A HOLISTIC APPROACH TO CONTROL SYSTEMS LABORATORY DESIGN

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Abstract. *This paper describes the development of a control systems laboratory for undergraduate students encompassing a holistic approach that addresses the needs of the student more globally. Using experiments from simple models such as mass-spring-dampers, to more complex ones, like the inverted pendulum, together with graphical programming tools like LabVIEW, it is shown how to setup a control laboratory class for undergraduate students with no background in hands-on and digital implementations. Also we will address the integration of ethics and leadership in order to understand the role of aerospace engineering in a global context.*

Keywords*: Engineering Education, LabVIEW, Control Systems, Ethics*

1. INTRODUCTION AND OBJECTIVES OF THE NEW LABORATORY

System theory is both elegant and powerful. The theory can, however, be daunting for many students, especially those who require a more direct experience (that is, "hands-on") to fully comprehend and internalize the subject matter.

Discovery-learning-based instruction, as laboratory classes, has proven to help develop abstract reasoning, enhance retention of concepts, and improve the student's attitude toward the subject matter (Armstrong, 2001), (Bissel, 1999). Many papers have been generated in the control literature to show high-quality controls laboratory programs, expressing the importance on the practical (Armstrong, 2001) – (Metzger, 1996).

This paper describes the development of a control systems laboratory for undergraduate students in aerospace engineering (ASE). It is shown how many key dynamics and control concepts can be taught using LabVIEW together with simple apparatus in order to cover basic principles of digital control and real-time implementation.

The use of experiments from simple models such as mass-spring-dampers, to more complex ones, like the inverted pendulum, enables the students to gain experience with "real-world" systems in terms of modeling and control system design. The same models or systems can be found in structural dynamics and linear systems analysis courses as a basic framework for more general problems, such as vehicle suspension, machine vibrations, and spacecraft dynamics.

The undergraduate curriculum in systems and controls in our department is comprised of two major courses. The first is a junior-level course in linear systems analysis, which includes the solution of differential equations, signal and systems properties, Fourier and Laplace Transforms together with convolution and frequency response methods. The sequence is then, followed by a class on classical and modern control design for single-input, single-output systems, where topics such as root-locus, frequency response methods, and state-space are introduced as design tools.

In the course, the theory is balanced with practical problems, using concrete "real-world" examples. The textbook used is *Modern Control Systems* (Dorf, 2005) which has over eight hundred end-of-chapter problems together with more than two hundred problems from its companion website. In addition, two major design problems involving aerospace models are assigned in place of two in-class tests. However valuable these concrete examples are, they cannot substitute for actual design and implementation in a laboratory.

One of the challenges in teaching control to aerospace students is the lack of a "hands-on" experience and the lack of a required course on digital control. Bridging the gap between the design performed in class and real-time implementation is an issue. Students face the real problem of understanding how a closed-loop block diagram can be implemented in the real world of the laboratory, i.e, how to connect the wires and cables to form the feedback loop.

Moreover, teaching control theory based only on practical examples without exploring the real implementation can bring a lack of demonstrations of the impact of bad judgment on the controller design. A good student, and eventually, a good engineer, must have a solid understand of the theory together with the impact of its technology in our lives. As the design paradigm has changed from a performance driven-model to a cost-driven model, many design ethics questions have emerged.

Having in mind this close connection between solid technical background with the "social" aspects of a controller implementation, the aerospace engineering department focused on the development of a holistic type undergraduate controls laboratory with the following objectives:

1. Introduce the student to the fundamentals of control systems theory with emphasis on design and Implementation.
2. Integrate key ethics and leadership cases in order to understand the role of aerospace technology in a global context.
3. Understand the fundamentals of the implementation issues related to classical and modern control systems, using industrial-type real-time hardware and software.

2. A HOLISTIC APPROACH

A key question comes to mind when deciding whether or not to incorporate aspects of ethics and leadership in a controls laboratory environment. Should a laboratory class in control systems provide students with hands-on design experience while simultaneously integrating topics of ethics and leadership?

There is no question that a good engineer must have a solid background on the technical aspects of their discipline. However, we must be aware that the engineer will also be engaged in their careers, mainly outside the university environment, in operations that require social skills and technology (Ben-Haim, 2000) So, confronted with ethical problems, the engineer must do more than simply make judgments; they must figure out what to do (Whitbeck, 1998).

In aerospace engineering, unethical behavior in the design of controls systems can lead to tragedy, including deaths of innocent people. Modern air transports must be safe and reliable. Smart weapons must perform as advertised and remain on target. Expensive space missions must have high success rates. The impact of technology on our lives and world history must be understood by the students so they realize the tremendous human efforts that were expended in creating those new ideas. (Whitbeck, 1998), (Feisel, 2005) and (Online, 2004)

It is known that on every design concept, the engineer cannot approach the problem without some idea of what came before (Bernstein, 1999). Also, the engineer must understand that in design there is rarely a single correct solution, yet some solutions are better then others. But, a wrong answer always exists. The student must learn from both the successes and failures of their design and acknowledge its impacts on ethical issues (Petroski, 1992).

Effective engineering leadership requires an understanding of the technology in a global context. While there is no precise data to point that in general engineering students have or have not reached leadership roles in aerospace, the general feeling is that we have indeed not reached high levels of leadership in large numbers. It is a fact that leaders are needed in all parts and all levels of engineering organizations. Also, Leadership is a very important tool, or even the art, of "leading" others to do what is ethical and suitable for the situation they are faced with.

It is also a fact that many engineering students never have the opportunity to interact with successful leaders in aerospace. There is a lack of, in the curriculum, opportunities to learn the skills of design judgement, teamwork, and delegation.

Therefore, a holistic approach will reveal the technical aspects of implementing control systems in hardware, while at the same time stimulating discussions and thought-processes surrounding the role that technology has in a global setting and the implications of ethics in the design process.

3. LABORATORY DEVELOPMENT

As pointed out by (Bernstein, 2003) buying an "off-the shelf" experiment is the best way to setup a control laboratory for educational purposes. This is due to an obvious reason: they provide a "turn-key" solution for the user, which means that they are already engineered and ready to run. Based on this fact, the aerospace engineering department opted for equipments from Educational Control Products (ECP).

In order to introduce the basic control theory and implementation and to positively impact several existing aerospace courses, the plants acquired were the spring-mass-damper and torsional disks, both with the Inverted Pendulum Accessory, as seen in Fig. 1. These equipments present models used as basic framework for more general problems, such as vehicle suspensions, machine vibrations, and spacecraft dynamics.

The laboratory was designed to cover several topics, such as ethics and leadership, system identification, digital control, transfer function units and hardware gain, LabVIEW programming, system modeling, and the control design itself. Some of those topics are discussed below.

3.1. Ethics and Leadership

This topic has been evolving incrementally over the years. The first time the class was taught, two speakers were brought to the class: (1) a business professor with a vast experience in ethics in the high-tech industry and (2) a professor in Aerospace Engineering and former NASA Deputy Administrator and Secretary of the Air Force. While the first speaker discussed ethics on the work place, focusing on engineering design and typical engineering day-to-day activities, the second speaker discussed how problems involving lack of leadership in the aerospace sector can lead to poor design and lack of initiative for correcting problems.

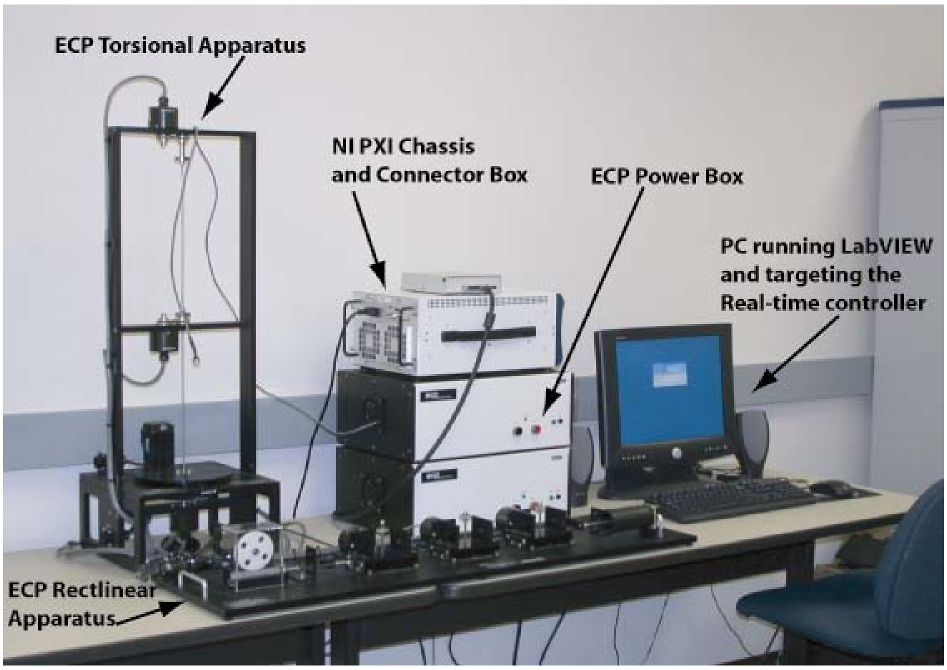

Figure 1. Aerospace Control Systems Laboratory (www.ae.utexas.edu/~controls).

3.2. Digital Control

In order to bridge the gap between the theory and implementation, mainly for aerospace engineering students that haven't had enough contact with sampled data systems, a short course in digital control is essential (Astrom, 1990), (Franklin, 1998). Although control design in a discrete framework is not pursued, problems concerning sampling are addressed and emulation methods are introduced for simulating and implementing the continuous-time controller designed either by root-locus, frequency domain, or state-space techniques.

3.3. Plant Identification

It is known that no matter how well analytical modeling is performed (Astrom, 1990), (Bernstein, 1999), some identification is always needed. Having in mind that the controls laboratory is comprised of fours equal stations, it is desirable that from time to time, the students perform system identification on the apparatus they are working with, since some parts, i.e, springs, masses and dampers, might be interchanged from plant to plant and they could use a different station to perform the control design from that identified.

3.4. Dimensions and units

Usually, dimensions and units are ignored in control theory. Rarely the undergraduate books on controls carry dimensions to transfer functions. Whereas dimensionless quantities can help on understanding issues on scale-independent variables, units are very important from an implementation and tuning point-of-view (Bernstein, 1999). This issue is covered from the very first class in the laboratory. Also, it is shown how to identify the units of the hardware gain not mentioned in most of the controls books.

3.5. LabVIEW

LabVIEW is a popular software suite developed by National Instruments. The name LabVIEW is short for **Lab**oratory **V**irtual **I**nstrument and **E**ngineering **W**orkbench. As its name suggests, LabVIEW provides an environment in which engineers can design their own laboratory instruments quickly and easily. These personally-designed laboratory instruments are called *Virtual Instruments* (VIs) and are developed in a graphical programming language known as G. G-code differs from standard sequential text-based computer code in that it relies on graphical symbols to describe procedures for the computer. In fact, the G-code of a given VI looks like a block diagram; inputs and outputs are transferred from block to block by wires that are color-coded by their data type. Each specific block represents a particular operation.

LabVIEW's simple interface and easy-to-learn programming language make it a perfect choice for developing control applications (Bishop, 2004). Data acquisition is handled easily with predefined block functions. Signals read from DAQ components are manipulated with standard block functions and the results of the program can be easily sent to an output board, which in turn sends signals to the plant.

4. LABORATORY EXPERIMENTS

The experiments are performed on plants from ECP, which are controlled by a National Instruments PXI chassis equipped with an embedded real-time controller and a reconfigurable multifunction I/O module. In order to cover the topics mentioned above, a LabVIEW platform was conceived using a real-time operating system and FPGA architecture.

4.1. Hardware and Software Architecture

The hardware chosen for the laboratory can be seen in Fig. 2. The National Instruments PXI-1042 chassis provides a foundation to which a variety of PXI expansion modules can be added. This makes it a highly customizable measurement and testing platform. In conjunction with the PXI-8186, a Pentium4-based, real-time embedded controller, the module can also run an NI developed, real-time operating system which allows it to work as a deployment platform for LabVIEW Real-Time applications. For the data acquisition module, the National Instruments PXI-7831R Reconfigurable Multifunction I/O provides input and output for both analog and digital signals. It is equipped with an FPGA (field processor gate array) which is configurable with the LabVIEW FPGA Module.

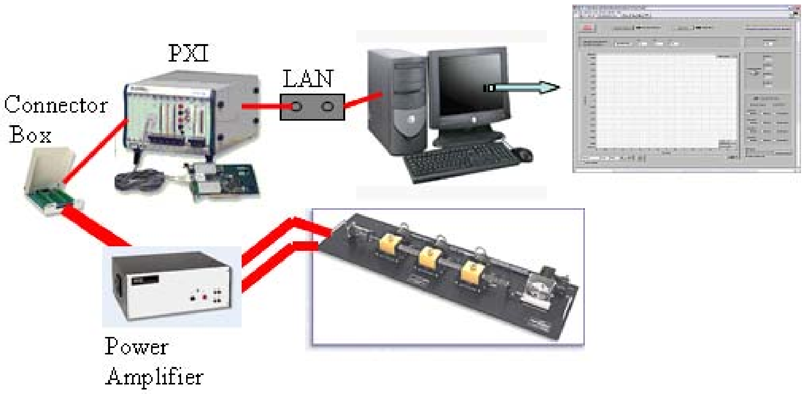

Figure 2. Integration of the controller systems.

There are two parts to every LabVIEW VI (Virtual Instrument), the front panel and the block diagram, as seen in figures 3 and 4. The front panel can be thought of as the user interface where one can input computational parameters (called *controls* by National Instruments) and also view outputs from the program (called *indicators*). This is analogous to defining input and output arguments in traditional programming languages. Values for controls are passed into the VI's block diagram, where the programming code executes, and then passed out and displayed on the front panel indicators.

The control system VI developed by The University of Texas at Austin Aerospace Engineering Controls Lab was written with the goal that virtually any controller could be implemented for the ECP plants without major modification to the VI's programming code. A quick look at the front panel (Fig. 3) shows that all important system information is displayed: encoder measurements, a system error indicator, and a response history graph. Controls on the front panel allow the user to specify a loop time, command reference trajectories, and select which response history plot(s) he/she wishes to view. Finally, empty space is left on the front panel for the user to add controller parameters that are to be passed into the block diagram.

The block diagram, as seen in Fig. 4, was written such that a control algorithm could be easily inserted into the existing VI without affecting the basic functionality of the programming code. Upon inspection of the block diagram, it can be seen that with no controller, the commanded signal passes directly to the analog output channel for the drive motor; hence, the open-loop response is obtained. Implementing a controller is as simple as inserting the control algorithm code into the block diagram, where now the commanded signal, in conjunction with encoder feedback, is passed into the control algorithm. The output signal from the control algorithm is then passed into the analog output channel for the drive motor, resulting in a closed-loop control system.

Several safety features has been coded into the software. The FPGA code for the model torsional disks plant has been written to detect when the relative position between the first and second disks exceeds *3000 counts*. This is to prevent damage to the torsional rod if a large torque is applied to the base disk. When this limit is exceeded, zero command voltage is output to the drive motor until the error is cleared. Also, both the spring-mass-damper and the torsional disks have drive motor overspeed/overvoltage protection incorporated into the FPGA code.

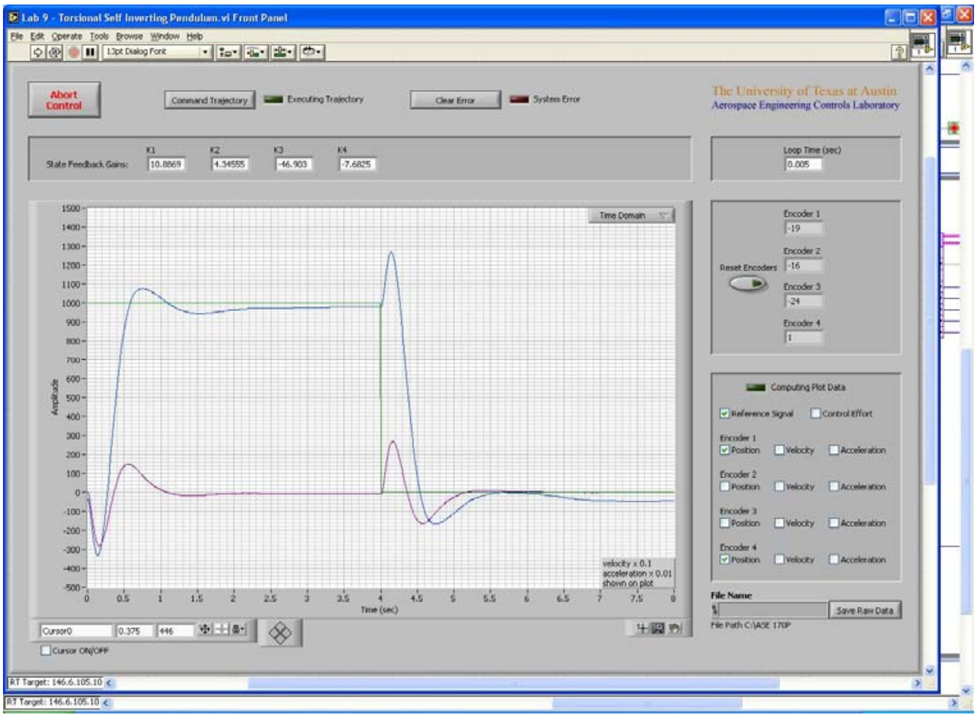

Figure 3. LabVIEW Front Panel.

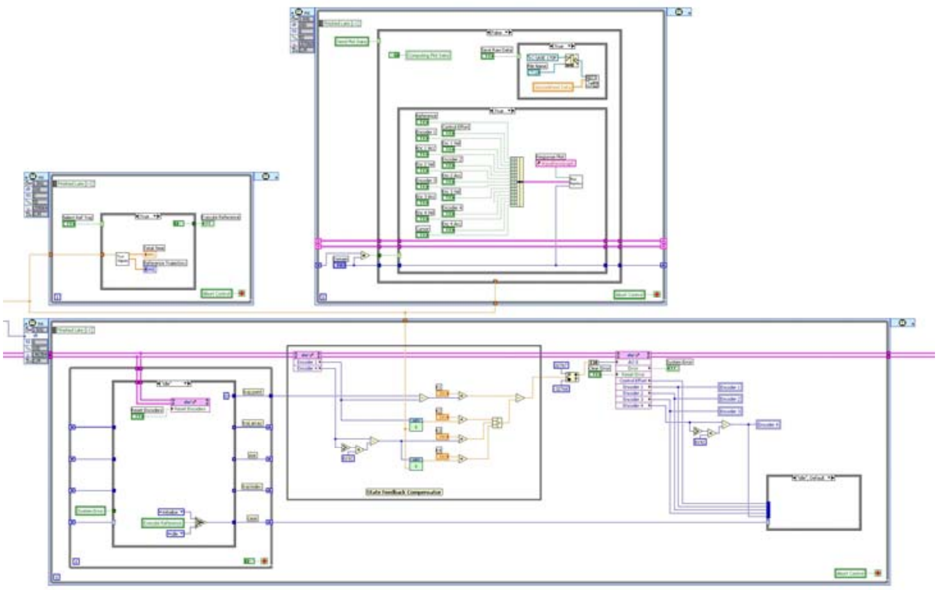

Figure 4. LabVIEW Block Diagram.

4.2. Course Outline

Although not entirely shown in this paper, the Controls Laboratory course involves fourteen weeks of lectures and hands-on experimentation. An outline of the course program is presented below. It is worth mentioning that the last design problem, the self-erecting inverted pendulum mounted on a rotational base, is given as a final design test for the students. They spend two weeks modeling, identifying, designing the controller, and coding their own LabVIEW VI's.

1. Course Introduction + Review of Classical and Modern Control Systems
2. Introduction to LabVIEW I
3. Ethics in Engineering Design Lecture + LabVIEW II
4. Introduction to Digital Control Systems
5. Plant Identification using the Rectilinear Control System
6. Rigid Body PD \& PID Control using the Rectilinear Control System
7. Non Collocated Control with 2 DOF – Rectilinear Control System
8. Plant Identification - Torsional Disks
9. Torsional Control System - Design of Phase Lead- Lag Compensator
10. State Feedback Control – Rectilinear Control System
11. Leadership in Aerospace Lecture + LabVIEW III
12. Inverted Pendulum Control System – Rectilinear Plant
13. Self-Erecting Inverted Pendulum Control System – Rectilinear
14. Plant Self-Erecting Inverted Pendulum Control System – Torsional Plant

As an example of the functionality of the software and hardware, the system identification and the inverted pendulum design are presented below.

4.3. System Identification

Two basic principles are used in the laboratory class for system identification: (1) the use of the decay envelope of the free response (Logarithmic Decrement Method), and (2) Identification by least-squares. Even though the first technique is very simple and well studied for second order-systems, it gives the student the opportunity to recall the theory from structural dynamics courses and make a connection to the specifications of a control system. The second method gives the student the opportunity to explore the basic principles of the rich environment of system identification.

Using a sine-sweep type of signal, as shown in Fig. 5, the least-square method can be used to identify parameters in the plant. Suppose we have the 1-degree-of-freedom configuration depicted in Fig. 5. If we let $T = KV$ be the torque applied to the plant through the motor and amplifier box (open loop), we can write for the estimated acceleration

$$\ddot{\theta}_{1est} = -k_1/J_1 - c_1/J_1 + (1/J_1)KV \Rightarrow \ddot{\theta}_{1est} = \begin{bmatrix}\theta_1 & \dot{\theta}_1 & V\end{bmatrix}\mathbf{P}_0 \tag{1}$$

where $\mathbf{P}_0 = \begin{bmatrix}k_1/J_1 & c_1/J_1 & 1/J_1\end{bmatrix}$. Assume $k = 1 \cdots N$ data are taken from the experiment and that $\theta_1(k)$ and $V(k)$ are measured directly. By approximating angular velocity and acceleration by central differences as

$$\begin{aligned}\dot{\theta}_1(k) &= \frac{\theta_1(k+1) - \theta_1(k-1)}{2T} \\ \ddot{\theta}_1(k) &= \frac{\theta_1(k+1) - 2\theta_1(k) + \theta_1(k-1)}{T^2}\end{aligned} \tag{2}$$

where T is the sampling time, we can define the estimation error using Eq. 1

$$e(k) := \ddot{\theta}_1(k) - \ddot{\theta}_{1est}(k) = \ddot{\theta}_1(k) - \begin{bmatrix}\theta_1 & \dot{\theta}_1 & V\end{bmatrix}\mathbf{P}_0 \tag{3}$$

This equation can be stacked up from $k = 2 \ to \ N-1$ and the least-square identification problem can be setup using the following performance index (PI):

$$\min PI(e) = \mathbf{E}^{\mathbf{T}}\mathbf{E} = \left[\mathbf{Y} - \mathbf{\Theta}\mathbf{P_0}\right]^{\mathbf{T}}\left[\mathbf{Y} - \mathbf{\Theta}\mathbf{P_0}\right] \tag{4}$$

where

$$\mathbf{E} = \begin{bmatrix}e(2) & e(3) & \cdots & e(N-1)\end{bmatrix}^T$$
$$\mathbf{Y} = \begin{bmatrix}\ddot{\theta}_1(2) & \ddot{\theta}_1(3) & \cdots & \ddot{\theta}_1(N-1)\end{bmatrix}^T$$

$$\mathbf{\Theta} = \begin{bmatrix} -\theta_1(2) & -\dot{\theta}_1(2) & V(2) \\ -\theta_1(3) & -\dot{\theta}_1(3) & V(3) \\ \vdots & \vdots & \vdots \\ -\theta_1(N-1) & -\dot{\theta}_1(N-1) & V(N-1) \end{bmatrix}$$

Since $\boldsymbol{P_0}$ was defined by the ratio of the parameters, and not its absolute values, another experiment should be performed changing the plant dynamics by adding masses to the disks. The value of the parameters vector can be evaluated as

$$\mathbf{P}_0 = \left(\mathbf{\Theta}^T\mathbf{\Theta}\right)^{-1}\mathbf{\Theta}\mathbf{Y} \tag{5}$$

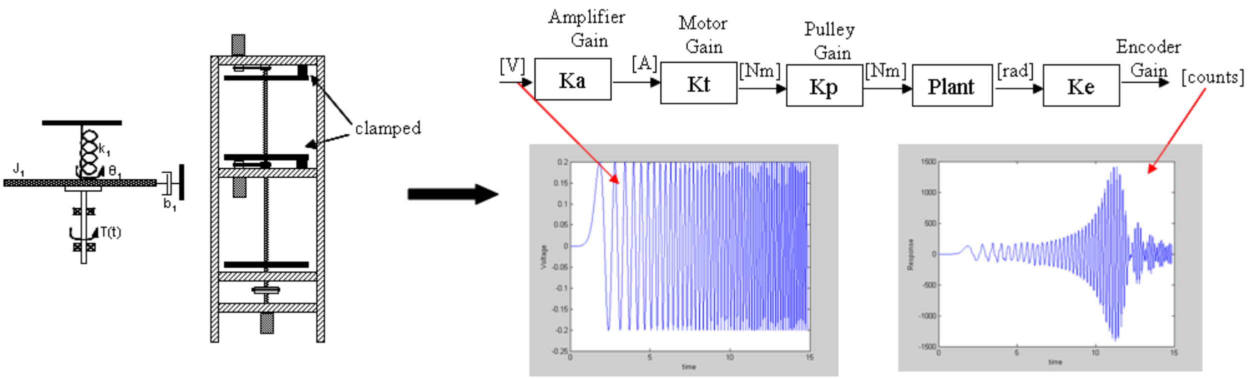

Figure 5. System Identification Concept using the Torsional Disk Plant.

4.4. Inverted Pendulum

The inverted pendulum system has many practical applications and is often used as a benchmark for testing new controllers. Its model can represent several interesting problems in aerospace applications as: (1) Controlling the vertical deviation of a space shuttle or rocket during take-off; (2) Balancing a rocket as it is transported to the launch-pad

The inverted pendulum apparatus can be setup on either the mass-spring-damper (rectlinear) plant or in the torsional disks plant, as seen in Fig. 6. There are essentially four modes of operation for the apparatus:

1. A normal pendulum keeping the pendulum in a certain angular position;
2. Keeping the pendulum inverted and stable regardless of disturbances on the system and ensuring that the cart position does not move out of range.
3. Applying a known input to the base, either the cart or disk, moving it from one position to another, while keeping the pendulum inverted and stable.
4. A fourth mode called "self-erecting" where the pendulum starts from its natural pendant position, increasing its momentum until it swings up to the inverted position, and then maintaining it there.

As can be seen from the above examples, the design problem is essentially one of stabilizing and altering the center of gravity of the pendulum to keep it in the upright or inverted position. It is also desirable to control the horizontal (or angular) position of the cart (or disk) due to the finite length of the cart (disk) displacement. Several algorithms can be implemented in those configurations. In the controls laboratory, state-feedback was chosen as the main design tool.

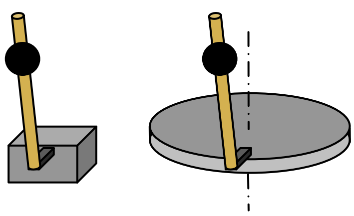

Figure 6. Inverted Pendulum Configurations.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

Can we develop a laboratory course that provides students with hands-on design experience while simultaneously integrating topics of leadership and ethics? There is a positive answer for the above question. A holistic approach to curriculum development, if initiated early enough in the course development process, and by no means restricted to new courses, can indeed be well-integrated.

The LabVIEW environment provides a flexible educational tool for teaching, not only digital control implementation but also control design concepts. Students who have taken the class have given positive feedback on LabVIEW and the integration of ethics and leadership lectures in the control curriculum. Gaining experience in designing and implementing control systems on industrial grade hardware and software is important in and of itself.

5.1. Future Work

At this point, the students and even professors should have realized that control knowledge is not static. Several topics in more advanced control theory can be studied in the laboratory environment. Currently, non-linear controllers have been successfully tested using the inverted pendulum. Robustness issues could be added and H_2-H_∞ problems could be addressed.

Moreover, ethics and leadership lectures could be expanded. The lectures could incorporate one or two case studies in aerospace engineering and a study on every student's design and implementation could be done in order to assess possible failures and successes. Also, a continued search of possible industry-experts for ethics and leadership lectures is essential.

6. ACKNOWLEDGEMENTS

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