Case for a Course in Digital Control in the Undergraduate Engineering Technology Program

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CASE FOR A COURSE IN DIGITAL CONTROL
IN THE UNDERGRADUATE ENGINEERING TECHNOLOGY PROGRAM

Abstract - To control is a basic instinct in human beings. Control engineering is required in almost every branch of engineering. With the advent of computers, more and more shift is happening towards their use in controlling systems. Educators have for a long-time believed that it is necessary to learn the control of continuous-time systems before moving on to discrete-time control (also known as digital control) systems. While disagreeing with this belief, the authors hold the view that, even though several physical systems operate continuously in time, sensing, measuring and processing of control data and corrective actions are basically discrete methods. Therefore, it is imperative that a course in Control should start with the discrete signals and systems. The basics learned from discrete signal and systems can be easily applied in continuous-time systems by using a very small sampling-time interval.

The proposed course starts with discrete-time concepts but concurrently introduces the continuous-time concepts and methods. The Z-transform and Laplace transforms are both introduced in a single chapter, moving on to discrete systems, responses and control methods, conversion of continuous-time systems to discrete systems for digital control. The later process requires working knowledge of Laplace transform and methods. The course tops off with the feedback control methods and implementation of the digital controller transfer functions using Digital Signal Processor.

The proposed course uses MATLAB extensively to illustrate the control concepts and examples. Each concept has an example which the instructor can take up in the classroom or assign for self-study. Students can use these numerous examples for experiential learning. The course also uses SIMULINK examples to show sample-by-sample processing of the concepts of control. Lastly the course gives examples of how to implement a digital controller using a Digital Signal Processor such as the Texas Instrument's 320C6713 processor. This course has been tested in the classroom.

The paper will present the detailed syllabus comprising of week-wise lecture topics and the laboratory exercises, as well as the student satisfaction survey, student's feedback at the end of the class, and instructor's self-assessment.

I. INTRODUCTION

To control a system in order to get a desired performance has been the longest desire of engineers and planners. The control requirements may be of different kinds: a) to stabilize an unstable system, b) to change the state of a system from one to another, C) to track the output of a system to a known variable, and d) to regulate the performance of a system in the face of variable inputs, loading of output, disturbances and external noise. The list is endless depending on the type of application.

Learning to control a system requires learning and developing a repertoire of tools for

1. Modeling of systems,
2. Actuation, sensing and transducing
3. Analyzing the characteristics of systems and
4. Modifying the characteristics to achieve the desired performance from the system.

Most important step in the control design is to develop appropriate mathematical model of the system derived either from physical laws or experimental data. It is to be noted that it is often not possible to model a physical system completely. It is enough to obtain a reasonable, approximate and simple model. Our knowledge of tools to analyze and control systems is limited to simpler models and that has enabled good engineering control. Modeling a system, furthermore, requires knowledge of several fields of science and engineering. It is best left to the experts in the fields and experienced interface engineers and technologists. In the proposed course, we will focus on the analysis of system models and methods and design of control subsystems.

Current trend in control system is to use software managed hardware. The software management is done locally or remotely. This helps in standardization and cost saving in design and maintenance. This approach has led to development a huge field of embedded systems. The hardware system to be controlled may be an analog system or a discrete system. Most of the physical systems and associated variables are continuous in time (also called the analog systems). However, the monitoring and measurement of associated variables is invariably discrete in time. Processing of the monitored and measured variables can be performed by continuous-time or discrete-time processes. The discrete-time process or system is also called digital system although it is not necessarily an accurate nomenclature. A discrete-time variable when quantized to fixed amplitude level is referred as the digital variable. Practicing engineers often mix the discrete and digital for the sake of simplicity. An example of a digital control system for an automobile is shown below in Fig. 1.

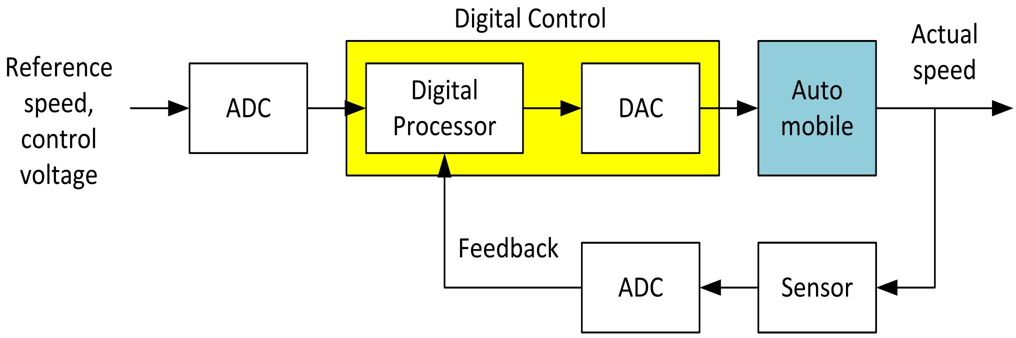


Fig. 1 Digital Feedback Control System[5]

The difficulty faced by the educators is that many of the textbooks[1] [2][3] on the subject are aimed for graduate studies. We have used a recent textbook[5], authored by one of the authors of this paper, which is very suitable for using at the undergraduate level instruction.

II. PURPOSE

Control is one of the important and essential track in the undergraduate program of Electrical or Electronic and Computer Engineering Technology. Each track has the room for 2 or 3 of the 3 credit courses. Let us also look at the knowledge base in Control track that we are required to package in this track:

a) Analog Control
b) Digital control
c) Real-time Control
d) Robust Control
e) Adaptive Control

Generally, two courses in a particular track in an undergraduate curriculum, focus on delivering fundamentals, knowledge of basic components and technologies and teach the advanced control technology in the third course. Traditionally, the first two core courses in the control track have been the Analog and the Digital Control. These courses cover the concepts and technology which have become outdated in the industry. The control industry has undergone transformation from analog to digital on a very big scale. Computers have come in front of all control systems and interfaces. The analog control concepts such as the Laplace transfer functions, frequency domain methods of feedback control now have only conceptual values. There is a need for the first course to start with the digital control technology and the knowledge related to serve that purpose. We will have to limit the technology of continuous systems and control to teaching of principles and working knowledge of techniques. Bring in the concepts and techniques of Z-transforms, conversion of continuous to discrete systems modeling and direct design of digital controllers. We suggest the following control track in the undergraduate program:

Course 1: Introduction to Digital control
Course 2: Advanced Real-time control

Next section of this paper presents the details of the first course in digital Control with all the above objectives in mind.

III. COURSE DESCRIPTION

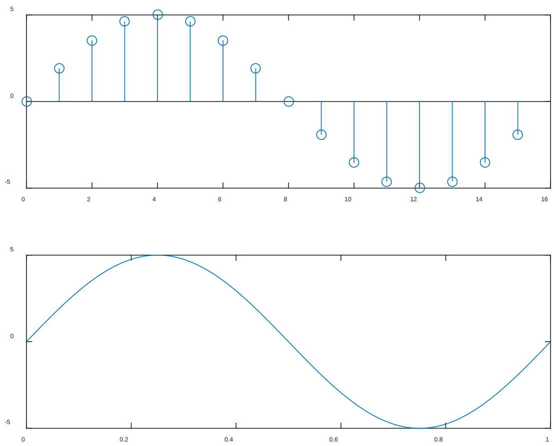
Below is the course syllabus in the undergraduate ECET program. This course may be used as a required core course if it suits a specific program objective.
Credits: class 2, lab 3, total 3 credits, 5 contact hours
Textbook: First Course in Digital Control – Jai P Agrawal, ISBN-13: 978-1533086334
Prerequisite: Electrical circuits, Basic programming skills in C and MATLAB/SIMULINK
Course Objectives: By the end of this course, the student should be able to master the mathematics associated with signals, systems and control. The lab portion of the course utilizes MATLAB/Simulink.
Instruction Outcomes:
1. Learn to use MATLAB and Simulink in analog and digital control signals and systems.
2. Learn to model control systems
3. Understand the stability of digital control systems
4. Design digital controller

Lecture Topics:
1 Intro to Control
2 Discrete and Continuous-time signals
3 Discrete and Continuous Systems- Modeling and Response
4 Digital Convolution
5 Transforms- Z and Laplace
6 System Response and Stability
7 Digital Feedback Control
8 Design Projects

We present samples of the topics and the pedagogy of the topics covered in the proposed course in the following sections.

3.1 DISCRETE-TIME AND CONTINUOUS-TIME SIGNALS AND SYSTEMS

3.1.1 Discrete-Time and Continuous-time signals in Time Domain



The course begins with discrete signal because it is easy to understand and easy to visualize. A discrete signal (also known as the digital signal, although not accurate), $x[nT_S]$ where x is the amplitude of variable, n is an integer and T_S is the finite time interval of sampling. Generally T_S is dropped for the sake of simplicity to x[n]. The continuous-time (analog) signal is presented as the special case of a discrete signal with an infinitesimally small sampling time $T_S \rightarrow 0$ (infinite sampling frequency). This is illustrated by a MATLAB program to display a sine wave signal as a discrete vs. analog signal. It is emphasized to the learners that even a continuous-time signal can be measured and recorded at discrete times. Therefore, the analog signals have essentially theoretical significance. They must be treated as the discrete signals for any useful processing.

3.1.2 Discrete-Time and Continuous-time signals in Frequency Domain

Next topic is the frequency spectrum of the digital signal, with the sampling frequency f_S, which of-repeats every nf_S, n=1, 2, … as shown below. Notice, furthermore, that the frequency spectra is symmetrical about the f=0 point on the frequency axis.

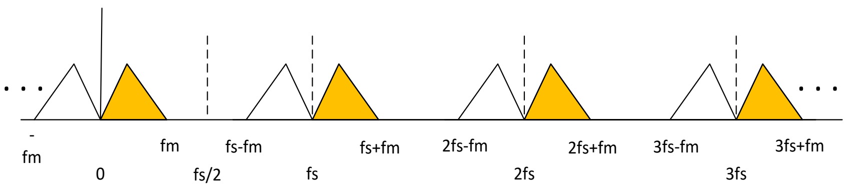


Fig. 2 Frequency spectrum of a sampled signal

Frequency spectrum of continuous-time signals also repeats every nf_S, n=1, 2, …, but the f_S itself is very high, that is far away to the right in frequency spectrum plot.

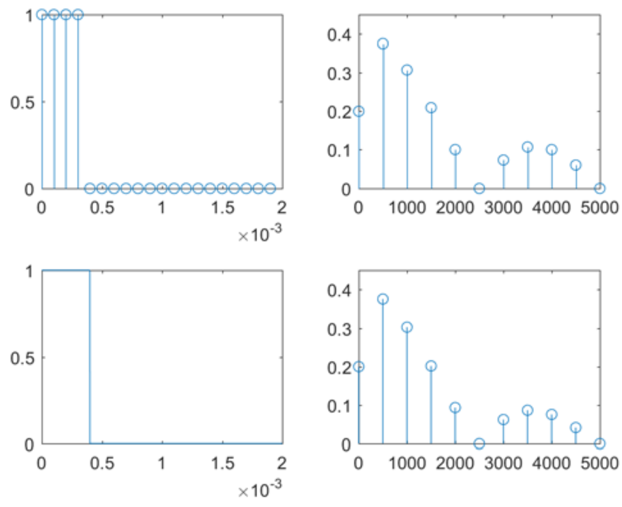
Frequency spectrum of non-periodic digital signal is continuous in frequency, while it is discrete for a periodic signal. The frequency content (or spectrum) of a periodic digital signal x[n] that repeats with of a period of **N** samples at the sampling rate f_S, consists of N lines, each line being a sinusoidal signal:

$$x[n] = \sum_{k=0}^{N-1} X[k]\, e^{-j2\pi \frac{n}{N} k}$$

where the Fourier Coefficients

$$X[k] = \sum_{n=0}^{N-1} x[n]\, e^{j2\pi \frac{k}{N} n}$$

X[k] is the peak amplitude of the k-th harmonic in the frequency spectra. Fundamental frequency of the frequency spectra is $f_0 = 1/NT_S = f_S/N$, which is also called the **line spacing or line frequency**. Each X[k] is represented by a line in the frequency spectra. Frequency spectra is also called **line spectra.** X[k] can also be found using the standard **fft** function in MATLAB or a user defined function *freqspectrum1* is used in both the discrete and continuous-time signals, the T_S in the later being very small. The line frequency in case of the periodic analog signal is $f_0 = 1/NT_S = 1/T$, where T is the period of the periodic analog signal.



In case of non-periodic digital or analog signals, where the number of samples N in a period is infinity, the line spacing is zero (or so small) that the whole frequency spectra appears continuous.

The signal is periodic with a period of 20 samples. We will, therefore, use a sample space of n=0 to 19 for calculating the frequency spectrum. The line frequency is given by $f_O = \frac{f_S}{N} = \frac{10000}{20} = 500\ Hz$.

3.2 MODELING OF DISCRETE AND CONTINUOUS SYSTEMS

The next topic in the course is mathematical modeling of discrete and continuous systems. The discrete systems are modeled using the difference equations whereas the continuous systems use the differential equations.

Modeling of systems is a multi-disciplinary activity for which the learners are not quite ready. Therefore, it is assumed that the learners have the difference and differential equations available before we start using various control tools, such as the transfer function, stability analysis, determining the response to standard input signals and ultimately the feedback control tools to obtain the desired performance. However, the instructors may find it useful to model a few systems in electrical, mechanical, medical, thermal and economic systems to provide a feel. It is not necessary at this point to focus on discrete systems alone. The learner should be aware that most of the practical systems are continuous systems, however, measurement, and processing for analysis and control are discrete in nature.

The difference and differential equations are converted to Z and Laplace transfer functions using MATLAB or table look-up to enable the analysis and control of performance. Teaching Z-transform methods is as easy and as convenient as the Laplace transform using MATLAB. The proposed course emphasizes on converting Transform methods to system block diagrams to further facilitate understanding the signal flow in the system. At this stage, the learners are provide the concepts and tools of interfacing system blocks to digital and continuous signals. A discrete system takes in discrete signal x[n] and produces a discrete signal y[n]. A continuous system takes in continuous signal x(t) and produces a continuous signal y(t). However, the instructors should educate the learners how to connect a discrete signal to a continuous block and how to obtain a discrete signal from a continuous block. On the other hand they should also know how to convert the output from a discrete block to a continuous signal and connecting a continuous signal to the input of a discrete block. Most important interfacing blocks for this objective are DAC, ADC, Sampler and ZOH.

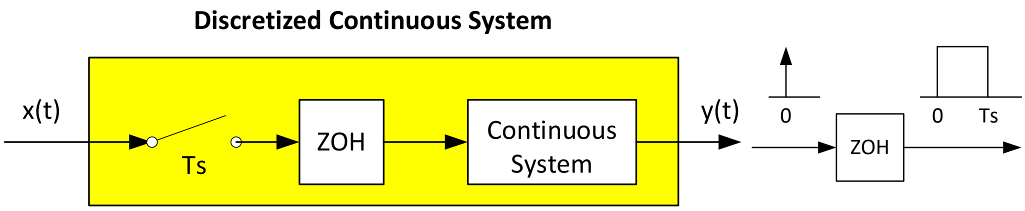


Fig. 3 a) Discretized Continuous system with continuous-time output

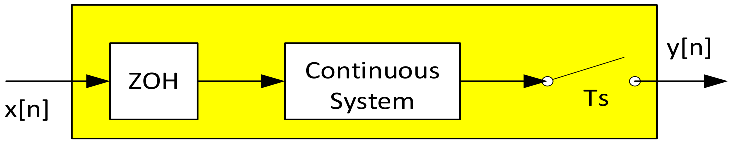


Fig. 3 b) Discretized Continuous system with discrete-time output

3.3 CONVERSION FROM CONTINUOUS SYSTEM TO DISCRETE SYSTEM

Many legacy systems have available the Laplace models of continuous systems/plants. In order to use digital control methods on continuous systems, we need to provide to the learners about the tools to convert them to discrete models, which includes interfacing a) the discrete signals to a digitized model and b) obtaining the discrete signals from the output of a continuous systems.

The Laplace transfer function of a continuous system is converted to discrete transfer function as shown below:

$$H_P(z) = \mathcal{Z}\{h1(t)\} - z^{-1}\mathcal{Z}\{h1(t)\} = (1 - z^{-1})\mathcal{Z}\left\{\frac{H(S)}{S}\right\}$$

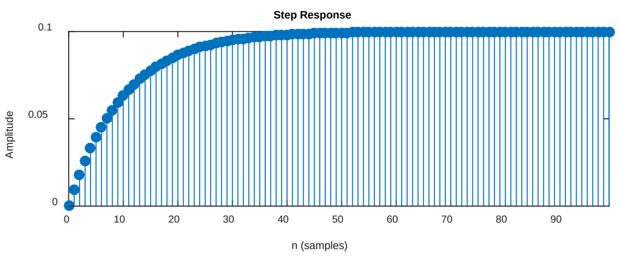
Using the above method, the Laplace transfer function of a first-order continuous-time system is converted to the discrete transfer function as

$$H(s) = \frac{A}{s+a} \qquad \rightarrow \qquad H_P(z) = \frac{B\,z^{-1}}{1-p\,z^{-1}}$$

and the difference equation is

$$y[n] - p\,y[n-1] = B\,x[n-1] \qquad where \quad B = \frac{A}{a}(1 - e^{-aT_S}) \qquad pole \quad p = e^{-aT_S}$$

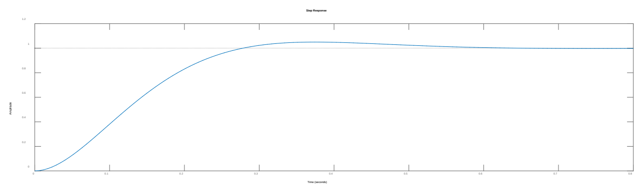
A standard MATLAB function is available to do this conversion c2d(sys,Ts,'zoh'). The following figure example below shows the step response of the converted discrete system is shown below:

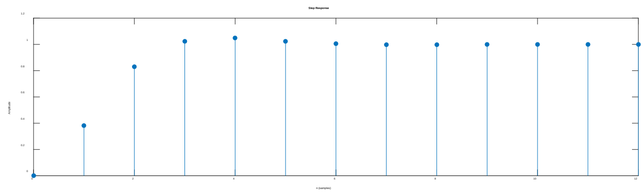


3.4 DETERMINING RESPONSE AND STABILITY OF SYSTEM

The next topic is estimating and determining the response of systems. Use of MATLAB enables easy determining the response of system in time and frequency domain for both the discrete and continuous systems. It is recommended to begin with the discrete systems for standard impulse and step input signals. Stability of systems is taught using the pole-zero analysis of systems and the root-locus methods. At this point, we will like to emphasize that we do not have to teach how to draw the root locus, but how to use MATLAB to obtain, understand, deduce stability issues and then ultimately use that information to devise methods to control and improve the performance. Further, the learners must be given the tools to devise the transfer functions to obtain the desired transient and steady state response systems. In doing so, we can start with the response of discrete systems but simultaneously teach response and stability of simple first and second order continuous systems. Sometimes, due to the availability of a huge literature in continuous system control performance, it is easier to first devise a Laplace transfer function for a desired response and then convert the it to the discrete format for applying the digital control methods of control. Below we show the example of devising the laplace transfer function of a second order continuous system for a desired performance and then converting it to discrete system: with zero steady state error, a 2% settling time of 0.5 seconds and 5% overshoot and then convert to the discrete system.

```
H =       134.4
         ---------------------------
          s^2 + 16 s + 134.4
Continuous-time transfer function.
H_z =     0.381 z + 0.2204
          ---------------------------------
          z^2 - 0.6005 z + 0.2019
Sample time: 0.1 seconds
Dcrete-time transfer function.
```





3.5 FEEDBACK CONTROLLER- DIRECT DESIGN

The last but very important topic in the course is to teach the digital feedback control. Besides the P, PI and PID control in digital domain, it is recommended to teach the direct design for the desired specifications and then reverse engineer to calculate the controller function. The first step in this design is to devise the system transfer function for the desired response, call it $H_D(z)$. The controller transfer function C(z) is then deduced from H_D (z).

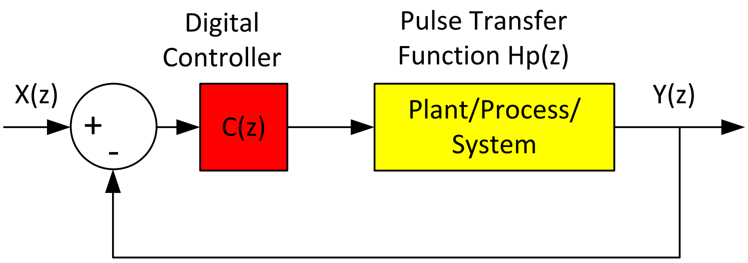


Fig. 4 A discrete feedback control system with C(z) in the forward path

The closed loop transfer function of a digital feedback system, which is $H_D(z)$:

$$H_D(z) = \frac{C(z)H_P(z)}{1 + C(z)H_P(z)}$$

The controller transfer function C(z) is obtained from

$$C(z) = \frac{H_D(z)}{H_P(z)(1 - H_D(z))}$$

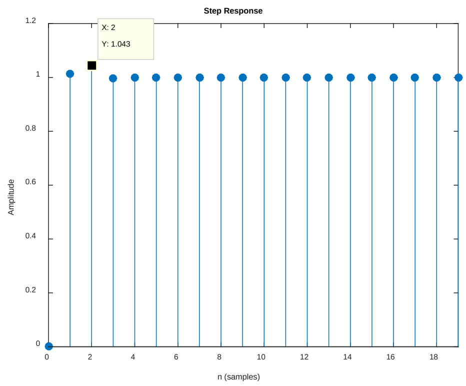
A general digital controller has a transfer function of the type:

$$C(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} \dots + b_M z^{-M}}{a_0 + a_1 z^{-1} + a_2 z^{-2} \dots + a_N z^{-N}}$$

MATLAB EXEPERIENCE[5]: Stabilize an unstable second order system of

$$H(z) = \frac{0.1515\, z^{-1}+0.5915\, z^{-2}}{1-1.697\, z^{-1}+1.44\, z^{-2}}$$

Design the feedback controller for the system to have the following desired response:



2% settling time $N_{02d}\, T_S$:	5 seconds
Sampling frequency T_S :	1 Hz
Peak overshoot PO:	5%

3.6 WHAT IT DOES NOT INCLUDE

Since the course is designed for the undergraduate program, it does not include the following topics:

a) State-space modeling and controller
b) Statistical control
c) Sensitivity issues in digital feedback control

IV. SIMULATION AND LABORATORY EXERCISES

Authors did not find a laboratory book or exercises [4][6][7][8] which could help in our course. We adopted a recent textbook[5] which also contains the laboratory and simulation exercises.

The laboratory exercises in the proposed course include introductory exercises such as the Time domain and frequency domain representation of discrete and continuous signals and systems. After introductory exercises, the course brings up the system response, stability vs. pole-zero diagrams, feedback control methods in digital control. The laboratory class is topped with a couple of design projects. A suggested list is given below:

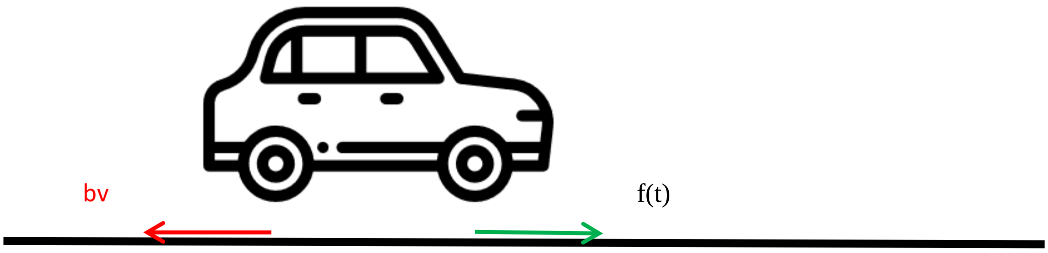
1 MATLAB Tutorial + Complex Math
2 SIMULINK Primer and Arduino Uno Basics
3 Lab 1 – Periodic Discrete Signal in Time and Frequency Domain
4 Lab 2 – Periodic Continuous-Time Signal in Time and Frequency Domain
5 Discrete Systems: Non-Recursive System + Recursive System + Continuous Systems
6 Digital Convolution and Simulation
7 Mechanical system +Electrical system + Simulation
8 Automobile speed + simulation
9 Digital control of automobile speed + Simulink
10 Speed control of DC motor speed
11 Angle Control of DC motor
12 Tank Level Control
13 Dead Beat Control
14 Digital control implementation using DSP

We present a few interesting simulation laboratory exercises to demonstrate the breadth and depth of the laboratory experience.

4.1 LABORATORY- AUTOMOBILE SPEED[5]

A Toyota Camry v6 weighs 1474 Kg. Its power train system generates a net force on the tire-road interface a typical driving force of 1000 Newtons. The automobile has to combat an opposing force due to rolling resistance and wind drag, which varies linearly with the moving velocity.

m: mass of the automobile = 1474 Kg
v(t): velocity of the vehicle in meter/sec
dv/dt: acceleration of the automobile
b: friction coefficient
= 40 Newton second/meter on the dry road condition
F: typical force generated = 1000 Newton



The above figure is repeated for convenience from Chapter 1 Fig. 1-7. This is a first order mass damper system.

a) Find the Laplace transfer function of the car speed to the driving force.
b) Plot the car speed and find the steady state car speed from the graph.
c) Digitize the continuous system to discrete system using a sampling time of 10 seconds.
d) Find the steady state car speed of the vehicle in m/sec and miles/hour (Conversion:1 m/sec = 2.23694 mi/hr).
e) Find the #samples to reach the 70% of the steady state velocity and the 2% settling time in discrete result.
f) Plot the car speed v[n] and verify the results of parts d) and e).

Summing forces in the direction of the motion we arrive at the following differential equation of the system:

$$m\frac{dv}{dt} + bv = f$$

The Laplace transform for this system assuming zero initial conditions is

$$m\, s\, V(s) + b\, V(s) = F(s)$$

The input signal is f(t)=1000 u(t) and $F(s) = \frac{1000}{s}$

and the transfer function is $H(s) = \frac{V(S)}{F(S)} = \frac{1}{ms+b}$

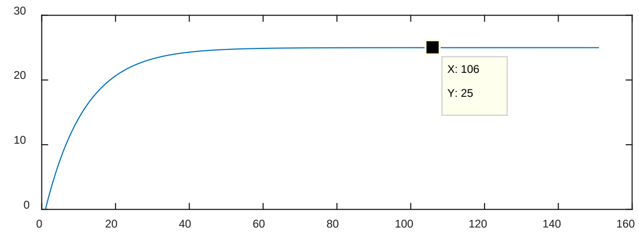
Laplace transform of the output is given by

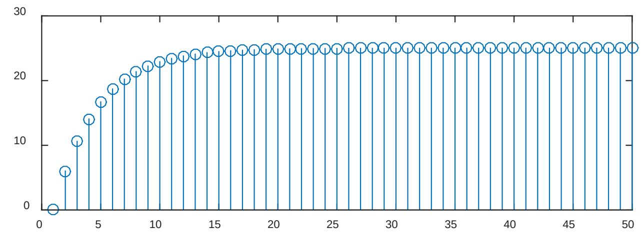
$$V(s) = \frac{1}{ms+b}\, F(s) = \frac{1000}{s\,(ms+b)}$$

The time domain output of car speed is obtained as the impulse response or inverse Laplace or by the impulse response of V(s). Digitize the above continuous system transfer function by using MATLAB function ***c2d().***

Find the numerator and the denominator coefficients **b_0, b_1 and a_1** of the new discrete system. Then find and plot the output (car speed) in the discrete form and determine the steady state car speed, the # samples for the car speed to reach 70% and 98% of the steady state value using following equations:

$$y_{SS}[n \to \infty] = \frac{b_0+b_1}{1+a_1} \qquad N_{02} \geq \frac{\ln(-0.02\,\frac{b_0 a_1 - b_1}{b_0+b_1})}{\ln(-a_1)}$$





4.2 DESIGN EXERCISE: DIGITAL CONTROL OF AUTOMOBILE SPEED[5]

We will design the digital K-controller for the Toyota Camry v6 in the laboratory exercise of Chapter 6 to reach the steady state in 40 seconds.

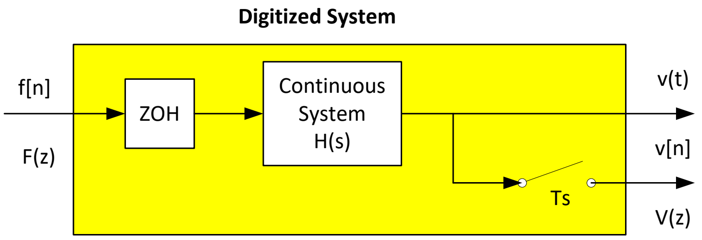
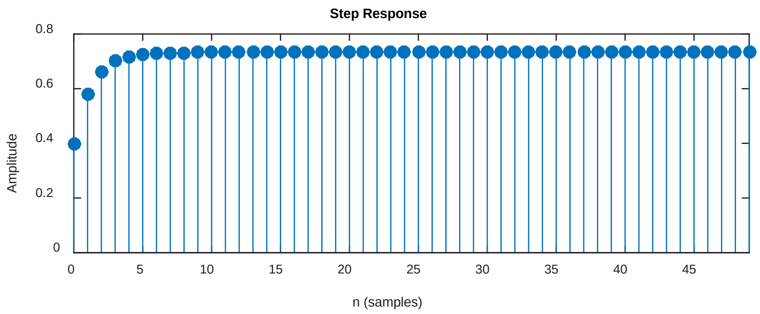
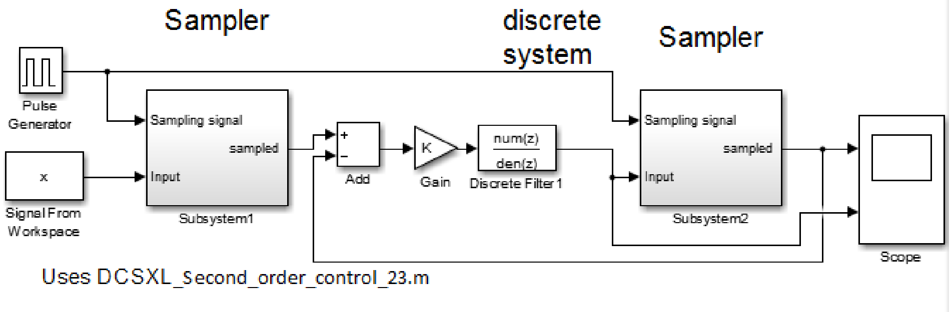


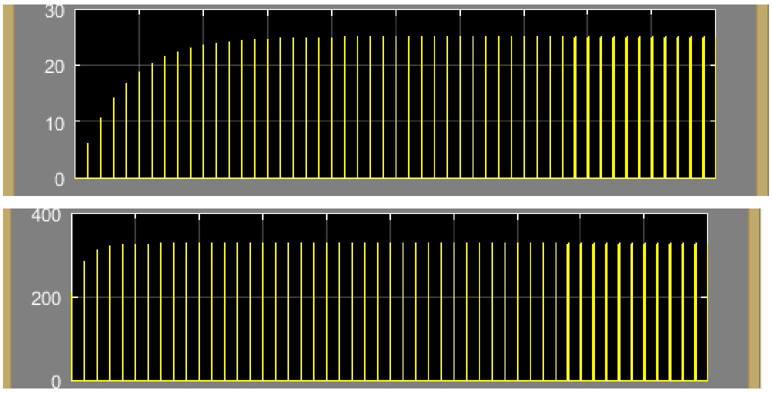
Fig. 5 Discrete input to a continuous-time system



4.3 SIMULINK EXERCISE



Set the controller gain K is set to a value 1 and run the simulation. The scope display should look like the following:



Now add the unity feedback and change the controller gain to K, which we have found from the MATLAB file and Gain Block:
K = 0.6595
Run the simulation. The scope display should look like the bottom figure.

4.4 DIGITAL CONTROLLER IMPLEMENTATION

Digital controller C(z) can be implemented by using a computer or a microcontroller. It is illustrated using Texas Instruments 6713 –DSK development board. This processor has integrated both analog to digital and digital to analog converters.

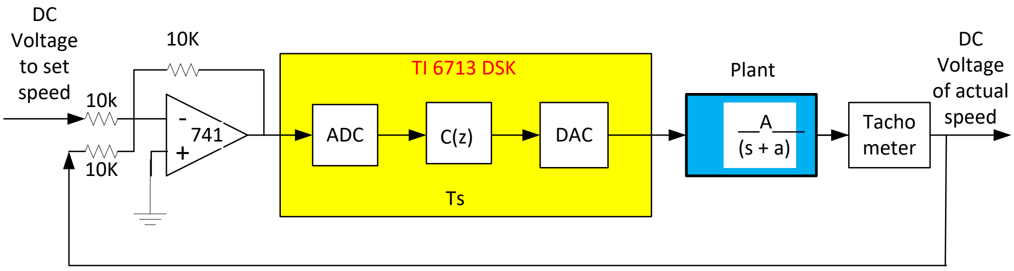


Fig. 6 Implementing digital controller transfer function using TI 320C6713 DSP

The proposed course includes an implementation of a 1st order digital controller transfer function using Texas Instruments DSP 320C6713.

$$C(z) = \frac{F(z)}{E(z)} = \frac{35.62 - 35.44z^{-1}}{1 - z^{-1}}$$

V. STUDENT AND FACULTY FEEDBACK REGARDING DEVELOPED COURSE

The proposed course was offered in the Fall semester of 2016 on the two campuses of Purdue University Northwest to a combined student population of 36. This course is a required course in the undergraduate ECET program. The pre-delivery survey was answered by 30 students. The post-delivery survey was answered by 27 students on the last day of the instruction.

5.1 PRE-DELIVERY SURVEY QUESTIONS, RESULTS AND COMMENTS

	Question	**Affirmative %**	**Negative %**	**No Response**
1	Is this course required in your program of study?	100	0	0
2	Do you have interest in pursuing a career in Electrical and Computer Engineering Technology?	60	0	40
3	Do you think this course will help you in achieving your future objective?	50	20	30

4	Do you feel your background knowledge is sufficient for the course syllabus?	30	0	70
5	Do you find the list of laboratory exercises interesting?	50	0	50
6	Does the course outline appear difficult to follow?	40	10	40
7	Did you find the textbook helpful or meet the need of the course?	50	0	50
8	Which part of the course you are excited about?	0	0	100
9	Why do you think you will benefit more by learning the digital control than the conventional analog control?	75	0	25

Question 4: no response from students of can be understood as due to inability to evaluate the course content as they have seen it only for the first time.
Question 6: the 40% students saying that the course content seems difficult as they have seeing topics about which they do not have prior knowledge.
Question 8: all said no idea of what is going to come.
Question 9: approximately 75% students answered that Digital Control is currently in practice.

5.2 POST-DELIVERY SURVEY QUESTIONS, RESULTS AND COMMENTS

	Question	**Affirmative %**	**Negative %**	**No Response**
1	Do you have interest in pursuing a career in Electrical and Computer Engineering Technology?	65	15	20
2	Do you think this course will help you in achieving your future objective?	65	15	20
3	Do you feel your background knowledge was sufficient for the course?	70	10	20
4	Did you find the laboratory exercises useful?	90	10	0
5	Was the course difficult to follow?	40	50	10
6	Did you find the textbook helpful or meet the need of the course?	70	0	30
7	Which part of the course you like the most?	75	20	5
8	Why do you think you will benefit more by learning the digital control than the conventional Analog Control?	80	0	20
9	Any suggestions making the course more alive and efficient?			

Question 5: in the post-delivery survey negative response of 50% is a significant improvement over the 10% negative opinion in the pre- survey question 6. The affirmative 40% in both the pre and post delivery response can be attributed to those students who are not interested in Controls as a subject and they feel that they are forced to take the as a required course.
Question 7:, approximately 75% students liked the laboratory exercises. But 20% wanted more hardware exercises.
Question 8: approximately 80% students answered that the industry demands Digital Control.
Some of the suggestions are to improve the course are as the following:

1. Have some hardware experiments involving dc and servo motors.
2. Plan a visit to some local communication industry.

The suggestions are all very good and will be kept in mind for future improvements.

VI. CONCLUSION

Authors believe that it is possible to teach digital control theory without having taught the analog control apriori. The proposed course starts with discrete-time concepts but concurrently introduces the continuous-time concepts and methods. The Z-transform and Laplace transforms are both introduced in a single chapter, moving on to discrete systems, responses and control methods, conversion of continuous-time systems to discrete systems for digital control. The later process requires working knowledge of Laplace transform and methods. The course tops off with the feedback control methods and implementation of the digital controller transfer functions using Digital Signal Processor. The proposed course uses MATLAB very extensively to illustrate the control concepts and examples. Each concept is explained with a MATLAB example which the instructor can take up in the classroom or assign for self-study. The course also uses SIMULINK examples to show sample-by-sample progress of control procedure. Lastly the course gives examples of how to implement a digital controller using a Digital Signal Processor such as the Texas Instrument's 320C6713 processor. This course has been tested in the classroom and student have responded with satisfactorily. The paper presents the detailed syllabus comprising of week-wise lecture topics and the laboratory exercises.

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