A First Control Laboratory with Computer Aided Learning

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Abstract: *This paper describes the philosophy and contents of a Signals and Linear Systems Laboratory, the first practical activity in control disciplines of the Industrial Automation and Control Engineering Course of the Systems and Automation Department at the Federal University of Santa Catarina. The simulation laboratory provides students with important concepts regarding the analysis of discrete and continuous dynamic systems. Scientific software, as Matlab/Simulink and VisSim, are utilized on an experimental control station to aid the simulation activities in modeling, transient analysis, steady-state behavior and frequency response tasks. A suggested routine is presented for every experiment to be carried out in lab classes and in the respective reports. Lab classes have yielded successful results for the past two years.*

KeyWords: dynamic systems, control education, software tools, laboratory, simulation.

Introduction

In Process Control Engineering the experimentation, based on lab activities — simulation on real processes — in addition to motivating students, provides a better ground for understanding the theoretical content of classes.

The evidence that most industrial plants have shifted their control systems to digital technology and, consequently, the fact that most of today's course on analysis and design of dynamic control systems are presented in their continuous (s-transform) and discrete (z-transform) domains, have led professors to introduce lab classes with analog and digital simulations. Learning necessities, didactic aspects and available funding are relevant as they will shape the adaptability of a lab [8], [4], [2].

Lab classes enable teachers to mimic industrial processes situations establishing connections that are important in recognizing the integrated features of different experiments. Analog and discrete systems have to be treated in an integrated way to tackle hybrid situations where systems are controlled by analog and digital algorithms [1], [6].

The students of the Industrial Automation and Control Engineering, a course of the Systems and Automation Department (DAS) at the Federal University of Santa Catarina, utilize the Process Control Laboratory for practical experiments in the different control disciplines of the course. In these lab experiences the students implement a task in a personal computer and utilize an academic software for analysis, design and simulation of analog and discrete dynamic systems with Matlab/Simulink or VisSim (all computational environments are useful for teaching control engineering principles) [5], [9]. Sometimes real processes are employed to verify and to ensure the mathematical results conducted in the practical part of the experiment. In addition to the practical experiments, the lab supports the development of basic software, instrumentation and constant research on new low-cost prototypes (financial resources are limited) to our control activities.

The experiments supplied for the DAS- 5111 students - Signals and Linear Systems (SLS) — first course for analysis of process control systems — are: i) Initialization for VisSim, Matlab and Simulink; ii) Analysis of Non-Linear System; iii) Impulse and Step Response; iv) Time Response of Dynamic Systems; v) Frequency Response of Differential Systems; vi) Analysis of Systems in the State-Space Domain; vii) Response of Second-Order Systems; viii) Disturbance Effect in the Dynamic of a *DC* Motor. The experiments are conducted during the course in eighteen weeks. Students are divided into groups of up to six and classes last three hours. A workbook laying out a roster of the experiments and presenting the laboratory tasks is given to the students in the first week. The experiments are developed with the aim to motivate students to developed their own capacity for solving process control related problems.

The purpose of this paper is to present both the content and the philosophy of initial activities involving analog simulation which are carried out in the Signals and Linear Systems lab classes of the Industrial Automation and Control Engineering Course.

Section 2 describes the current infra-structure of the Process Control Laboratory where the experiments are carried out. Section 3 illustrates the contents for the different experiments with analog simulation. Aspects of the 8th lab class, including the proposed philosophy, and conclusions are presented in sections 4 and 5, respectively.

Infra Structure of the Process Control Laboratory

The Process Control Laboratory has six control stations based on PCs and a supervision computer, all linked to a external and local communications network which enables the connection to other laboratories elsewhere. Figure 1 shows a picture of part of the lab.
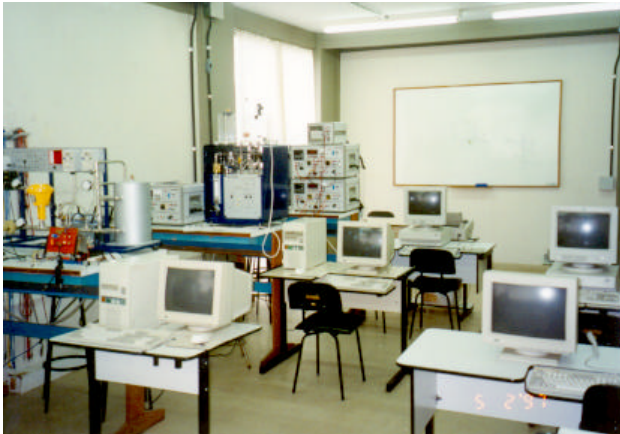

Figure 1 - Process Control Laboratory.

Each control workstation runs on Windows 95 and is equipped with Matlab/Simulink and VisSim simulation software, and Pascal and C++ for programming control activities. The different lab tasks of the SLS discipline employ this standard structure. Various disciplines of the Industrial Automation and Control Engineering — Feedback Systems, Digital Control, Identification, Advanced Control, Control Instrumentation — can share information through a data communication card. This important tool in the context of data acquisition and process control was designed and implemented by students in the early stages of the lab to go around financial constraints: similar card can be found in the Brazilian marketplace for around US$ 600 — US$ 300 in the USA (Figure 2).

The basic devices that constitute the input/output card are eight channels for the A/D converter, one channel for the D/A converter and, four channels for eight-bit parallel communication, including two digital inputs and two digital outputs. The A/D converter is obtained through ADC0808 integrated circuit which has the following characteristics: eight channels, conversion time of 60 µseconds for a clock frequency of 1 MHz and data resolution of eight-bit (range of 0 to +5 volts). The D/A converter is implemented with the LM324 integrated circuit and a R-2R resistor circuit. This converter has data resolution of eight-bit and the final band selection adjusted to operate in the standard ranges of 0 to +5 volts or 0 to +10 volts (output range). The real-world can also be controlled by devices or equipment that are operated through analog or digital outputs generated by

the computer. To deal with these cases, there are four digital I/O lines (being two for digital input operation and two for digital output operation) [3].
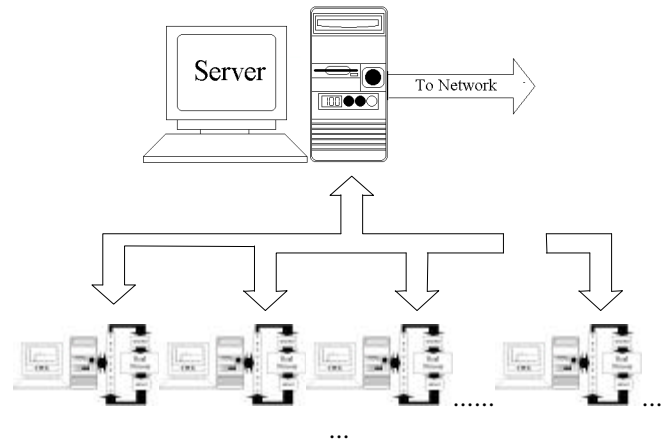

Figure 2 - Composition of the control network.

Experiments of the SLS Laboratory

Among the topics contemplated in the laboratory experiments there are: Introduction to VisSim, Matlab and Simulink Software; Analysis of Nonlinear Systems; Impulse and Step Response; Time Response of Dynamic Systems; Frequency Response of Linear Systems; Analysis of State-Space Systems and, Response of Second-Order Systems. All the experiments are conducted using both analog and discrete systems. The final experiment addresses the "Disturbance Effect in the Dynamic of a *DC* Motor: *P* and *PI* Velocity Regulation". A full description of all these experiences is available in [2].

Experiment 1 - *Introduction to VisSim, Matlab and Simulink Software* - In the process control area there are different computational programs that allow users to simulate various kinds of physical systems with reduced complexities (extremely friendly interface). Students have a first chance to know the basic principles of these very popular simulation software programs.

Experiment 2 - *Analysis of Nonlinear Systems* - In practice, many electromechanical, hydraulic and pneumatic systems, among others, present a nonlinear relation between their variables. For example, the output of a component can saturate input signals with high amplitude (the signal from a *PID* controller implemented by operational amplifiers) or the presence of a dead zone that can impair the dynamic behavior of a velocity or position servomechanism. In these experiments the behavior of different nonlinear and linearized processes are compared and evaluated using a level and a pendulum processes.

Experiment 3 - *Impulse and Step Response* - Electrical, mechanical and economic systems, among others, can be mathematically modeled through linear differential or difference equations. For analyzing and designing of a control system it is necessary to compare the performance of various control systems. These comparisons are done by measuring the response of the systems to a particular input test signal. So, from the mathematical representation and test signals it is possible to evaluate the dynamic behavior of different plants. This experience analyzes some process properties such as impulsive response, step response and convolution.

Experiment 4 - *Time Response of Dynamic Systems* - The time response is utilized to describe the output of dynamic systems for a given input signal. When a ramp or step input is applied to a system, the response can be divided into two parts: transient and steady-state. The behavior of the transient response depends on the roots of the characteristic polynomial of the system, and in some cases, on the initial conditions. The purpose of this experience is to study the properties of the time response of systems governed by differential and difference equations. Particularly, the step response of continuous and discrete systems, under various initial conditions, is evaluated.

Experiment 5 - *Frequency Response of Differential Systems* - The frequency response method is an alternative approach for the control operators and engineers for the analysis and synthesis of control systems. Using this method, it is possible to investigate the system stability (it is not necessary to calculate the characteristic polynomial roots), to determine experimentally a transfer function of a given linear system, and also to control its bandwidth in order to minimize the presence of high-frequency noise. So, a stable linear time-invariant system and subjected to a sinusoidal input presents, at steady-state, a sinusoidal output with the same frequency of the input; the output amplitude and phase, however, are, in general, different from the input signal. The objective of this experience is to study the properties of the frequency response of continuous systems. Especially, a second-order system (armature-controlled *DC* motor, in a simulation case) and a first-order system (RC circuit in a practical experiment) are assessed by the students.

Experiment 6 - *Analysis of State-Space Systems* - The actual trend of process control engineering systems is to be more complex, due to the necessities to realize difficult tasks and to present an adequate performance (precision). Because of the necessity to satisfy hard performance specifications, to understand complicated multiple-input and multiple-output systems and to show the importance of using computers to study the modern control theory via state-space, the analysis of control systems in space-state is introduced. The purpose of this experience is to study the state-space representation of control systems, to investigate the stability and to assess the time response of a continuous system (double-tank) and a discrete system (changing the sampling period for a second-order process and observing the stability).

Experiment 7 - *Response of Second-Order Systems* - The response of systems is constituted by transient and steady-state components. Both present important information on the characteristics of the control systems, for example, the steady-state error of a system is determined as the difference between setpoint and output and, the response velocity can be inferred from the transitory component. Another features of the system can be obtained from the time response. This experiment aims at analyzing the dynamic behavior of continuos and discrete systems of second order. System quality is evaluated through the step response.

Experiment 8 - *Disturbance Effect in the Dynamic of a DC Motor: P and PI Velocity Regulation* - Control Systems are designed to perform specific tasks. The requirements imposed to the control system are established as performance specifications. Generally, they concern precision, relative stability, response speed, and minimization of load disturbance in the closed-loop dynamic. This experiment evaluate the performance of *P* and *PI* controllers in a *DC* motor velocity system subjected to load disturbance using the performance specification — overshoot, steady-state error, settling time.

Aspects of the 8ᵗʰ Experiment

In order to illustrate the philosophy of the proposed laboratory course, some aspects of the 8ᵗʰ experiment will be discussed.

Introduction

The gain adjustment is the first procedure in controlling a given system to satisfy a set of performance specifications. However, in many practical situations a modification of the gain can provide an oscillatory or unstable behavior of the system. Frequently, increasing the gain value a better steady-state behavior can be obtained, but penalizing the relative stability. So, it is necessary to retune the system in order to modify the overall system performance to satisfy the desired specifications by the user. An additional element inserted into the system for this purpose is called a compensator or controller. This device compensates the deficit performance of the original system [7].

The objective of this experience is to evaluate the performance of *P* and *PI* controllers when applied in a *DC* motor velocity system and subjected to load disturbance.

Velocity Regulation of the Controlled System

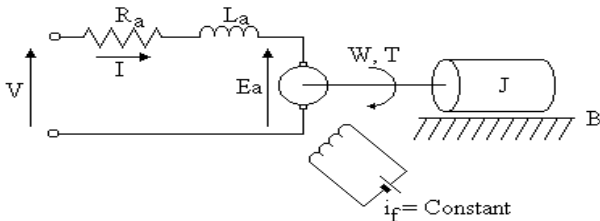Consider the armature-controlled *DC* motor as shown in Figure 3.

Figure 3 - Diagram of the armature-controlled DC motor.

The typical differential equations defining the dynamic behavior of the *DC* motor are:

$$J \frac{d\omega(t)}{dt} + B\omega(t) = T(t) - T_c(t)$$

$$T(t) = K_a I(t)$$

$$E_a(t) = K_b \omega(t)$$

$$L_a \frac{dI(t)}{dt} + R_a I(t) + E_a(t) = V(t)$$

The interest variables are: R_a is the armature resistance, L_a is the armature inductance, *I* is the armature current, *V* is the armature voltage (input), E_a is the back emf, *W* is the angular velocity, *T* is the torque developed by the motor, *J* is the equivalent moment of inertia of the motor and load referred to the motor shaft, *B* is the equivalent viscous-friction coefficient of the motor and load referred to the motor shaft, i_f is the field-winding current and T_c is the disturbance torque. The diagram of the velocity control system is represented in Figure 4.
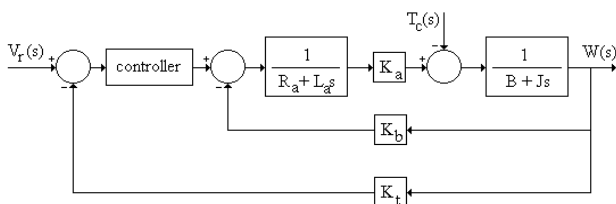

Figure 4 - Control conception of the velocity system.

4.3 Laboratory Tasks

- Assume J = 0.06Kg.m^2, B = 0.0207N.m/rad/s, $K_a = K_b =$ 0.543V.s/rad, R_a = 1.4Ω, L_a = 42mH, K_t = 0.5053V.s/rad and 10% of the input magnitude for the

step load disturbance (insert in 2 seconds). Consider all initial conditions zero and a step reference velocity (V_r) of magnitude 10.
- Verify how the disturbance can modify the motor velocity dynamic without and with velocity regulator. It is possible to observe the steady-state error and transitory of the system when the gain of the *P* controller is changed.
- Evaluate the response characteristic of the closed-loop system by using the following gains: *P* controller (K_c = 2, 5 ,10) and *PI* controller (K_c = 10 and K_i = 2).

Simulation Results

Matlab/Simulink and VisSim environments can be used to analyze the performance of the *DC* motor under *P* and *PI* control conception. The student rapidly learns about their effect on the transient and steady-state responses and on the control effort need to attain the desired design specifications. The control system, process and controller diagrams can be implement using VisSim, as shown in Figures 5, 6 and 7, respectively. Figures 8 and 9 exhibit the closed-loop behavior of the angular velocity.
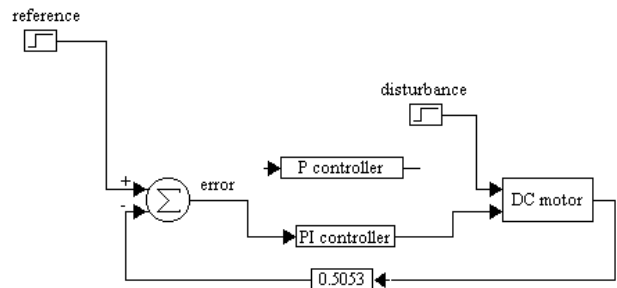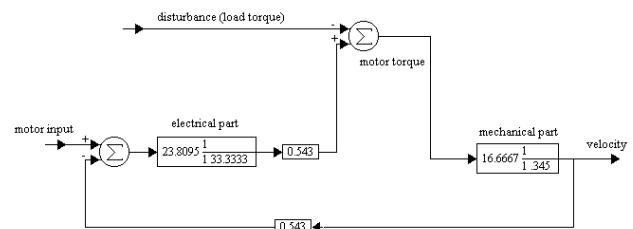

Figure 5 - DC motor and control system diagram.
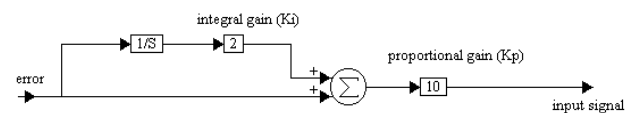

Figure 6 - DC motor implementation.

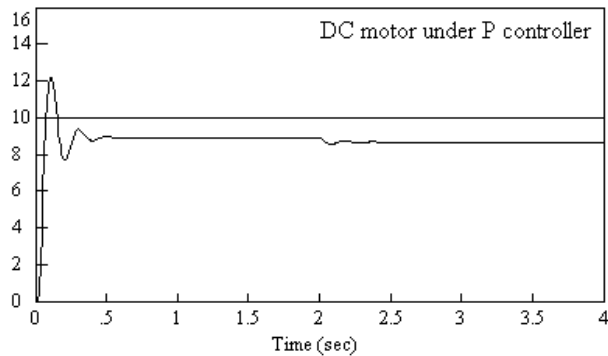*Figure 7 - PI controller implementation.*

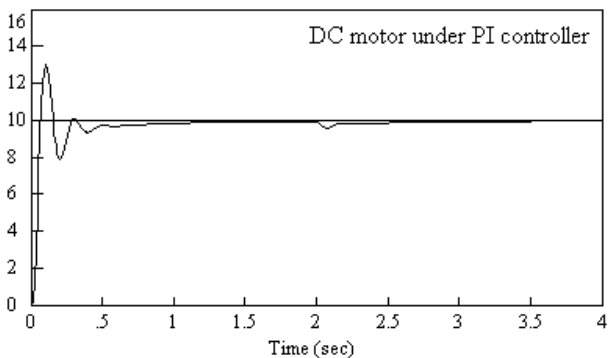*Figure 8 - Closed-loop velocity behavior with P control.*

Figure 9- Closed-loop velocity behavior with PI control.

According to the simulation results it is possible to verify that only the *PI* controller provides zero steady-state error and minimizes the presence of the disturbance. So, using this simulation material, the students can get an adequate feeling of the performance of the *P* and *PI* controllers and can understand how the control gains can modify the closed-loop dynamic of a controlled system.

Conclusion

This paper has reported the contents of an initial laboratory experiments used to assess dynamic systems in the discipline of Signals and Linear Systems of the Systems and Automation Department at the Federal University of Santa Catarina. Experiments use simulation software programs — Matlab/Simulink and VisSim — to integrate analog and digital simulations. The authors believe that this set of lab classes is one the most adequate ways to introduce, to the students, basic concepts in modeling, design and implementation of dynamic systems with the additional advanced of bridging the gap between theoretical and abstracts concepts and practical applications.

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