An Integrated Modular Senior Design Laboratory for Electrical Engineers

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ABSTRACT

The authors propose an integrated modular design laboratory to enhance the existing senior design experience in Electrical Engineering at Clarkson University. This laboratory integratea physically-based device-s and components within a PC-based data acquisition and control environment. The new design sections offer an integrated systems approach for the rapid development and implementation of both hardware and software components in a complete engineering design.

I. INTRODUCTION

At Clarkson University, undergraduate electrical engineering students are required to complete a sequence of three laboratories culminating in the senior capstone design laboratory. The first two electrical engineering laboratories are taken during the sophomore and junior years, respectively, and are common to all electrical engineering disciplines. In t hese introductory laboratories, students are introduced to the techniques, circuits, and instruments used to make electrical measurements. The laboratory work provides experience in the use of ammeters, voltmeters, oscilloscopes, bridges, signal generators, and other instruments. All experiments in these two laboratories are well structured and include some introductory design projects. A majority of the undergraduat e design experiences are obtained, however, in the senior design laboratory which has historically consisted of five ad hoc sections (instrumentation, electronics, robotics/control, power, and solar car), and provides senior students with the laboratory specialization of their choice.

In recent years, this senior laboratory has undergone significant changes in the electrical engineering curriculum based on accreditation requirements. Several sections of this course were taught in areas of strong departmental expertise, such as controls, robotics, power engineering, power electronics, electronics, instrumentation, and the solar car project. Each senior design section was taught by a separate faculty member and enrollment was limited to at most 30 students per section. This course typically involved a series of design projects in each area of interest and required different prerequisites. Students typically worked in design teams and got involved in a series of design steps including planning, analysis, preliminary design, simulation, construct ion, t esting and evaluation, class demonstrations, oral presentations and documental ion. The goal in each case was to provide the student with the opportunity to develop a complete solution to one or more design problems and to develop effective communication skills.

A. The Need for an Integrated Modular Design Laboratory

Unlike the well-structured sophomore and junior laboratories, the various senior design sections were run independently of each other, with little in common other than the overall design spirit. According to the personal experience of the investigators, many students performed poorly due to a number of deficiencies which can be attributed as follows:

1. Meaningful senior design projects require interdisciplinary teamwork between students of various electrical engineering backgrounds. Present efforts to involve groups of students from several disciplines have been hampered by the fact that there is no common framework for the senior design as opposed to the sophomore and junior laboratories.

2. The prior senior design laboratory did not take advantage of current microprocessor technology and modern digital instrumentation for data acquisition and control purposes.

3. The prior senior design laboratory did not provide enough "hands-on" experience with machines and drives, without which meaningful design projects are difficult to implement in areaa as diverse as power engineering, power electronics, controls, and robot ics.

4. New and emerging technologies (e.g., in the areas of electric/electronic control of power processing/conversion), require a changing educational focus towards more elaborate, systems-oriented design applications, Only a few schools are adapting to this changing environment [1]-[4].

5. Given the current state-of-the-art, undergraduate students must have greater exposure to an integrated system design [5] approach (i.e., the integration of both hardware and software in a complete engineering design). The prior emphasis was on the design of hardware-related projects only.

6. An important element of the design process which is currently overlooked is the inclusion of reliability concepts and techniques in all stages of the design process.

II. Revised Senior Design

The goal of the proposed undergraduate laboratory development is to enhance the existing senior design experience in electrical engineering. The deficiencies associated with the current senior design laboratory can be remedied by introducing a new modular laboratory structure with a revised curriculum. The modular laboratory structure integrates physically-based devices and components within a microprocessor based data acquisition and control environment. As shown in Figure 1, the initial laboratory structure would consist of four design modules (power engineering, power electronics, controls, and robotics).

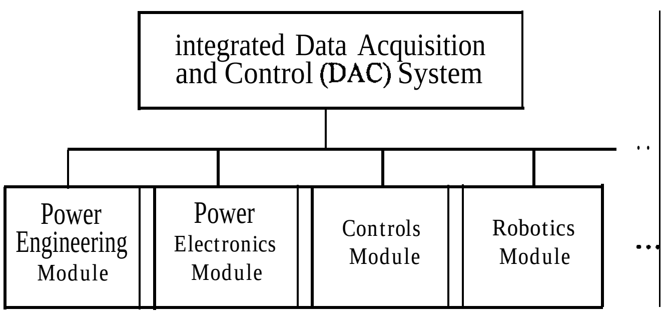

Figure 1: A Modular Design Laboratory.

A. Educational Objectives

The proposed laboratory structure offers several advantages over the existing, traditionally-based, senior design laboratory [12]. First, it introduces a greater degree of commonality in the design methods learned and the state-of-the-art equipment utilized for each project across all disciplines. Secondly, it accommodates the addition of new design modules from other electrical engineering disciplines (digital signal processing, communications, etc.), as future expansion.

The proposed laboratory curriculum will also be revised to meet the following specific objectives:

1. Teach the fundamentals of electric machinery, power electronics, electric drives, motor control, robotics, and other feedback applications.

2. Teach fundamental system concepts such as stability, feedback, linearization, analog and digital controller design, classical and advanced cent roller design for various plants.

3. Teach both hardware and software interfacing of sensors, computers, and modern digital test instruments with various plants.

4. Integrate the computer as a tool for design, simulation, data acquisition, and control of various plants.

5. Include reliability evaluation techniques at all stages of the design process.

Simple introductory experiments (using similar, yet less advanced technology), will also be integrated into the sophomore and junior laboratories, in order to better prepare students for the proposed senior design experience.

B. Laboratory Setup

The integrated laboratory framework is provided by eight PC-based data acquisition and control (DAC) workstations. The DAC workstations serve aa computational engines for the individual design modules. As shown in Figure 2, each DAC workstation consists of a 486/PC equipped with specialized hardware/software and dedicated test instruments. The remaining components are modular in nature and dependent on the particular design section considered. A typical design module would consist of a system plant (a synchronous machine, an inverted pendulum, a robot arm, etc.), which is interfaced to the DAC system and analyzed/controlled by appropriate 1/0 signals.

The “brains” of each DAC system is a high-performance, floating point, digital signal processor (DSP) board which resides on the 486/PC bus [6]. The DSP interfaces with each design module via appropriate 1/0 boards which also reside on the 486/PC bus, In this way, sensor signals are passed from the module hardware to the DAC system for analysis (using the DSP), while control signals (generated by the DSP), are passed from the DAC system to the module hardware. The proposed set-up facilitate the rapid design and implementation of complete engineering systems using real-time data acquisition and control.

The proposed module structure brings several innovations [14] to the present laboratory practice. First, the use of personal computers and embedded DAC systems are integrated to facilitate elaborate and challenging design projects for senior undergraduate students. In addition, the DAC environment’s use of “language” modules makes it system language flexible. This allows students to describe systems using popular simulation package languages like Matlab/Simulink or Simnon. The specific new experiments to be conducted, and the associated principles and phenomena taught, are now discussed for each of the integrated design modules proposed.

1. Power Engineering/Power Electronics Modules

The support courses for this section include a required electromechanical energy conversion course and a elective course on electric machines and drives. The students will gain hands-on experience with these conventional machines by using them, for example, in the design of adjustable-speed drives. The new design projects are systems-oriented and include many fundamental concepts from other areaa within the Department such as controls, computers, electronics, and communications.

Typical projects in the power engineering and power electronics sections include the following:

- Design of voltage regulators, power system stabilizers, and torque-angle transducers for synchronous machines.
- Design of static solid-state power converters (DC-DC switch-mode power supplies, DC-AC single-phase inverters, etc.)
- Design of computer-aided motor drive controllers for DC and AC machines.

For example, a team of students will design a classical digital controller (lead/lag, PID) to improve the damping of the electromechanical oscillations of a synchronous generator. In this case, the system plant of Figure 2 is a synchronous generator driven by a dc motor and synchronized to the network. Students will design a power system stabilizer whose output signal is used to modulate the reference voltage of the regulator exciting the field winding of the synchronous machine. Students can describe the system under study using popular simulation languages like Matlab/Simulink or Simnon. Using the DAC environment for simulation, the students may vary controller parameters until a final satisfactory design is obtained. The language flexibility of the DAC software environment facilitates the design of even advanced control strategies, such as adaptive control or robust control algorithms. The control performance of the simulated and physical models can then be directly compared by using the DAC environment for experimental implementation (i.e., by acquiring real-time waveforms using modern digital instrumentation and torque-angle transducers). The parameters of the experimental control system can then be retuned until the physical model meets the desired performance object ives.

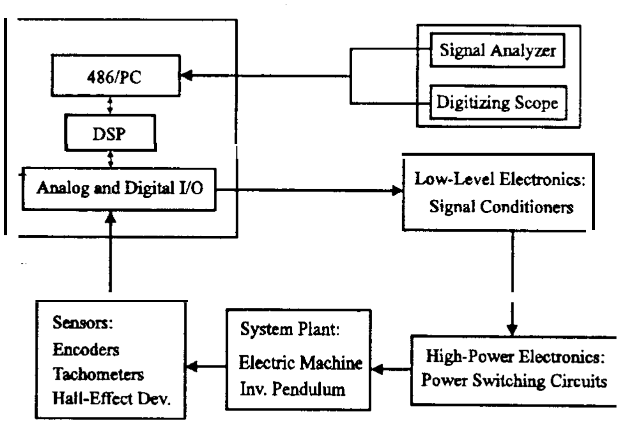

Figure 2: A Typical DAC Workstation.

2. Controls Module

The controls module examines fundamental control engineering concepts through various task-oriented design projects [7], [13], [15]. Each project focuses on controller design for a particular class of system (the plant), and various control objectives are associated with each plant. Several design projects would be completed by senior level undergraduate students within a single semester. A typical design project involving the design of trajectory tracking controllers for permanent magnet brush dc motors is described below.

The proposed project compares the time and frequency-domain responses of nonlinear tracking controllers with those of classically designed linear controllers. The control objective is to provide accurate position tracking of an inertial load directly-driven by a brush dc motor. Controller performance will be judged according to the following criteria:

- Static Performance
  - steady-state tracking error (i .e., accuracy, reliability),
- Dynamic Performance
  - speed of response (i.e., delay/rise/settling times);
  - maximum overshoot/undershoot.
- Frequency Performance
  - control bandwidth, slew-rate, and energy requirements.
- Robustness/Reliability of Performance, with respect to
  - plant parameter changes;
  - neglected dynamics (i.e., static friction);
  - sensor failure (i.e., partial-state feedback);
  - actuator/controller saturation;
  - quantization error.

The associated design strategies and laboratory procedures can be summarized as follows:

- Model the coupled motor/load dynamics, including relevant mechanical and electrical effects, to obtain
  - a nonlinear, time-domain model of the plant (i.e., a set of differential equations);
  - a linearized, frequency-domain model of the plant (i.e., a transfer function description);
  - where appropriate, the DAC system is used for system identification purposes.
- Given the system models, design voltage level control inputs which provide some measure of trajectory tracking (for step, ramp, or arbitrary inputs), The types of controllers explored include

nonlinear controllers such as computed torque control (i.e., feedback linearization), adaptive control, and robust control;

– classical/linear controllers (PID control, lead-lag, pole-zero cancellation, feedforward compensation, rate feedback, and pole-placement/integral control using state feedback.

- Use the DAC system to analyze the stability of the proposed controller designs by applying relevant control theory, such as Lyapunov analysis, state-variable analysis, time-domain analysis, frequency-domain analysis (e.g., root locus, Nyquist plot, Routh-Hurwitz, etc.).

- Support the theoretical results by numerically simulating the proposed controllers using the DAC system. Compare the simulated system response to the theoretically predicted behavior.

- Experimentally implement the proposed controllers using the DAC system and compare the results to the theoretical and simulated results.

- Change the controller operating conditions (i.e., adjust control gains, change motor loads, etc.) to see how these changes affect the theoretical, simulated, and actual system responses,

- Repeat the above steps, comparing the performance of one class of controller with that of another (i.e., adaptive versus PID). State the advantages and disadvantages associated with each class of controller.

The concepts learned in the proposed controls module directly support Analog Control and Digital Control, which are regularly offered undergraduate electives.

3. Robotics Module

The goal of the robotics module is to design and construct control systems for a simple robotic arm [8]. The individual projects are designed to be completed in one semester. A typical project is outlined below:

- Construct a two-axis articulated robot arm from a mechanical kit of parts. A horizontally jointed SCARA configuration is one possibility.

- Interface [10] the individual joint motors, encoders, and tachometers with the DAC system. The DAC system will be used for both low-level (i.e., servo) control and high-level control (i.e., simple path planning).

- Develop kinematic and dynamic models of the arm, including both forward and inverse kinematic equations.

- Develop and test control algorithms for the arm, such as single-axis PID position control [9].

- Perform useful work with the arm using the kinematic model and the developed control algorithms (e.g., positioning the arm to precise locations in the workspace).

- Design and construct a simple end-effecter for the arm, such as an electro-magnet. Interface this tool to the DAC system and demonstrate its functionality in accomplishing a simple task (e.g., placing a metal ball into a cup).

As in other modules, students will form design teams with each member responsible for one or more aspects of the design. Each design team will submit a time table showing proposed objective completion dates and provide written progress reports for each objective, including a final report. These reports will describe the approaches considered (both successful and unsuccessful), as well as the final adopted designs. An oral presentation will be given by each design team to the entire class, including a demonstration of the completed design.

C. *Inclusion of Reliability Concepts*

It is realized that, in order to compete effectively in the current marketplace and design systems to meet high-quality standards, our future engineering students need to be introduced to reliability and maintainability (R&M) design concepts, Specifically, the Department of Electrical and Computer Engineering (ECE) at Clarkson University is making extensive efforts to integrate R&M concepts into its curriculum with a strong focus on design for reliability and cost effectiveness. As a first step toward this goal, the ECE department is offering two engineering reliability courses to its students. The first course, Engineering Reliability y, is currently being offered to undergraduate students at junior and senior levels. The second course, Engineering Systems Rereliability, is offered to graduate students. In these courses, the students are taught the need for designs with very low probability of failures (i.e., high reliability) at competitive costs, warranty periods, and maintenance schedules. They learn about various system reliability structures, such as series, active redundancy, partial redundancy, standby redundancy, and various other configurations. Using several statistical modeling techniques, such as Weibull, exponential, Erlang and normal distributions, students are taught to analyze and compute the probability that a design will successfully perform its intended function for a specified period of time under a given operating condition.

D. The DA C Programming Environment

Each embedded DAC system is centered around a Spectrum Signal Processing TMS320C30-based DSP board, 12-bit differential 1/0 (32 A/D and 16 D/A channels), 32 digital 1/0 channels, 2 channels of 12-bit quadrature encoder interfacing, and a 16-bit high-speed parallel expansion bus (DSP-Link) which supports data transfer rates of up to 10 MB/see between the DSP board and the supporting daughter 1/0 boards. The 486/PC communicates to the DAC system through an 1/0 mapped hardware port. This embedded DAC structure is attractive [14] because it is completely independent of the PC's ISA data bus, and as such, can support very high rates of data throughput (i.e., fast sampling rates on multiple channels). User-defined DAC algorithms are designed and implemented using standard, high-level programming languages, such as Matlab/Simulink or Simnon, from within the DAC environment. This environment (co-developed by one of the investigators), runs under Windows 3.x on the host 486/PC. It provides a seamless interface between popular simulation and analysis packages, such as Matlab/Simulink or Simnon, and the DSP-based DAC system by generating the necessary low-level C-code which actually runs on the DSP board. Each DAC workstation is also equipped with an ethernet card to provide access to the various resources available on Clarkson's computer network (e.g., laser print ers, scanners, etc.).

The DSP board serves two functions under the DAC environment: (1) it is the computational engine for the DAC system, and (2) it provides a real-time link between the user-defined DAC algorithms and the individual design modules (i.e., plants). Sensor signals are passed from the module hardware to the DAC system for analysis via the DSP, while control signals generated by the DSP are passed from the DAC system to the module hardware. Since the DSP-Link is completely independent of the PC bus, the DSP board is free to perform real-time DAC operations while the host PC performs other related DAC tasks, such as communicant ing with the dedicated test instruments, storing data to the hard drive, or displaying graphic data. This flexible setup facilitates the rapid design and implementation of user-defined DAC algorithms in either a simulated [11] or real-time fashion.

The main thrust of the development work thus far has centered on the creation of a Windows 3.x-based DAC environment (i.e., a 16-bit application). As noted, this environment forms a bridge between the DSP-based DAC hardware and the PC-based workstation by facilitating the creation, simulation, and real-time execution of DAC algorithms for the individual laboratory modules The Windows 3.x operating system was selected for the initial development work due to its wide commercial distribution and user-friendly nature. 32-bit versions oft he DAC environment (i.e., Windows 95/NT) are planned for the future.

The DAC environment consists of four basic components: a graphical user interface (GUI), a DSP application programming interface (API), a DSP-specific library, and Windows virtual device drivers (VxDs). The GUI is used for creating, modifying, running, and displaying real-time DAC algorithms and data. The GUI allows students to write DAC algorithms in high-level user-defined languages, such as Matlab/Simulink or Simnon, rather than low-level hardware specific source code, such as C or Assembly language. A Clarkson developed high-level language compiler builds the low-level DSP source code. This compiler makes use of hardware specific information to provide DAC 1/0 and PC communication compatibility. This time-saving approach enables students to focus more time on fundamental systems concepts, rather than hardware specific details. The GUI is, in effect, the shell through which the outside world interacts with the DAC system, The GUI interface was written using Borland International's Object Windows Library (OWL), which provides a full family of object-oriented classes for all Windows objects. This object-oriented approach will make it easier to port the completed DAC environment to more sophisticated (i.e., 32-bit), multi-tasking operating systems, such as Windows 95/NT or OS/2.

The DSP API lies below the GUI shell and provides a common DSP protocol for interfacing the GUI with DSP-specific libraries and VxDs. In essence, it links the GUI with the DSP hardware. This approach makes the DAC environment flexible, so that many types of DSP hardware can be used (e.g., the original DSP hardware can be updated/replaced as newer and more sophisticated models appear). The DSP-specific libraries and VxDs are the low-level portions of the DAC software environment and provide a stable real-time kernel (RTK) for DAC operations, such as data transfer between the GUI (which runs on the 486/PC processor) and the DAC algorithms (which run on the DSP processor).

E. Design Overview

Engineering design is a creative process that identifies a customer's need and then devises a product to fill that need. Depending on the inclination of the supervising faculty, the senior design projects can be assigned in various formats. For example, some projects can be developed in three to four weeks and are referred to as mini-projects. Three or four such mini-projects could be completed in one semester. Alternatively, a single semester-long project could be assigned. Different semester-long projects could be assigned in one section and these projects may or may not be independent of each other. In the Clarkson solar car race section, the various projects are interdisciplinary and need coordinated efforts of both electrical and mechanical engineering students,

The major design activities and typical tasks are listed below [16]:

1. Needs Identification
2. Project Plan
   - Project Definition (Goal of the project)
   - Project Objectives (Specifications, constraints, assumpt ions)
   - Strategy (Idea of how to solve the design problem)
   - Plan of Action (List tasks to design, build, and test)
   - Project Schedule (Schedule tasks)

3. Project Implementation

- Literature Search
- Analysis (Balance trade-offs between specifications and constraints)
- Synthesis (Generate a possible solution)
- Technical Design (Partition system into functional modules)
- Evaluation/Decision (Review design, try another solution)
- Prototype Construction
- Evaluation
- Documentation and Reporting

An important aspect of the course is the evaluation and documentation of the prototype. Ample time should be reserved for the final evaluation of the prototype intended to demonstrate that the project works indeed and meets the specifications. The results of the prototype evaluation should reveal the merit of the student design concepts. Regarding the documentation of the project, the following list of items has been used in the past:

1. Literature search
2. Mini-proposal (three or four-page proposal)
3. Progress reports (weekly or biweekly)
4. Laboratory notebook
5. Preliminary and final reports (typed reports)
6. Oral presentations

F. Example Design Project: Inverted Pendulum System

This example [17] involves the positioning of a carriage at a desired location while balancing an attached inverted pendulum in a vertical position. The concept of balancing systems is related to stabilizing missiles or robots.

1. *Problem Statement.* The objective of this project is to design a discrete time controller which balances the inverted pendulum at a desired carriage position. The pendulum is connect to the carriage by a simple pivot. The effective length, 1, of the pendulum is 250 mm. A servomotor is available to control the position of the Carriage.

2. *Performance Specifications.* As this is a very difficult system to control, the main objective is simple to balance the inverted pendulum. The general guidelines are to design a well-damped system ($\zeta \approx 0.7$) which settles quickly.

3. *Design Evaluation.* What is the 5% settling time of the final system? What is the effect on the final design of a 20% variation in the effective length of the pendulum? What is the effect of neglecting the servomotor dynamics on the overall system performance?

4. *Design and Instrumentation of the Rig.* Although the position of the top of the pendulum, y, cannot be measured directly, it can be inferred from knowledge of the angle of the pendulum and the position of the carriage. The angle of the pendulum, θ, can be obtained by attaching a potentiometer to the pivot (or by making the potent iometer the pivot). The position of the carriage can be measured by attaching a cable to the carriage, which in turn is connected to a potentiometer to produce a signal proportional to the carriage displacement, x. Figure 3 shows a schematic diagram of the inverted pendulum system wit h the associated instrumental ion.

5. *Controller Design.* Using simple geometry, it can be shown that y is related to x and θ by the following relation (assuming small angles)

$$y = l\sin(\theta) + x \approx l\theta + x.$$

At this point a strategic decision is required whether or not to: (a) use a secondary servo to position the carriage, or (b) to apply feedback around the entire loop in order to derive the control signal to the servomotor. A secondary position servo offers a number of advantages: (1) the response of the carriage position control system is faster, and (2) by putting feedback around the servomotor, the overall stabilization problem is eased (i.e., aa an additional integrator is not introduced in the feed forward path), (3) the servo subsystem can be independently designed to behave like a well-damped second-order system without position error, (4) step response and frequency response tests can be carried out on this subsystem without introducing the complicating factor of the inverted pendulum. Experimental tests on an actual inverted pendulum rig show that the servomotor can be modeled as a second-order transfer function with a natural frequency of about 10 Hz and a damping ratio of about 0.7.

(a) Servo Dynamics *Neglected.* Assuming a gravitational constant g of 9.81 m/sec^2, experimental tests on an actual inverted pendulum rig show that it can be modeled aa a second-order transfer function of the form

$$\frac{Y(s)}{X(s)} \cdot \frac{-\omega_n^2}{s^2 - \omega_n^2} = G_p(s),$$

where the natural frequency of the pendulum is given by

$$\omega_n = \sqrt{\frac{g}{l}} = \sqrt{\frac{9.81}{0.25}} \doteq 6.25 \text{ rad/sec}.$$

According to this transfer function, the pendulum system has two real poles of equal magnitude, i.e., one stable pole in the left-half s-plane and one unstable pole in the right-half s-plane, in addition to an inherent negative gain. Stabilization of the system can be achieved by inducing the unstable pole in the right-half plane to move to the left. This can only be achieved by using negative gain, $K<0$, in the controller (i.e., positive feedback), which counteracts the negative gain inherent to the system. But negative gain alone is insufficient to stabilize the system. One simple way to force the unstable pole into the left-half plane is to use a lead compensator of the form

$$G_c(s) = \frac{s+\omega_n}{s+\frac{1}{T}},$$

where the compensator zero cancels the stable pole in the plant and is replaced by a faster compensator pole with time constant -r. The fastest possible system response (i.e., as allowed the natural frequency of the servomotor) is obtained by defining the time constant of this compensator pole to be $\tau = \frac{1}{10\omega_n}$. A root locus plot confirms that the resulting closed loop system has the desired damping ratio of $\zeta \approx 0.7$ when the control gain is set to $K = -5$. Experimental tests (e.g., step response, etc.), are now performed to verify that the proposed control design meets performance specifications using an actual pendulum system.

(b) *Servo Dynamics Included.* If the second order servomotor dynamics are included in the overall controller design, the resulting system transfer function is fourth order. A pole canceling compensator of the form outlined above can once again be designed to satisfy the desired performance specifications, although the resulting steady-state error is somewhat larger. It is helpful to vary the parameters of the experimental controller to see how they effect the overall system performance.

III. Module Development

In conjunction with the development work on the DAC software environment, preliminary progress has also been made on the development of individual modules. For example, initial work on the robotics module has focused on the construction of a prototype direct-drive, two-link SCARA-type manipulator. This device will be used to perform the robotics experiments described above. Initial work has also begun on the controls module. This work includes the set up of a servo motor test stand which consists of a permanent magnet brush dc motor and mounting bracket, pancake type load, cabling from the motor to the amplifiers and DAC system, etc. Relevant motor models were developed from experimentally measured motor parameters (using standard test instruments) and motor nameplate data. Control algorithms were then designed and successfully tested using a prototype of the DAC software environment. Similar tests were also made using the inverted pendulum systems. Development of the DAC environment will be complete during the Summer of 1996 and the cent rols module will be offered to senior EE students for the first time in the Fall of 1996.

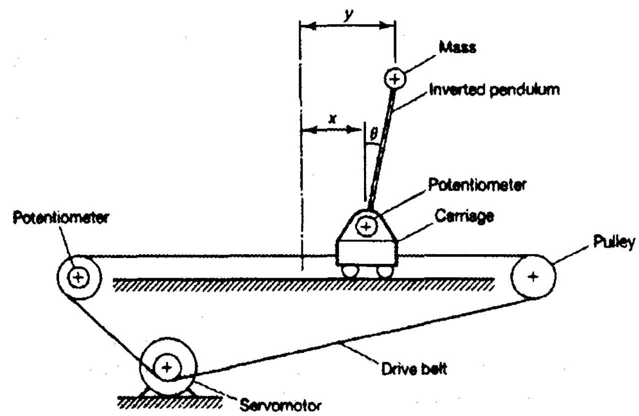

Figure 3: Diagram of Inverted Pendulum System.

IV. Conclusions

The authors propose an integrated modular senior design laboratory to enhance the existing senior design laboratory experience in Electrical Engineering at Clarkson University. This laboratory integrates physically-based devices and components within a PC-based data acquisition and cent rol environment. The new design sections offer an integrated systems approach for the rapid design and implementation of both hardware and software components in a complete engineering design.

Acknowledgments

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