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The Temperature Box: An Introductory Control Systems Project

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Abstract

There is a heightened awareness in the academic controls community about the need to attract the best and brightest students to the discipline. To achieve this end, change is needed in the standard approaches to educating, recruiting, and training students. In this paper, the "Temperature Box" experiment is presented. This experiment involves the design and implementation of a feedback temperature control system. At the United States Naval Academy, the Temperature Box is used to motivate the material in an introductory system engineering course at the sophomore level. This experiment would also be suitable for use in a freshman engineering course, a control systems laboratory course, or an electronics course as a controls application of analog and digital electronics.

1 Introduction

There is a heightened awareness in the academic controls community about the need to attract the best and brightest students to the discipline. To achieve this end, change is needed in the standard approaches to educating, recruiting, and training students. A number of ideas have been presented in [1]. It has been shown that the Problem-Based Learning (PBL) approach helps students to synthesize material far more effectively than traditional subject-based learning [2]. In the PBL approach, a problem is presented at the beginning of the course and, subsequently, is used to motivate the material that the students need to learn to solve the problem. The PBL learning approach increases student enthusiasm, confidence, and consequently, their retention.

In [3], this approach was called "motivation-by-challenge" and was applied successfully to a Junior and Senior level introductory control systems course. Benefits cited by the author included significantly higher student grades, student enthusiasm, self-initiated student exploration of the material, and a great increase in the number of students selecting control system electives and controls as a career.

These results indicate that this type of change needed in the academic controls community. The goal of this paper is to introduce a problem, the "Temperature Box", that can be used to motivate students early in their academic career, that is, at the Freshmen and Sophomore level. The Temperature Box problem is a closed loop temperature control system and, as an experiment or design problem, is not new. However, the contribution of this paper is to demonstrate how this problem is used to motivate the material in an introductory course in systems engineering at the United States Naval Academy. Additionally, the paper provides a description of the Temperature box so that it can be used in a similar capacity at other schools.

In the experiment, the temperature of a room (cardboard box) is controlled by opening or closing a relay connected to a hair dryer. The control signal sent to the relay is determined by comparing measurements from a temperature sensor with high and low temperature set points. The comparison involves both analog and digital components.

In the Systems Engineering Department at the United States Naval Academy, this experiment is used as a "challenge-problem" for a first course in systems engineering at the sophomore level. This course is intended to provide an introduction into the analysis, simulation, and implementation of control systems. A variety of topics are covered including: solutions of systems of algebraic equations, solutions of differential equations using Laplace transforms, numerical simulation using MATLAB and SIMULINK, operational amplifiers (op-amps), and digital logic circuits. The design and construction of the temperature box experiment draws from each part of the course and provides an example of a feedback control system.

The experiment itself stands alone and provides an illustrative example of the elements of a feedback control system: measurement, comparison, and actuation. In addition, the control problem is intuitive and so it does not require extensive motivation or sophisticated mathematics. In a freshman engineering course, this experiment could be used to attract students to the field of control systems. In a control systems laboratory course, it could be used to introduce the concept of feedback control. In an electronics course, it could be used as a final laboratory in analog and digital electronics.

The paper begins with a short description of the introductory course to systems engineering in Section 2. In section 3, a description of the Temperature Box experiment is presented. This description includes a discussion of how this problem can be used to motivate the study of control systems and to introduce the tools used by control systems engineers. Student evaluations are summarized in Section 4. Conclusions and suggestions for future improvements are given in Section 5.

2 Introduction to Systems Engineering Course

In the Systems Engineering Department at the United States Naval Academy, the Temperature Box experiment serves as the motivating example for the first course in systems engineering in the sophomore year. This course provides an introduction into the analysis, simulation, and implementation of control systems. The objective is to prepare the students for the core courses in classical and state-space control as well as elective courses in digital control, communications, computer engineering, and/or robotics. The course is divided into four sections

1. Solutions of systems of algebraic equations
2. Solutions of differential equations
3. Transfer functions and operational amplifier circuits
4. Digital logic circuits

A particular emphasis is placed on problem solving skills and, as a result, each section is constructed around the solution of a certain type of problem. A brief description of each section is presented below to establish the background material used in the Temperature Box experiment.

The first section addresses the existence and uniqueness of a solution of a system of algebraic equations. Basic matrix operations and linear algebra concepts are introduced. Given a set of algebraic equations, the students are expected to determine if a solution exists and, if so, is the solution unique. In addition, the concept of fitting a polynomial to experimental data is discussed using the least squares technique. The classroom material is supplemented with computer exercises in MATLAB.

In the second section, analytical and computer methods for solving an ordinary differential equation are discussed. Specifically, the Laplace transform is presented as a tool for obtaining an analytical solution to a differential equation. The primary focus is on computing an inverse Laplace transform using partial fraction expansion methods. Concurrently, the students use SIMULINK and C programming to solve differential equations numerically.

In the third section, transfer functions are introduced as an alternative descriptive of a differential equation. The notions of poles and zeros are discussed as well as the relationship between a pole and its mode. The implementation of a simple transfer function using op-amps is presented. In the laboratory, the students examine several basic op-amp circuits: amplifiers, summing junctions, and first order transfer functions.

The final section of the course covers the design of sequential digital logic circuits. First, the students are introduced to basic logic gates and combinational logic. Using Karnaugh maps, combinational logic circuits are designed and implemented. Next, flip-flops are presented as a means for storing information. Finally, all the above elements are combined to achieve a sequential logic design. Throughout the section, the students examine and build the various circuits in the laboratory.

3 The Temperature Box experiment

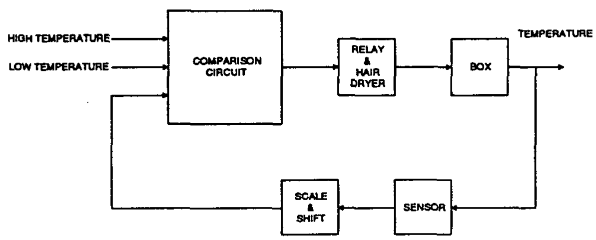

Figure 1: Block diagram of the Temperature Box.

The Temperature Box experiment involves the design and construction of the closed loop temperature control system shown in Figure 1. The physical components of the system are a cardboard box (plant), a relay and hair dryer combination (actuator), and a temperature sensor. The control system consists of a signal conditioning circuit known as the "scale and shift" circuit and a comparison circuit. The circuits are implemented using op-amps and digital logic. The design and implementation of these circuits are described in Sections 3.1 and 3.2.

The project was originally conceived as a laboratory in a senior level elective on environmental engineering at the United States Naval Academy [4, 5]. As a senior level laboratory, the objective of the project was to regulate the temperature using computer control (via a C program). For the introductory systems engineering course described in the previous section, the experiment has been modified to emphasize the use of op-amps and digital logic and to motivate and connect the variety of topics covered in the course.

In this experiment, the temperature within the cardboard box is controlled by turning the hair dryer on and off. The hair dryer turns on when the measured temperature falls below a predetermined low temperature setting and turns off when the measured temperature rises above a predetermined high temperature setting. For measured temperatures between the low and high set values, the hair dryer remains in its current state. The temperature comparison is implemented using op-amps and digital logic. A relay switch is used to regulate the power supply to the hair dryer based on the outcome of this comparison.

3.1 Scale and shift circuit

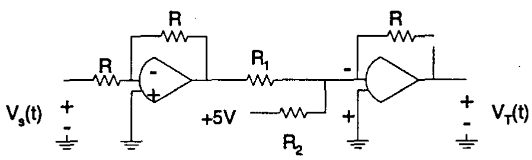

Figure 2: Scale and shift circuit.

The temperature sensor converts temperature to voltage through a temperature-dependent resistor. In this experiment, the AD22100 temperature sensor from Analog Devices was used. The relationship between temperature and voltage is linear for a wide range of temperatures and is given by

$$V_s = 0.975 + 0.0125\,T_F \tag{3.1}$$

where V_s is the sensor's output voltage and T_F is the temperature in Fahrenheit. To proceed with the design, the students need this calibration curve. This provides a perfect motivation for finding a least square linear fit of the experimental data.

After some trial and error, it was determined that the high and low temperatures should be well above the ambient temperature to achieve sufficiently fast cooling [1]. The high temperature was chosen at 95^oF and the low temperature was chosen at 85^oF assuming at ambient temperature of 70^oF. The sensor output voltages are $1.85\,V$, $2.04\,V$, and $2.16\,V$ for 70^oF, 85^oF, and 95^oF, respectively. It follows that there is only a $0.12\,V$ differential between the high and low set temperatures.

The scale and shift circuit is used to increase the sensitivity in the temperature measurement. Specifically, this circuit modifies the sensor output to achieve a larger slope in the temperature/voltage relationship. The scale and shift circuit shown in Figure 2 modifies the sensor output by the relationship

$$V_T = \alpha + \beta\,V_s \tag{3.2}$$

where V_T is the voltage supplied to the comparison circuit in Figure 1, $\alpha = -5\,\frac{R}{R_2}$ and $\beta = \frac{R}{R_2}$. In order to obtain a larger voltage differential, V_T is set to $0.5\,V$ at 70^oF and $4.5\,V$ at 95^oF. Under these conditions, the scale and shift relationship in equation 3.2 yields two equations

$$\begin{aligned} 0.5 &= \alpha + 1.85\,\beta \\ 4.5 &= \alpha + 2.16\,\beta \end{aligned} \tag{3.3}$$

The solution of these equations is given by $\alpha = -23.4$ and $\beta = 12.9$. Using the scale and shift circuit to modify the sensor output, a temperature of 85^oF produces $3.0\,V$ and a temperature of 95^oF produces $4.5\,V$. As a result, the voltage differential has been increased from $0.12\,V$ to $1.5\,V$. An op-amp implementation of the scale and shift system is shown in Figure 2 with $R = 100k\Omega$, $R_1 = 7.75k\Omega$, and $R_2 = 21.75k\Omega$.

The development of the system of equations (3.3) serves as motivation for a discussion on solutions of systems of algebraic equations. Furthermore, since the system in (3.3) has only two equations and two unknowns, it is possible to use this example to present various solution methods (i.e. matrix inverse, Cramer's rule, or row reduction). In addition, the implementation of this circuit using op-amp is a valuable exercise in op-amp circuit design and signal conditioning.

3.2 Comparison circuit

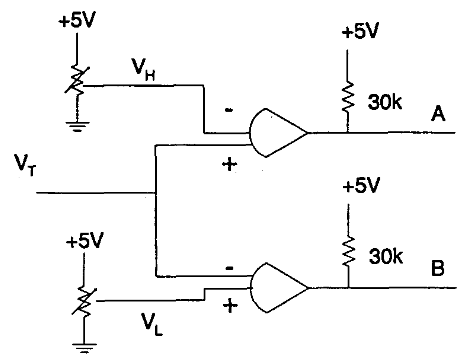

Figure 3: Op-amp comparators for the comparison block.

In Figure 1, the scaled and shifted sensor voltage is compared to the predetermined high and low temperatures. A decision is made (using digital logic) whether to open or close the relay and, hence, turn the hair dryer off or on. Let V_H denote the voltage corresponding to the highest desired temperature (95^oF) and V_L denote voltage corresponding to the lowest desired temperature (85^oF). Note that these voltages must be consistent with the voltage at the output of the scale and shift circuit. In this experiment, $V_H = 3.75\,V$ and $V_L = 2.75\,V$. The decision is based on three rules

1. The relay is on if $V_T \leq V_L < V_H$.

[1]In future versions, an exhaust fan will be included to accelerate the cooling cycle.

2. The relay is off if $V_T \geq V_H > V_L$.

3. The relay state is unchanged if $V_L < V_T < V_H$.

Define logical variables $A = (V_T < V_H)$ and $B = (V_T > V_L)$ and let R_k and R_{k+1} denote the current and next relay states, respectively. Note that A and B can be obtained using comparator op-amps as shown in Figure 3. The three rules above can be rewritten as

1. $R_{k+1} = 1$ if $B = 0$.

2. $R_{k+1} = 0$ if $A = 0$.

3. $R_{k+1} = R_k$ if $A = 1$ and $B = 1$.

$AB \backslash R_k$	0	1
00	X	X
01	0	0
11	0	1
10	1	1

Figure 4: Karnaugh map for comparison circuit.

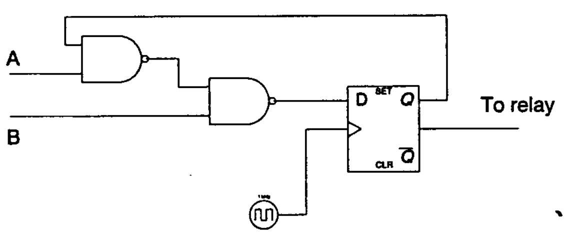

Figure 5: Sequential digital logic for comparison block.

From this information, a truth table and a Karnaugh map can be compiled. The Karnaugh map is shown in Figure 4. Note that the $X's$ occur whenever a particular combination of inputs is impossible; that is, $V_T < V_L$ and $V_T > V_H$. Grouping the logical 1 terms and the $X's$, the following logical expression is obtained

$$R_{k+1} = \overline{B} + A\,R_k \tag{3.4}$$

Using DeMorgan's law, the expression in 3.4 can be rewritten as

$$R_{k+1} = \overline{B\,\overline{A\,R_k}} \tag{3.5}$$

The expression in (3.5) can be implemented with 2 NAND gates and a D Flip-flop as shown in Figure 5.

The design and implementation of the comparison circuit provide interesting applications of op-amps, digital logic gates, Karnaugh maps, and sequential logic design. In the introductory systems course at the United States Naval Academy, the various stages of the circuit are designed and built as the course progresses. As a result, at the end of the semester, the students need only connect the individual circuits together to assemble the comparison circuit and the scale and shift circuit.

4 Student evaluations

The students' evaluation of an experiment is an important measure of its success. Generally, there are several means for students to comment on the course including the end-of-semester faculty evaluations. For this course, a questionnaire was developed to determine the effectiveness of the Temperature Box experiment in enhancing their understanding of the course material. The students were asked to indicated their level of understanding of the various sections of the course. The responses from 28 students are compiled below.

Section	Confusing	Understood	Well Understood
Scale and shift circuit design (Matrices)	2	13	13
SIMULINK simulation	3	12	13
Scale and shift circuit (op-amps)	4	14	10
Comparator/ decision circuit (digital logic)	1	12	15
Temperature box construction	2	15	11

Figure 5: Summary of student responses

The vast majority of students developed an understanding of the course material and indicated that the Temperature Box experiment enhanced their understanding. In particular, the following comments summarize the students' impression of the experiment.

- "The lab was exciting. It showed that what we had been learning in class actually worked. It also felt great to see (that) the work that we put in over the last five weeks (come together)."

- "Labs like this, which are enjoyable, spark an interest in future labs and class periods. This lab really made all of the class (material) ... very understandable."

- "I liked that it (the experiment) incorporated all the math and logic (that) we (had) covered over the semester and that once it was built, it worked."

The main criticism of the experiment was that the laboratories were too structured. One student commented:

- "By the end of the experiment, we were just following the instructions in the lab manual and not flexing our knowledge of the material.".

This critique is valid because the instruction in the laboratory handouts were quite detailed.

5 Conclusion

In this paper, a "Temperature Box" experiment is presented in which the temperature of a room (cardboard box) is controlled by opening or closing a relay connected to a hair dryer. The students were challenged to apply linear algebra, analog and digital electronics, and basic control system concepts in the analysis, design, and construction of a feedback control system. Two comments were raised in the student evaluations: the experiment enhanced the students' understanding of the course material and the laboratories procedures were highly structured. These comments indicate the tradeoff that was addressed in preparing the experiment. The primary objective is to reinforce the material presented in lecture. Additionally, the experiment provides an opportunity for the students to design, build, and troubleshoot analog and digital circuits. However, neither of these objectives can be met if the students can not build the Temperature Box successfully. Therefore, due to the introductory nature of the course, the emphasis was placed on learning as opposed to design and, specifically, the laboratory procedures were written with the goal that all students could build a working Temperature Box. The students will have ample opportunity for design in subsequent courses. A secondary benefit is that the success of the experiment would motivate students to continue in a control system curriculum.

In future version of this course, several changes will be made. An exhaust fan will be added to assist in the reducing the temperature in the box after the hair dryer is turned off. The addition of the fan will improve the performance of the system because the current version relies on a temperature gradient alone to cool the box. Due to our department's desire to update the curriculum, a microcontroller may be included in the experiment and used to perform the voltage comparison in place of the digital logic.

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