the three existing courses, two are from the Electrical Engineering program, (1) Basic Engineering Circuit Analysis and (2) Principles and Applications of Electrical Engineering. The third course, Control System Engineering, is the introductory controls systems course offered in the Mechanical Engineering program. Mechatronic System Design I was a new course specifically developed for the mechatronics sequence. A second course, Mechatronic System Design II, will be added to the sequence and offered in the near future.

A brief description of the course contents is presented in the following sections and the syllabi for each course are included in Appendix 1.

Basic Engineering Circuit Analysis

A basic course in electrical engineering covering circuit elements and methods of circuit analysis. Topics include: AC analysis, Phasors, AC power calculations, Power factor/correction, Three phase circuits, Transformers and analysis, Complex frequency, Laplace transforms, Two port networks, Filters, Fourier series.

Principles and Applications of Electrical Engineering

A course in electronics covering the basic operating principles of solid state devices. The course covers (1) discrete component circuits (power supplies, amplifiers), (2) Op Amp chip based circuits (filtering, summing, amp,…), and (3) Logic circuits (boolean algebra, combinational logic, sequential logic). This course includes a lab in which students will construct breadboard prototypes of electronic circuits, use lab instruments such as multimeters and oscilloscopes, to analyse test data and prepare technical reports.

Control System Engineering

An introductory course in mechanical engineering covering methods of system modeling, analysis, and basic compensation techniques. Topics covered include: Block diagram modeling, Laplace Transform, Control System Performance Metrics, and Root Locus design/analysis of single input/single output control systems. Several design projects will introduce students to computer applications including VisSim, Matlab, and Labview.

Mechatronic System Design I

A first course in Mechatronics covering (1) General system behavior, representation, and simulation, (2) Electrical, electronic, mechanical, and electromechanical systems and characteristics, (3) Basic sensors – operation and governing equations (including error analysis), (4) Actuators including solenoids and motors, and (5) Computer "in the loop" issues including sampling, A/D and D/A conversion, aliasing, and computer architecture. Students use VisSim or Labview applications for simulation and real time experiments. An important part of this course is a design project in which students work in teams on a realistic mechatronics application. Each team presents a semester-end summary of their design project and results both orally and written in a technical report format.

Mechatronic System Design II

This course will address the following six topic areas;

1. Signal Processing – theory and application; System ID from data
2. Control system design – SISO only (PID, hysteresis (on/off), decoupling, linearizing, Fuzzy, Fuzzy + NN)
3. Micro-electromechanical Systems
4. Advanced sensors
5. Using wide area and local area networks (WAN, LAN) including Ethernet
6. Elements of enterprise systems: client server architecture, remote connectivity, remote upgradeable s/w, applications (machine health and monitoring, energy management, electronic service,…).

3. LANGUAGE-NEUTRAL TEACHING APPROACH

Historically, mechanical engineering has focused on machine improvement through mechanical design. Ease of assembly and service, weight, efficiency, and reliability are all metrics considered in the design but the majority of design solutions are deployed in the mechanical design itself and do not involve cross-discipline (software and electronic) technologies.

Today, a mechanical engineer with training in mechatronics offers three new benefits. First, a mechatronics engineer is familiar with the benefits and limitations of cross-discipline technologies in software and electronic hardware. Second, a mechatronics engineer has been trained on how to apply this knowledge to optimize a mechanical design. Third, a mechatronics engineer understands how to rapidly prototype and test various embedded solutions to develop a final solution.

Due to the extensive use of microelectronics, materials and control, many of the processing circuits, which were historically part of the external configuration, are now routinely built, or integrated, into the product. For example, smart sensors with integrated microelectronic circuits for linearization and signal conditioning make sensors modular and easy to use in a wide variety of applications. Microsensors and microelectromechanical systems have found countless applications in consumer products, healthcare, process control, military/aerospace and environmental engineering. Their small size, exceptional performance, and broad applicability offer engineers new potentials for enhanced system designs.

One of the major challenges of any mechatronics sequence is the process for software design, implementation, and test. Basically there are two teaching approaches; (1) focus on the embedded software programming and embedded hardware aspects which include language, computer architecture, and development tools or (2) focus on visual language-neutral programming applications, such as Simulink, Labview, VisSim, and others, which generate less efficient software but do not require the time needed to gain an intimate knowledge of a language and its development environment.

At the University of Hartford the second approach has been successfully applied for several years and is enthusiastically endorsed. It is the author's belief that embedded software development cannot and should not be a focus area for mechanical engineers. Such development requires extensive knowledge of software, hardware, and development environments which is, after all, the focus of most computer science programs. Even in industry today, multi-discipline teams consisting of systems (mechatronics), software, and hardware, are most commonly found. It is the exception, not the rule, that a mechanical (mechatronic) engineer today would be expected or even considered to develop and test an embedded software application in its native language and hardware.

4. MECHATRONICS TECHNOLOGY DEMONSTRATOR

The Mechatronics Technology Demonstrator (MTD) is a low cost technology demonstrator, developed and refined by the authors. It is a mass – spring – damper system with an electromagnetic force actuator and a non-contact position sensor. It is built from low cost components available at most electronic, hardware, and home supply stores. It is suitable for studying the key elements of mechatronic systems including; mechanical system dynamics, sensors, actuators, computer interfacing, and application development.

The MTD can be constructed in two configurations, vertical (Figure 4) and horizontal (Figure 5). The vertical configuration offers greater motion control over shorter distances while the horizontal configuration provides just the opposite.

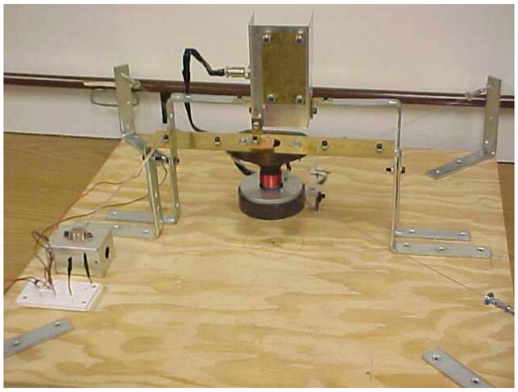

Fig 4: Vertical MTD Configuration

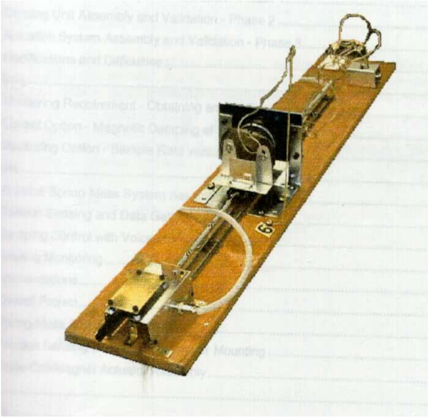

Fig 5: Horizontal MTD Configuration

Regardless of the configuration, position of the mass in the MTD is measured using a position sensing detector (PSD) device. The PSD outputs a voltage proportional to the intensity of the light cast upon it. The light source, a laser similar to the type used for overhead presentations, is fastened to the base of the MTD and aimed at a mirror attached to the mass. The laser is adjusted until the reflected beam just hits the center of the PSD when the mass is motionless and in its normal position. As the mass moves around its normal position the reflection angle changes which, in turn, changes the area (intensity) of the light hitting the PSD and hence its voltage. Aside from the initial "tuning" of the laser beam angle, the motion sensing method is extremely accurate, non-contact, and extremely easy to implement.

To provide force inputs to the mass for motion and/or active damping a voice-coil/magnetic actuator is used. Basically a small loudspeaker is used with the paper cone coated with fiberglass resin to provide a firm mounting area. The magnet is separated from the voice coil and attached directly to the mass. The voice coil is attached to the base of the MTD. Application of current to the coil results in either vertical or horizontal motion of the magnet depending on the orientation of the mounting. Alignment of the magnet inside the voice coil is somewhat critical to reduce binding. The vertical configuration offers additional benefit in this area. Figure 6 presents the vertical configuration of the actuator.

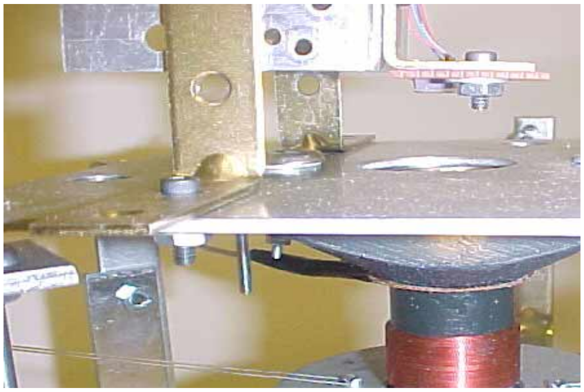

Fig 6: Voice coil/magnetic actuator – Vertical Configuration

Both the sensor and the voice coil actuator are connected to the PC based visual modeling and real time simulation application using a general purpose I/O card. The voltage output by the PSD is ample for direct connection without the need for amplification. The current used to drive the voice coil, however, does need amplification. The amplifier circuit used to power the actuator is shown in Figure 7.

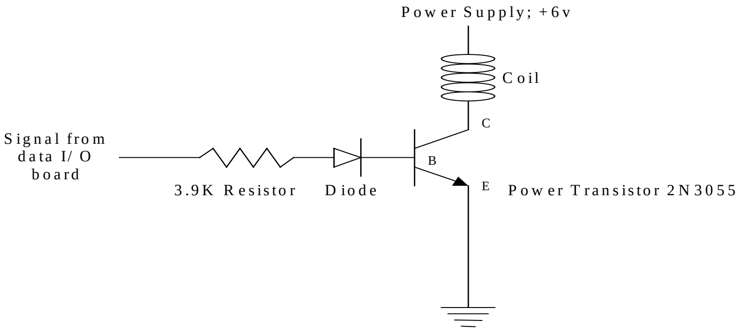

Fig 7: Actuator amplifier circuit

Experiment Options: The MTD can be used for several study options in mechatronics including modeling, simulation, monitoring, and closed loop control. A brief description of two of the options follows.

Option 1 - Modeling and Simulation:

1A: The physical model of the mass spring system is constructed using the block diagram. The model will provide prediction from a force input to the mass displacement (and velocity). To verify the performance of the model, the experiment is conducted in parallel with actual data obtained along with a plot of comparison displacement outputs. Model parameters are adjusted until good performance correlation exists. An example of a block diagram model is shown in Figure 8.

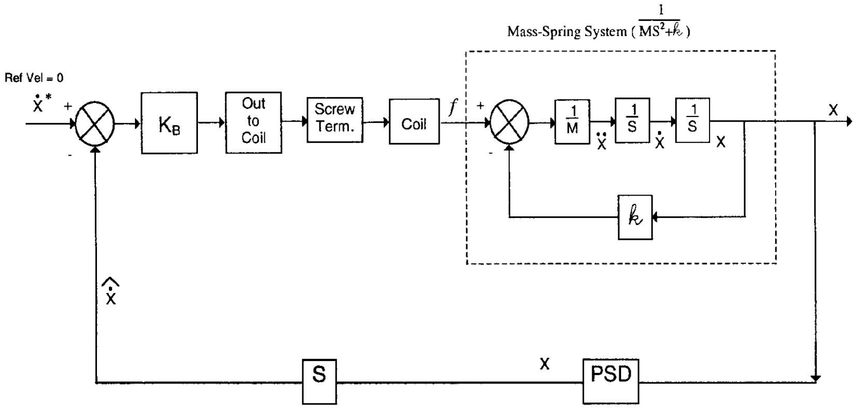

Fig 8: Physical system block diagram for MTD

1B: A Least Square model of the mass spring system is developed using a step force input to the mass and recording the resulting displacement. The parameters in the second order model are computed using the least square method with gradient adjustment. To verify the performance of the model, it is run in parallel with additional data records.

Option 2 - Control:

Closed loop control is used to provide additional electronic damping to the MTD in order to smooth the time response. Two control options are considered; rate feedback control design and validation and on/off control design and evaluation.

2A: Design a model based control algorithm of the “rate feedback” type to electronically increase the damping applied to the mass. This will require installation and calibration of the magnetic actuator and design of the rate feedback control algorithm.

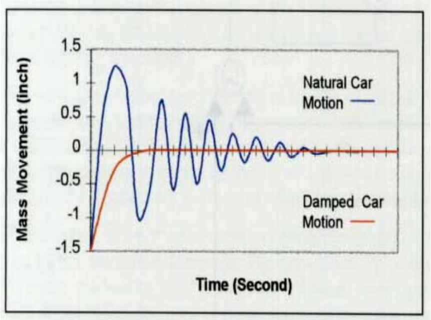

Fig 9: Mass displacement response with rate feedback control

2B: Design an on/off control which increases the damping applied to the mass. This will require installation and calibration of the magnetic actuator and design of the rate feedback control algorithm. The algorithm will sense peak points of mass acceleration, negate them and send the information back to the actuator.

5. CONCLUSIONS

The University of Hartford mechatronic curriculum incorporates a language-neutral teaching approach for mechatronics system design courses that links the educational experience more closely with the processes and projects found in industry. This paper has presented and discussed three topics; the University of Hartford's mechatronics sequence and curriculum which is suitable for adaptation in other universities, a language-neutral teaching approach which makes the sequence possible to teach in limited time, and a low cost mechatronics demonstrator suitable for many investigations.

REFERENCES

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Schlemer, L and Alptekin, S " *Team based product Development in Mechatronics Design Class"* ASME Presentations, 1998-WA/DE-19

APPENDIX 1: MECHATRONICS COURSE SEQUENCE SYLLABI

A1.1: Basic Electrical Engineering Circuit Analysis Syllabus:	**A1.2: Principles and Applications of Electronic Engineering Syllabus:**
TOPICS & [PROBLEMS]	**Topics and [Problems]**
2d order DC ckts, Sinusoids [1,2,4,5]	Circuits Review [2.48, 3.19, 4.47, 6.21]
Sinusoids, complex forcing functions, phasor relationships [6,7,8]	Diode characteristics, large signal model
Impedance/Admittance [12,13,15,21,26]	Diode small signal model, load line, ratings [8.8, 8.11,8.15]
Phasor Diagrams, Basic Analysis using Kirchhoff's Laws [31,35]	Diode circuits, rectifier, regulator [8.24, 8.26]
Advanced Circuit Analysis Techniques [68,70,89,90]	Diode signal processing applications, limiter, peak detector, clamp, LED [8.37, 8.42, 8.47]
Pspice Analysis Techniques [	Transistor introduction, biasing, switch and amplifier circuits
Instantaneous, average, max power transfer [6,7,19]	BJT operation and region of operation [9.6, 9.8, 9.10]
RMS, Power factor, Complex power [28,34,47,49]	MOSFET transistor operation
Power Factor Correction, Measurement, Single Phase [54,60,62]	Small signal BJT models for amplifier applications [10.7, 10.9]
Applications [71,72]	BJT small signal amplifier analysis, voltage and current gains
3 phase ckts, connections, source/load connections, EXAM 1 take home	**Exam 1 Review**
Source/load connections, EXAM 1 Due [2,3]	BJT small signal amplifiers, analysis
Source/load connections, Power [6,27,30,37]	Op Amps: inverting, noninverting, summer, subtracter, integrator, LPF [diff eqn ckt]
No Class	Op Amps; frequency response, bode magnitude plots [12.35, 12.36, 12.39]
Power, measurement	Op Amps; frequency response (cont)
Mutual Inductance, Energy Analysis, (Pspice)	Op Amps; instrumentation amp, Gain-BW constant, filter design [12.46, 12.53, 12.56]
Ideal transformer	Op Amps; analog equation solution, CMRR, slew rate limit
(Pspice), Autotransformer, 3 phase transformers	Review
Applications, EXAM 2	**Exam 2**
Sinusoidal frequency analysis, Bode Plots	Binary Number System, Boolean Algebra [13.1, 13.4, 13.6, 13.7, 13.9]
Bode plots, Resonant circuits	Boolean Algebra
Resonant circuits	Thanksgiving Recess, No Class
Scaling, passive filters	Basic Logic Gates [13.27]
Active Filters	Combinational Logic Circuits, Karnaugh Maps [13.29, 13.40, 13.47]
Thanksgiving Recess, no class	Sequential Logic Circuits, SR Flip Flops [13.59]
Filter applications	JK, D, T Flip Flops, pulse counter [14.1, 14.2, 14.3]
Two port networks, admittance and impedance	Review
Interconnection of two port networks	**Exam 3**
Review, FINAL	**Final Exam**

A1.3: Control System Engineering Syllabus:	**A1.4: Mechatronic System Design I Syllabus**
Topics and [Problems]	**Topics and [Problems]**
Intro to Control Systems, terminology, basic concepts	**Introduction to Mechatronics**
Functional Block Diagrams, manipulations [1,2,3,4]	Introduction to Mechatronics
Laplace Transform (LT) Solution of Differential Equations	Error Analysis [ch 3 hw]
LT (cont): [chap 1: 11,12,13,14]	**General Systems – Behavior and Representation**
No Class	System terminology, operators, states, transfer function and block diagram representation of systems
Block Diagram – Transfer function manipulations [7,8,13]	Continuous time system modeling (representation), block diagram manipulations
Modeling and Simulation: Electrical circuit modeling [13,15]	Intro to Vissim and Labview - Kondo
Electric circuit modeling (cont) [17,19,20]	Response characteristics; steady state gain, time constant, time delay, damping, natural frequency
Analogies for mechanical systems [21,22], **Project 1**	Simulation of ODE, mass-spring-damper system using vissim – **Simulation Experiment Assigned**
Analogies (cont) [26,29,38]	**Physical Systems – Operation and Representation**
Analogies (cont)	Electrical Systems; Basic components, Ohms law, series, parallel, voltage and current dividers
Intro to Vissim**, Project 1 due, Exam I – take home**	Electrical Systems; Power, transformers, impedance matching – Kondo
Performance Specifications: S-Plane, Poles, Zeros, PZ Diagrams, time constant	Electronic Systems; Basic operation and use of Diodes, transistors (BJT, FET), OpAmps
Transient Response [2,4,6], **Exam I due**	Electronic Systems; Op-Amp applications; inverting, noninverting, summer, integrator, difference amp, instrumentation amp – Kondo
Transient Response - 2d order system [16.19,20]	Application: Using I/O cards with Labview, Vissim– Kondo – **Data Acquisition Experiment Assigned (light sensing, temp sensing)**
Stability, Routh-Array [4,5,7,19,26]	Mechanical Systems; translation, rotation, Electromechanical coupling
Stability (cont)	Midterm Exam
Steady State Error, Error Coefficients [1,4,15,24,49]	**Sensors – Basic types and Operation**
Steady State Error (cont), Review	Position, speed, and acceleration (vibration); proximity sensors, potentiometers, LVDF, piezoelectric – **Final Project Assigned**
Exam II – In class	Stress and strain measurement; resistance strain gage, wheatstone bridge
Analysis Tools: Intro to Root Locus [1,2,3] **Project II**	Temperature; bimetallic strip, electrical resistance thermometer, thermocouple,
Root Locus Sketching [5,9,18,21]	Pressure and Flow;
Root Locus Sketching (cont) [24,34]	Semiconductor and MEMS;
Time delays, gain from RL	**Actuators – Electromechanically**
Design Tools: Root Locus Compensation [1,2]	Solenoids, relays, electric motors
Root Locus Compensation (cont) [3,4,6]	DC PM motors; governing equations, dynamics, control
Root Locus Compensation (cont) [19,20]	Stepper Motors; operation, equations, control – Kondo, OptoIsolator + stepper motor control
Root Locus Compensation (cont) [21,23,24] **Project II due**	Motor selection
Review	**Real Time Computer Systems for Data Acquisition and Control**
Final	Computer architecture, Embedded System architecture, Network architectures
	Analog – Digital conversion; basic process, aliasing, oversampling, Nyquist frequency and Sampling theorem
	A/D and D/A converters; successive approximation, integrating
	Project 2 Due: Report and Class Presentation
	Final Exam

APPENDIX 2: OTHER INSTRUCTIONAL PROJECTS

Data Acquisition Examples

- Testing of Transportation Bridge Surface Materials
- Transducer Calibration System for Automotive Applications
- Strain Gauge Weighing System
- Solenoid Force - Displacement Calibration System
- Rotary Optical Encoder

Data Acquisition and Control Case Studies

- Solenoid Force - Displacement Calibration System
- Thermal Cycle Fatigue of a Ceramic Plate
- PH Control System
- *De-Icing Temperature Control System*
- Time Delay Blower
- Position Control of a Vane using air blower

Controlling temperature of a hot/cold reservoir

The system is designed to control the output water temperature of a mixing valve fed by two reservoirs. Output temperature is measured by a thermister, voltage of thermistor is utilized as analog input to data acquisition cards. The simulation returns the temperature of water. Position of the valve is monitored by reading voltage across pot and simulation software determines the position of the valve

Computer monitored automated torque wrench for threaded fasteners

Used to tighten nuts to a specified value. Torque range is 25 to 100 LB-in. within +/- 2% error. Closed loop, torque sensor, analog output, range 0 - 100 LB-in is 0 to 5 volts. Actuation with a rely control to a dc motor actuator, on-off control is used.

Inverted pendulum control

A single inverted pendulum system driven by a DC motor is controlled by VisSim. Input is the pendulum angle with respect to vertical read by a potentiometer on the pendulum axis. A transducer is used to control the car near the midpoint of the track.

Precision position sensing using computer interface

Based on an xy table with motion measured by encoders, the outputs of the encoders are fed to the interface. Actuation uses two stepper motors in the x and y directions. One encoder is coupled to each lead screw (axis) and the position is fed back to vissim to control the position of each stepper requires 4 digital outputs for each stepper and each encoder is read as an equivalent voltage.

Auditorium podium height control system with computer interface

An overhead sensor measures distance of speaker to microphone. 2 Ultrasonic sensors are used to sense distance (output analog voltage), the podium height is controlled by stepper motor with a step down gearbox.

Tension control system

This type of system is used in wire extrusion or tape industries. It maintains constant tension in line subject to varying capstan radius.

Computer controlled fluid power operated hydraulic winch

Tangential velocity of a cable on a winch is controlled at a constant value. A sensor measures the wrap radius and the linear velocity of cable is measured by a roller to a tachogenerator, the output is feedback voltage. The set point is a reference voltage corresponding to a cable velocity. Wrap radius is used to linearize the nonlinearity.

Proportional control and monitoring of metal forming operation

Metal forming operations, which take place between a punch and die block, have a need for continuous monitoring of velocity, and position. An encoder is used to obtain position, which is differentiated to get velocity. When the punch goes down the position information is taken, if displacement exceeds limit, process will stop. Useful in forming operation for aluminum containers because if you exceed the limit a thickness variation is created.

Monitoring of bulk materials in transit using computer interface

Continuous inspection and quality control of bulk materials in transit (food products industry). Conveyor system which carries different bulk materials. Boxes are continuously weighted on a weighing platform using an LVDT. Pass or fail depending on limit range.

Telemeterized temperature measurement of biomechanical implant in knee joint of animals

These type implants are used in the knee joints of dogs. The device will measure the variation in the temperature of the knee joint over a period of time by telemetry. A sensor plus transmitter is used to send data through a data acquisition card and VisSim. Signal conditioning is used to remove the transmission noise. Then a calibration of voltage to temperature is used for remote monitoring of temperature.

Evaluation of human muscle performance using sensor interface and vissim

Hand functions of an injured person in the process of recovery are to be evaluated for rehabilitation purposes. Involves a testing machine and equipment to monitor the velocity, acceleration and torque of human joints using torque sensors, position and velocity detectors.

Neural network and pattern recognition using industrial robot and vissim

Involves a 5-degree of freedom robot driven by 5 stepper motors. The steppers are powered from an external power supply controlled from the serial port of the PC. Sensors are read by VisSim, pre-processed, and used to detect the quality of the filters. The information is then sent to a neural network program (VisSim Add-on) which outputs information to the robot to either pass or fail the part. The robot movements are pre-programmed open loop.

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