Issues in Undergraduate Controls Education

Mark L. Nagurka, Thomas R. Kurfess
Carnegie Mellon University

Abstract

A five day NSF-funded workshop, entitled "A Unified Classical/Modern Approach for Undergraduate Control Education," focusing on undergraduate controls education was held at Carnegie Mellon University from June 21-25, 1993. The participants were twenty professors representing different ranks (from assistant to full professors including a department head) from a wide variety of institutions (ranging from large state universities to small undergraduate schools). Different disciplines were represented including aerospace, agricultural, chemical, computer, electrical, industrial, and mechanical engineering.

This paper describes the workshop and reflects upon a few of the lively interchanges of ideas. The discussions were further stimulated by two undergraduate students, supported by the NSF REU program, who attended the workshop. Their input was especially appreciated as they kept the faculty calibrated to undergraduate student concerns. Feedback received from the participants following the workshop has suggested strongly that the material and concepts presented are being integrated into undergraduate curricula.

Introduction

A consequence of replacing laboratory experience with inexpensive computer power has engendered students with limited physical insight and a mentality of jumping to numerical solutions disjointed from physical reality. Faculty attitudes support the contention that students only want "plug and chug" problems that have specific numerical solutions, as opposed to practical, open-ended, design-oriented, real-world problems. Students see course work almost exclusively emphasizing theoretical development (*i.e.*, engineering science vs. engineering) and being "top-heavy" toward mathematical concepts as opposed to real-world applications. Both perspectives are consistent and justifiable. The graduating student entering engineering practice is expected to apply his/her engineering education to real-world problems, yet most students feel ill-prepared to undertake this challenge.

Engineering students are trained to be detailed-oriented mathematicians with sharp computer skills. Students are lost in the "trees" of mathematical details, and often do not see the engineering "forest." The trend of divorcing the physical reality from the mathematics translates into young front-line engineers who are not prepared to tackle the real-world problems of industry. Clearly, with the fierce global competition, we as educators have an obligation to train students as "thinkers" as well as "doers."

Having recognized this challenge, we have tenaciously pursued the approach of emphasizing physical systems at all stages in our courses. Although we have centralized on actual physical systems (as opposed to starting with seemingly random sets of differential equations), we maintain a macro level to gain physical insight yet draw on micro level perspectives to address specific details. For example, in the undergraduate controls curriculum a physical design problem (*e.g.*, the control of a continuous stirred tank reactor) is not tackled using one specific controls method. Rather, it is solved via an integrated combination of available tools.

Classical control theory has been taught in engineering curricula for several decades. Powerful tools such as Bode plots, Nyquist diagrams and the Evans root locus plot have played an integral part in the fundamental understanding of control theory. In our courses we promote a unified treatment of classical and modern control methods, integrated with computational software, that is consistently linked to physical systems.

In a one week workshop faculty members who teach undergraduate controls courses shared their teaching methodologies. The workshop fostered the development and use of physical system models, global perspectives on system dynamics and control theory, computer and manual graphical visualization methods, computer analysis and design techniques, and real-world problem development.

Classical Control Theory

There were many pioneers in the area of control theory, including the important engineers that derived the concepts of what is today considered classical control theory. Classical control theory is derived mainly in the frequency domain, and is based on the Laplace transform of time domain linear differential equations. To most control engineers, four individuals, H. Nyquist, H.S. Black, H.W. Bode and W.R.

Evans, come to mind when discussing frequency domain techniques. These four individuals proposed (in landmark papers) the now famous classical controls "basics" of the Nyquist Diagram (Nyquist, 1932), amplification in feedback control systems (Black, 1934), Bode plots (Bode, 1940), and Evans root locus plot (Evans, 1948 and 1950), respectively. In so doing, they provided engineers with tools that are still employed in control system analysis and design. A development of these tools based on geometric relations is presented to most students in their undergraduate controls course(s) and its history is well covered in the literature (*e.g.*, MacFarlane, 1979). An alternate and novel geometric perspective of fundamental control system tools is presented in (Kurfess and Nagurka, 1994).

The importance of the graphical classical controls tools is the ease with which they may be employed. These tools possess simple sketching rules that permit a control engineer to perform *back–of–the–envelope* analyses to gain significant insight into the performance, stability and robustness of a system. Most control engineers are capable of completing a reasonably complex analysis of a control system in a matter of few minutes by hand–sketching the root locus and Bode plots. Such techniques provide an excellent foundation for engineers designing control systems.

Modern Control Theory

With the advent of computers, modern control theory, based on a time domain analysis of systems, became increasingly popular. The time domain analysis poses the controls question as a set of n first order differential equations that can be solved with ease via computers. Time domain based control theory draws heavily on the use of the computer for control system analysis and design. Classical control theory has, to a certain extent, failed to achieve the same success in computer implementation. Programs for computer generating the root locus and Bode plots are available, but they fail to convey the most appealing aspects of these graphical tools, i.e., the rich intuition and quick sketching rules.

Another major advantage is that time domain techniques are readily extendable to multivariable systems. Current research literature is teeming with articles on frequency domain analysis of multivariable systems and this is an important research area in which significant progress has been made; however, the level of theory involved is far beyond the comprehension and capabilities of most undergraduate students. This is unfortunate since many students do not choose to continue their education at the graduate level, yet they will face multivariable systems in industry. Thus, some modern control theory should be part of an undergraduate student's control education.

Integrating Classical & Modern Control Theory

In most undergraduate textbooks and courses, classical and modern control theories are treated separately. A typical course may develop classical frequency domain techniques first and subsequently introduce time domain concepts. Usually, some linkage is provided between the two domains; however, the relation is generally vague to the undergraduate students. Our method of teaching undergraduate (as well as graduate) students is to teach classical and modern control theory in an integrated fashion that permits comparing and contrasting the two techniques. In this manner, we nurture the students intuitive understanding of control theory through classical analysis and synthesis, as well as develop their skills in modern control theory permitting them to analyze systems with powerful computer tools.

An excellent example of combining classical and modern techniques is the design of a control system yielding specific performance. For example, a typical control problem might be to design a controller, k(s), to stabilize a system with an open–loop plant transfer function

$$g(s) = \frac{1}{(s+3)(s-1)} \tag{1}$$

employed in a unity gain feedback configuration depicted in Figure 1. Clearly, the open–loop system is unstable with a pole (or eigenvalue) at s=+1 in the right–half s–plane. Thus, we must design a controller to *pull* the unstable pole into the left–half plane. Such a controller needs to yield a system with poles possessing negative real components, and thus stable solutions to the differential equations that they represent. We may also have other specifications, such as a 10% maximum over–shoot for a step response and no system time constants less than 0.5 sec.

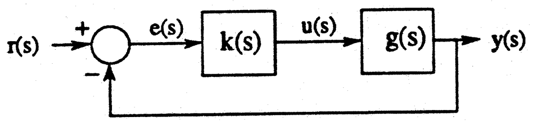

Figure 1. Closed–Loop Negative Feedback.

This problem may be addressed in the frequency domain and/or the time domain. However, it is simplest to employ both domains to generate a quick and intuitive solution. First, classical control tools are useful to determine the form of the controller. Subsequently, modern control techniques are effective to determine the controller parameters precisely. From Bode plots, it can be seen that an appropriately placed lead controller will stabilize the system. For example, a controller of the form

$$k(s) = K\frac{(s+2)}{(s+6)} \tag{2}$$

where K is an adjustable proportional constant is a reasonable choice. The controller places a pole at s=–6 and a zero at s=–2. Figure 2 is a root locus plot of the system when this lead–lag controller is employed and shows the trajectory of the poles as the gain, K, is increased from zero to infinity. Most students in an undergraduate controls course are taught the sketching rules for drawing the root locus.

The remaining step in the design of the controller is to determine the proportional gain, K. Clearly there is a range of K that yields a stable system. Several classical techniques may be employed to show that stable behavior is obtained for K>9. For example, since the closed–loop system is third-order all coefficients of the denominator of the closed–loop transfer function must be of the same sign. Thus, the conditions on K for stability may be determined by inspection from the closed–loop transfer function

$$g_{CL}(s) = \frac{s+2}{s^3 + 8s^2 + (9+K)s - 18 + 2K} \qquad (3)$$

What is not clear by inspection is the value of K that will yield a system with desired characteristics. A simple method of determining a proper value for K may be to numerically solve for the value of K that places the unstable pole in the left–half plane with a real value less than –0.5. This is relatively simple with the third order configuration, since the roots of the characteristic equation may be computed that generate a solution for s=–0.5. However, with more complex systems, a simple iteration may be employed to determine that a value of K≈13.75 results in a pole location of approximately –0.5. Furthermore, the iteration employing time domain tools reveals that the complex conjugate pole pair is at a location of approximately $-3.75 \pm 2.22j$. Thus, the 10% maximum overshoot is achieved based on an analysis of the complex conjugate pole angles.

The entire point of this exercise is to demonstrate that time domain and frequency domain tools may be used in concert to generate a quick and intuitive control design. Each domain has its own set of powerful tools, with advantages and disadvantages. The entire controller design was achieved efficiently using a combination of time and frequency domain approaches. If the analysis had been conducted exclusively in either of the domains, the process would have required more time and may not have produced the same insight into the actual system behavior.

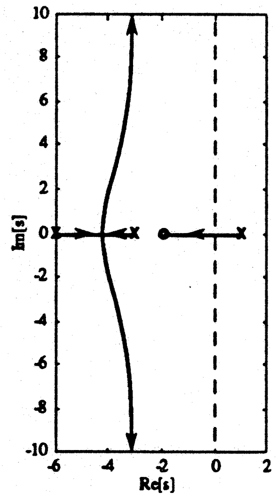

Figure 2. Root Locus for Closed–Loop System.

Using Computers to Enhance Control Education

To permit participants to fully employ the concepts presented in this program we chose to implement our computer laboratory work in MATLAB. MATLAB possesses its own programming language that is simple to employ and offers several significant advantages as an underlying analysis package for this course. First, it is utilized extensively in both academia and industry. Second, it runs on many platforms.

To fully employ MATLAB, computer integrated classrooms or *clusters* were employed. We fully immersed the participants in the computer laboratories/classrooms to maximize their exposure to computer tools and their use in controls education.

Closing

It was a rare and rewarding opportunity to exchange undergraduate controls education approaches with faculty members representing a variety of fields and backgrounds. The interdisciplinary nature of controls was highlighted during the workshop. Fielding different perspectives enriched all participants (faculty as well as students).

Acknowledgments

The authors would like to thank Dr. Norman Fortenberry of the National Science Foundation for enthusiastic support of this work. The authors are also grateful to the participants of the workshop for their valuable input.

This work was funded by the National Science Foundation under the Undergraduate Faculty Enhancement Program with Grant Number DUE-9255567. The government has certain rights in this material. Any opinions, findings and conclusions or recommendations are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Black, H.S., "Stabilized Feedback Amplifiers," *Bell System Technical Journal*, vol. 13, pp. 1–18.

Bode, H.W., 1940, "Relations Between Attenuation and Phase in Feedback Amplifier Design," *Bell System Technical Journal*, vol. 19, pp 421–454.

Evans, W.R., 1948, "Graphical Analysis of Control Systems," *Transactions of the American Institute of Electrical Engineers*, vol. 67, pp 547–551.

Evans, W.R., 1950, "Control System Synthesis by Root Locus Method," *Transactions of the American Institute of Electrical Engineers*, vol. 69, pp 1–4.

Kurfess, T.R. and Nagurka, M.L., 1994, "Geometric Links Among Classical Controls Tools," *IEEE Transactions on Education*, Vol. 37, No. 1, pp. 77-83.

MacFarlane, A.G.J., 1979, "The Development of Frequency–Response Methods in Automatic Control," *IEEE Transactions on Automatic Control*, vol. AC–24, no. 2, pp 250–265.

Nyquist, H., 1932, "Regeneration Theory," *Bell System Technical Journal*, vol. 11, pp 126–147.

MARK L. NAGURKA

Professor Nagurka received his B.S. and M.S. degrees in mechanical engineering and applied mechanics from the University of Pennsylvania in 1978 and 1979, respectively, and his Ph.D. degree in mechanical engineering from M.I.T. in 1983. Following graduation, he joined Carnegie Mellon University. His research work focuses on the development and integration of control methods into practical mechanical systems, and is applied to projects in precision engineering, biomechanics, and vehicle dynamics. Professor Nagurka is a registered Professional Engineer, and is active in several engineering societies, including ASEE, ASME and IEEE. He is currently serving as a Technical Editor of *ASME Applied Mechanics Review* and a Technical Associate Editor of *IEEE Control Systems Magazine.*

THOMAS R. KURFESS

Professor Kurfess received his S.B., S.M. and Ph.D. degrees in mechanical engineering from M.I.T. in 1986, 1987 and 1989, respectively. He also received an S.M. degree from M.I.T. in electrical engineering and computer science in 1988. Following graduation, he joined Carnegie Mellon University. His research work focuses on the design and development of high precision manufacturing and metrology systems. In 1992 he was awarded a National Science Foundation Young Investigator Award, and in 1993 he received the National Science Foundation Presidential Faculty Fellowship Award. He is a registered Professional Engineer, and is active in several engineering societies, including ASEE, ASME, ASPE, IEEE, NSPE and SME. He is currently serving as a Technical Associate Editor of the *SME Journal of Manufacturing Systems.*