A System Approach to Teaching Control Principles

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Abstract

It was the first semester for Dr. Foust as a professor and he taught, among other classes, a class on mechatronics, which he did under the mentoring of Dr. Watt. This class began with lectures on DC and AC circuits, linear systems, solving linear systems, and then went into greater detail on mechatronics issues, such as dynamic systems, feedback, sensors, actuators, and data acquisition. The curriculum started with rigorous lectures and ended with groups solving an open-ended problem, which was the design of a sensor/controller for the water level within a bucket.

A major emphasis of the class was to treat the subject from a system approach and using the scientific learning cycle method. This is applied to mechatronics in the following manner: several scientific principles were presented throughout the class and it was shown how these principles permeate all of mechatronics. These principles included superposition, linear systems and solving linear systems; conservation of charge and energy; and dynamic system methods.

Introduction

Last Fall, Dr. Foust began as a professor at Nicholls State University and among the classes he taught that semester was a mechatronics class and laboratory. Mechatronics is the application of computer and electrical principles to a mechanical system. This class began with a standard fare of DC and AC circuit principles, which can be summarized as applying the conservation of charge, conservation of energy, and linear system principles to electrical systems. Subjects with more of a mechatronics emphasis included filters, data acquisition, and Op Amps. The laboratory component to the class culminated in the class addressing the following problem.

How do we sense the water level in a bucket and keep this water level at a prescribed level when water is leaving the bucket through an outlet in the side?

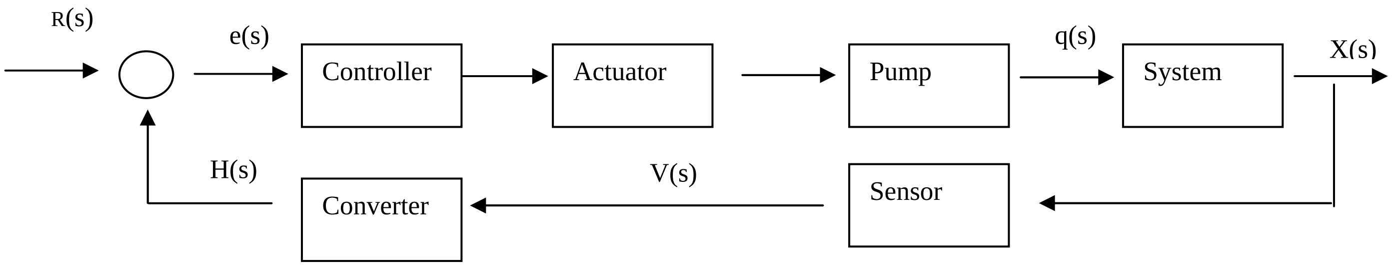
To answer this question, several components need to be addressed:

- How do we sense the water level?
- How do we turn this into a signal a controller can use?
- How do we tune the parameters of the controller?
- What is the dynamic model for this system?

These components are given in **Figure 1**. Several teams were formed to answer the problem stated above. These groups included sensor, actuator, system engineering, dynamic system and feedback groups. The sensor group was tasked to find a means to determine the current water level in the bucket. The actuator group determined a means to add water instantaneously to the bucket based on the instantaneous water level. The dynamic system group determined a dynamic model of the system and worked with the feedback group who defined the parameters of the PID controller. PID control is a form of industrial controller. The system-engineering group coordinated all groups.

The actuator and sensor groups essentially worked as one group. The dynamic system, feedback, and system engineering groups essentially worked as one group.

Figure 1 – System Diagram



Where R(s) is the set point water level to maintain, V(s) is a voltage, H(s) is the current observed water level, q(s) is a discharge into the bucket, and X(s) is the current water level.

To understand the curriculum this course is embedded in and the emphasis on student groups (teams), the following section discusses the manufacturing engineering technology program and the learning style that was adapted.

Educational Background

Our manufacturing engineering technology program is built around a core series of project courses that serve as the capstone-manufacturing experience requiring implementation of the technical and business management courses. The novelty of these project courses is that the students from three grade levels (senior, junior, and sophomore) participate in the projects. This approach provides both horizontal and vertical integration of the design/manufacturing project, which is not common [1]. The students are divided into several teams with each team functioning as a division in a small company [3, 6, 7]; each team will participate in a two semester long project. The tasks assigned each class level are designed to be compatible with the courses that a typical student should have completed or be taking at the sophomore, junior, or senior levels. The intent of this project approach is to give the students some more realistic engineering experience while they are still in the university so they will be better prepared for their first "real world experiences." We continue to consider approaches that allow the faculty to meet student learning needs. In so doing we have chosen two courses in which to explore some of the relevant teaching and learning theories we think are particularly applicable to engineering technology curricula. The theories are Piaget's [9] intellectual development theory and scientific learning cycle [9].

Piaget's theory discusses the stages of intellectual development from new born to adult, but our concern is only with the stages of concrete operational and formal operational and the transition from the first to the second. Concrete operational relates to ability to do mental operations only with real (concrete) objects, events or situations. Formal operational relates to being able to think abstractly; formulate hypotheses without relating to real objects, events or situations; testing hypotheses and logical alternatives; and generalizing from real objects to abstract notions and ideas. At the formal operational stage the student is capable of learning higher math and is capable of applying it to the solution of new problems. Engineering technology education requires at least some ability to operate at the formal operational level. Students operating at the concrete operational level learn math by memorization and are usually unable to use it to solve new or unusual problems and consequently will have difficulty with an engineering type of curriculum. Piaget felt that the transition from concrete operational to formal operational was complete by the twelfth year, but more recent studies have shown that as much as 60% of the adult population appears to still be in the transitional phase between the two phases. A critical question is "How do we help our students move more toward formal operational intellectual development." Piaget proposed that the transition is initiated by the introduction of new ideas that don't fit the individual's current mental structures thus creating a disequilibrium that the individual must deal with in some way. The new ideas may be dealt with by rejecting them or if they must be dealt with they are memorized, but not understood (this is often what the concrete operational individual does), if they are not too dissimilar they may be accommodated into the existing mental structure, if they are quite different from the existing mental structure they may be transformed to fit the mental structure or, ideally, the mental structure is changed and grows to be able to assimilate these new ideas. As the assimilation occurs, the individual's intellectual development stage becomes more formal operational and less concrete operational. Two well known learning cycles have been proposed that have the potential to create the needed disequilibrium and help guide students in assimilating the new ideas.

The Scientific Learning Cycle is a three-stage cycle. The first stage is an exploration or self-discovery phase where students explore a new phenomenon with minimal guidance and try to learn how it works by using it. The exploration phase could involve computer simulations to explore a process or device. Phase two is called the term introduction or invention phase or the concept invention or introduction phase where the instructor fills in the parts the students missed in the exploration phase. And, finally, the concept application or expansion phase where students apply the new ideas, terms, and/or patterns to new examples by homework, discussion, laboratory exercises, etc. This learning cycle is simple and straight forward in principle, but can take a great deal of preparation by the instructor to have a properly designed self-discovery phase. The essential Scientific Learning cycle was used, but not exactly as discussed.

Our desire is to take the students through all stages of the learning cycle by carefully chosen lectures, often occurring in a just-in-time manner; discussions; discovery experiences; working in teams; analyzing; synthesizing; building; and testing. Our emphasis on systems will allow both analyses and syntheses.

The final project brought the students through the complete cycle because several projects were assigned and completed without specific guidance. These other projects included windmills and digital tachometers. In subsequent mechatronics classes the Scientific Learning cycle will be supplemented with the full Kolb Learning Cycle [9] will be used and the approach will be to "teach through the cycle." The remainder of the paper describes the details of the approach taken in this attempt to apply the scientific learning cycle method.

Sensor and Actuator Group

The bulk of the work for the sensor and actuator group involved understanding the equipment to be utilized and integrating the various pieces. This group did the bulk of the empirical work on this project.

It had been proposed to use strain gauges, PID control, and a submersible pump to affect this system, but that approach was modified due to time constraints. The sensor and actuator team decided on a sonic depth sensor instead of a strain gauged cantilever beam. The dynamic system and feedback and system engineering teams developed the dynamic model for the system, linearized this model around the set-point water height, determined the parameters for a PID controller, and simulated the nonlinear system using state feedback PID control. Due to time constraints, these simulation results were not implemented into the final design.

Dynamic System, Feedback and System Engineering Group

The dynamic system, feedback, and system engineering groups did the theoretical part of the project [4]. The theory developed in this part of the project was not utilized, because PID control was not used.

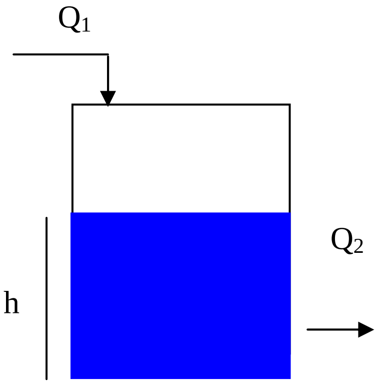
Empirical Work

It was felt by the instructor and the teams that an empirical approach to finding the bucket discharge at various water heights would give the best estimate. This is due to the fact that Torricelli's Law [5] needs to include a head loss component and this is best determined through an empirical study. The results of the empirical study determined that the relationship between water level (h) and pumping rate (Q) is quadratic.

Dynamic Model

Given in **Figure 2** is a diagram of the Bucket, which is amenable to determining the mass balance equations.

Figure 2 – Control Volume



From **Figure 2,** the following mass balance is derived:

$$\frac{\partial V}{\partial t} = A\frac{\partial h}{\partial t} = Q_1 - Q_2 \quad (1)$$

$$and$$

$$A\frac{dh}{dt} + f(x) = Q_1 = Q$$

Where A is the cross-sectional area of the bucket, V is the volume of the bucket, h is the current water height, Q_1 is the rate of water entering and Q_2 is the rate of water leaving the bucket. The typical form of f(h) is given from Torricelli's law, which appears without head loss corrections (A' is the area of the opening),

$$Q = A'\sqrt{2gh} \quad (2)$$

But an empirical study, discussed above, found that a quadratic form was appropriate. This form is utilized in the sections below.

Linearization

Equation (1) is nonlinear and cannot be used for the controller design, but a linearized form of Equation (1) can. The set-point [R(s) from **Figure 1**] is 2 and f(h) takes the following form

$$f(h) = h^2 + Bh \quad (3)$$

$$where$$

$$A = 4, B = 2$$

The derivative is

$$m = \frac{\partial f}{\partial x} = 2h + B = 2h + 4$$

and

$$[h, f(h)] = (2{,}8) \Rightarrow \; f(x) \approx 6h - 4$$

and

$$4\frac{dh}{dt} + 6h = Q + 4 = u$$

Results in

$$G(s) = \frac{h(s)}{u(s)} = \frac{1}{4s + 4} \quad (5)$$

Controller Design

The controller design was based on using PID control, which is the most used form of control for industrial application. The form of tuning was to use fixed structure control [8].

The calculations are given below. In the next section, how well the controller design works will be demonstrated.

The method works by ensuring the closed loop denominator matches a characteristic polynomial, P(s), which has suitable performance and stability characteristics. Where G(s) is the system to be controlled and K(s) is the controller.

$$G(s) = \frac{N_P}{D_P} = \frac{1}{As + K} \quad (6)$$

$$K(s) = \frac{N_K}{D_K} = \frac{K_p s + K_i}{s}$$

where

$$P(s) = s^2 + 2s + 2$$

and

$$P(s) = N_P N_K + D_P D_K$$

From which,

$$K_p = A(2 - K / A) = 2 \quad (7)$$

$$K_i = 2A = 8$$

Simulations

Figure 3 gives a Simulink representation of the dynamic system, the bucket, and the PID controller. It can be seen from **Figure 4** that the state initially overshoots the set point, but quickly dies down to 2.

Discussion

How well did this class and laboratory work in terms of the bucket project itself and the method of instruction? What could be done differently for next semester? The first question will be answered in this section, the second in the conclusion section.

It was found that the students learned the most when teaching each other in an environment of discovery. This should be the primary learning environment. Lectures, home works, exams and projects should guide that discovery.

Conclusions

Next fall, when this class is again taught, concepts will be prefaced with motivational demonstrations. The concepts will be reinforced with homework's, exams, and lectures in a just-in-time manner. The final project, the bucket project, will be shown the first day and reinforced throughout the semester as the goal of all work. The result that will be sought is to implement the Kolb Learning Cycle for the students and use teaching methods that take the student through all four stages of the Kolb Learning Cycle.

It is hoped that fundamental concepts, such as continuity of mass and energy, go through a complete Kolb Learning Cycle and by the end of the semester students have gone through the cycle several times.

A system approach is utilized to tie concepts together that, at first glance, appear to be unrelated. The system approach also facilitates an approach the students can apply when they are working in their chosen field.

Figure 3 – Matlab System

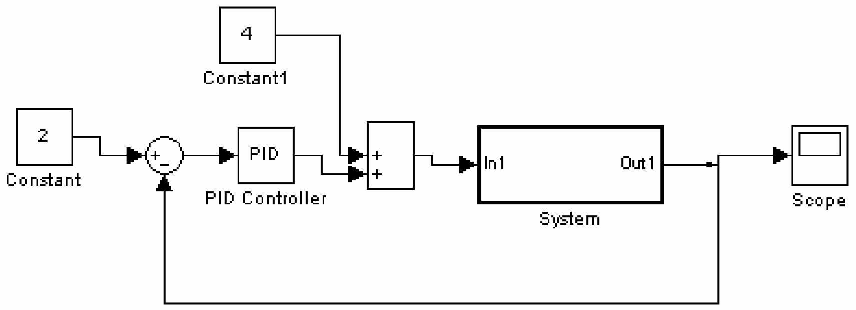
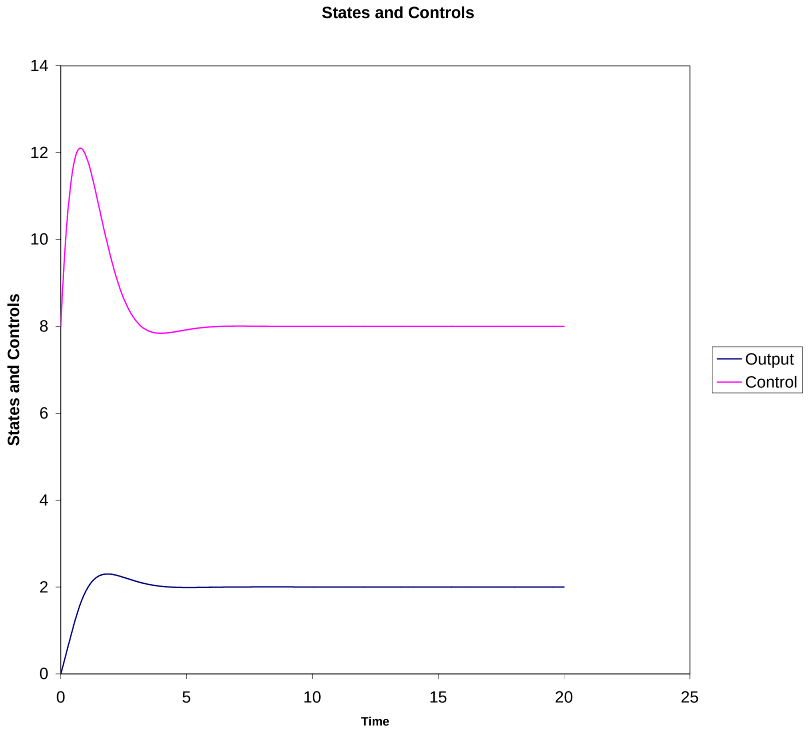


Figure 4 – Response



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Biography

Henry Foust is an Assistant Professor in the Department of Applied Sciences at Nicholls State University, which is near New Orleans, Louisiana. He teaches and conducts research in a manufacturing engineering technology program. His research is in the use of control methods towards environmental systems and energy systems.

George Watt also works in the Department of Applied Science at Nicholls State University as an Associate Professor. He teaches and conducts research in a manufacturing engineering technology program. His research is in teaching engineering.

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We’d like to thank our students for their continued patience while we figure out what it means to be a teacher and how best to do this.