special section

Enhancing Undergraduate Control Education

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Education must be both conceptual and experiential. Abstract concepts are elegant and powerful, but learning is always enhanced by direct experience, concrete examples, and real-world relevance.

Control theory and much of control education is highly conceptual. In fact, control engineering tends to be the least tangible of all subjects in the engineering curriculum. In the hope of tipping the balance from the conceptual to the experiential, I offer the following modest suggestions. These suggestions encompass modeling, control, technology, and cultural issues. By discussing these issues in an undergraduate control course, the instructor can emphasize some of the more practical aspects of the subject. My hope is that these suggestions will enhance the teaching and appreciation of a rich and intellectually exciting subject.

Modeling Issues

1. Stress the technological dimensions of control.

Remind students that "control" is a transitive verb, and control is meaningless without something to be controlled. Control engineering depends on technology, and this technology is highly interdisciplinary.

2. Use dynamic analogies.

Since control engineering is highly interdisciplinary, students of mechanical and aerospace engineering need to understand power requirements, circuits, and computers, whereas students of electrical engineering and computer science need to understand mechanical design and the dynamics of the systems being controlled. One way to bridge this gap is by means of dynamic analogies. Students can benefit by learning to represent circuits by mechanical systems and vice versa. However, these analogies are incomplete, since nonlinear mechanical concepts such as friction and three-dimensional rotational motion don't have electrical analogs.

3. Employ dimensions and units.

Dimensions and units are almost universally ignored in control theory. Even transfer functions have dimensions. On the other hand, dimensionless quantities are helpful in certain fields of engineering, but how useful are they in control? While little has been written about this question, two points can be made. First, to resolve questions of controller architecture and achievable performance, dimensionless quantities can clarify issues in a scale-independent way. However, for controller tuning, which often depends critically on the knowledge of certain parameters, the use of dimensionless variables can obscure the role of modeling information and physical constraints such as actuator saturation levels.

4. Emphasize identification.

No matter how well analytical modeling is performed, some identification is always needed. Real hardware abounds with unmodelable effects and sensitivities. Modeling the effects of a mundane task such as torquing a bolt can be daunting. In addition, modeling a system in a piecemeal fashion is rarely useful for controller tuning because components can interact dynamically in complicated ways due to spurious feedback paths and unexpected couplings. The need for identification is crucial, and end-to-end identification is desirable whenever possible. In addition, it is important to clarify the environment in which the identification is performed, for example, whether ambient disturbances can be turned off during identification. (Engines can be turned off; turbulent wind noise around a moving vehicle cannot.) Also, identification is only practical for stable plants, whereas unstable plants require either extensive modeling or

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adaptive stabilization methods. Adaptive stabilization in the presence of exogenous disturbances presents a severe challenge to control engineering.

5. Expect unexpected plant changes.

It is important to realize that any given plant can change in an unexpected manner during operation. Identification can be useful for empirical modeling and controller tuning, but what happens if the plant changes between the time that modeling was performed and the controller is implemented? Furthermore, tiny physical changes in a plant can have a great effect on its dynamics. For example, as lubrication dissipates, time constants can change and friction can increase in an unpredictable way. More generally, while plant phase at crossover is crucial knowledge for control engineers, it is a hidden detail to other disciplines. The problem of unexpected plant changes lies at the heart of control engineering, since one of the main reasons for implementing a feedback control system is to achieve performance in the presence of uncertainty. Determining what modeling information is needed is essential for obtaining satisfactory performance. In any event, the need for some form of on-line identification and adaptive control is unavoidable.

6. Distinguish plant and control architecture design from controller tuning.

Control architecture design and controller tuning are strongly interrelated but nevertheless distinct tasks in control engineering. Control architecture design refers to the selection of sensors and actuators that need to be specified and designed to achieve a control task. The design of the control architecture and associated hardware usually depends on a solid understanding of the basic physics along with detailed physical modeling. In addition, the control engineer must determine what variables to measure. For example, position, velocity, and acceleration differ by "only" an "s" but may require vastly different technology to measure. In practice, this distinction is significant, since integrators are affected by bias, whereas differentiators suffer from noise. However, control architecture design is often only loosely coupled with the choice of the control algorithm and its tuning. In fact, the modeling information used for control architecture design is usually inadequate for controller tuning.

7. Reveal the joys of controller tuning.

Controller tuning includes the choice of a control algorithm along with the choice of parameters required by the algorithm or design procedure. Controller tuning is where the real fun of control engineering lies. Unfortunately, control engineers spend most of their effort on the control architecture phase (and later, the failure prevention phase). Controller tuning methods range from classical techniques, which require little plant modeling, to robust control methods, which require nominal plant and uncertainty modeling, to adaptive control methods, which involve automatic gain adjustment. In all cases, controller tuning must account for all available modeling information, and it must be forgiving to unexpected plant changes. Controller tuning often invokes mathematically sophisticated techniques. Yet no controller synthesis technique can account for all real-world effects. Consequently, controller tuning is an art to be practiced and mastered.

8. Expose the myth of the linear unstable plant.

Although unstable plants are invariably nonlinear, they are often introduced as linear plants with one or more open right-half-plane poles. (A plant with a chain of integrators is also unstable, but less seriously.) In my opinion, the distinction between stable and unstable plants is vastly underemphasized. An unstable plant provides almost no opportunity for identification and therefore must rely heavily on analytical modeling and extrapolation from stable regimes. Unstable plants are unforgiving in the sense that once large deviations occur, saturation limits may prevent recovery. Furthermore, linearizing a nonlinear unstable plant may obscure the actual saturation recovery limits, which are invariably smaller than those of the linearized model. In contrast, stable plants are much more forgiving, since the zero controller is always stabilizing and identification (at least in the absence of ambient disturbances) is feasible. Finally, controller start-up is a serious problem for unstable plants that sometimes require unstable controllers.

Control Issues

9. Emphasize measurement and actuation technologies.

Every working control system requires real sensors and real actuators. Sensors are needed for measurement, which is a challenging and important aspect of technology. The control systems engineer may need to measure a diverse collection of physical quantities. In addition, actuation is equally if not more challenging (due to power and weight limitations) and requires skills in electromechanical technologies. Measurement and actuation technologies are essential for control systems engineering and must never be taken for granted.

10. Clarify control objectives.

There are numerous objectives in control, including stabilization, disturbance rejection, modification of dynamics, and command following. Although these objectives are interrelated to some extent, it is helpful to clarify and distinguish them. For example, stabilization is an equilibrium-focused requirement that can be expanded to include disturbance rejection. On the other hand, stabilization and disturbance rejection may be transformable into certain command-following problems and vice versa. However, these problems are not equivalent, since disturbances are rarely known, whereas commands are usually known, sometimes in advance. In addition, command following in general may or may not be related to the notion of equilibrium. For example, an aggressive aircraft maneuver is not an equilibrium-dependent control objective.

11. Explain the physics behind the control law.

When a feedback controller is applied to a physical system, it has a physical (not magical) effect on that system. It is important to understand how the control system modifies and exploits the physics of the uncontrolled system. Energy balance analysis is often useful here. Unfortunately, the relevant effects are often obscured by the mathematics used to express feedback control laws. For example, if a control law "adds damping," it is important to understand the physical mechanism for the increased energy dissipation.

12. Don't slight passive control.

We tend to think of control in terms of active electrically driven devices. However, feedback algorithms are often implemented by nonelectrical means (for example, using pneumatic actuators) as well as through passive devices. The escapement mechanism in a clock, the speed governor, and the vibration absorber are passive control devices with "hard-wired" control algorithms.

Technology Issues

13. Analyze everyday control systems.

Have students analyze control systems that can be found in everyday life. Examples include toilets, thermostats (in the house, refrigerator, and oven), garage door openers, cruise control, engine (automatic choke), etc. It is interesting to examine the performance and reliability of these control systems.

14. Analyze control systems in technology.

Control systems abound in technological applications, and students from various disciplines can analyze control systems that are most familiar to them. Students of electrical engineering can analyze circuits in radios and televisions that use feedback, mechanical engineering students can analyze motion control systems, and aerospace engineering students can analyze autopilots. Low-cost, accessible control systems can be identified and reverse-engineered.

15. Observe person-in-the-loop control systems.

People are ready-made control systems in one convenient package that is fully equipped with multiple sensors, processors, and actuators. This allows humans to perform feats that require feedback, such as standing, walking, running, catching, hopping, swinging, juggling, biking, unicycling, yo-yoing, skating, skate-boarding, skiing, surfing, driving, parking, and flying. It can be extremely informative, interesting, and challenging to observe and analyze control systems with human controllers. I believe that control systems engineering can benefit from an understanding of the control strategies that humans use, whether consciously or unconsciously. Building machines to perform these tasks is an engineering challenge and a lesson in humility.

16. Use ready-made demos for illustration.

Ready-made control demos deprive students of control architecture design. However, these devices give students the chance to gain experience in controller tuning. Feeling the increasing tug of a motor under integral control is a graphic reminder of how this control law works.

17. Build working control systems, no matter how rudimentary.

Nothing can be more educational than building and tinkering with a working control system. Simple control systems can be built from inexpensive components and lots of ingenuity. Some great sources of components are auto parts stores and high-tech surplus vendors.

18. Stress safety and reliability.

Any real system that depends on a control system involves issues of safety and reliability. Even normally benign feedback loops can wreak havoc on a system in the event of unexpected changes arising from failures of almost any kind. Dealing with such failures is the job of the control systems engineer and is of extreme importance if human lives can be threatened by unreliable operation.

Cultural Issues

19. Discuss the implications of feedback in other disciplines.

Feedback has significant implications in other fields. For example, consider economic and biological systems, which have deep similarities. Both applications involve numerous interacting components that either compete or cooperate to achieve their goals. These interactions are bidirectional and are thus governed by feedback. (Game-theoretic control is relevant here.) In economic systems, some of the most basic issues, which also have political ramifications, concern self-regulation versus centralized control. Physiological and ecological systems contain numerous examples of feedback control. Regulation is essential for life.

20. Tell the history of control.

Talk about the clock escapement and how it made accurate timekeeping practical, thereby ushering in the scientific revolution. Talk about the governor and how it made the steam engine practical and thereby ushered in the industrial revolution. In those days, power generation was not centralized and thousands of steam engines needed thousands of governors. Hundreds of old patents show the incredible ingenuity of early control engineers and the importance of control engineering in the development of technology.

Conclusion

21. Balance the abstract and the concrete.

Control engineering is highly multidisciplinary, with issues and features that are distinct from those of other branches of engineering. These issues are numerous and subtle, and often the most important aspects depend on the seemingly most insignificant details. Historically, the subject has advanced by employing abstraction to extract principles that are potentially applicable to a broad range of applications. Unfortunately, this abstraction often obscures the practical ramifications of important ideas. A more concrete approach to the subject can rejuvenate and reinvigorate education in this exciting and important area of technology.

Bibliography

The subject of measurement engineering, which is essential to control engineering, is the topic of

C.P. Wright, *Applied Measurement Engineering,* Prentice Hall, 1995.

An excellent overview of different types of sensors is given in

P. Elgar, *Sensors for Measurement and Control*, Longman, Essex, 1998.

Actuators are discussed in

T. Kenjo, *Electric Motors and Their Control*, Oxford University Press, 1991.

D.K. Miu, *Mechatronics: Electromechanics and Contromechanics*, Springer-Verlag, New York, 1993.

W. Stadler, *Analytical Robotics and Mechatronics*, McGraw-Hill, New York, 1995.

I. Boldea and S.A. Nasar, *Linear Electric Actuators and Generators*, Cambridge University Press, 1997.

I. Busch-Vishniac, *Electromechanical Sensors and Actuators*, Springer-Verlag, New York, 1999.

Dynamic analogies are discussed in most control texts. A detailed treatment of the subject is given in

H.F. Olson, *Dynamical Analogies,* Van Nostrand, New York, 1943.

A modern treatment of this interdisciplinary subject would be welcome. The history of control engineering is told in

O. Mayr, *The Origins of Feedback Control,* MIT Press, Cambridge, 1970.

S. Bennett, *A History of Control Engineering 1800-1930*, Peter Peregrinus Ltd., London, 1979.

S. Bennett, *A History of Control Engineering 1930-1955*, Peter Peregrinus Ltd., London, 1993.

Some nice illustrations of mechanical control systems appear in

L. Maunder, *Machines in Motion*, Cambridge University Press, Cambridge, 1986.

A popular account of some control concepts and their sweeping implications in evolution and self-organizing systems is given in

K. Kelly, *Out of Control*, Addison-Wesley, Reading, 1994.

A brief synopsis of control concepts is given in

D.S. Bernstein, "A Student's Guide to Classical Control," *IEEE Control Systems Magazine*, vol. 17, no. 4, 1997.

The role of experiments in control research is discussed in

D.S. Bernstein, "Control Experiments and What I Learned From Them: A Personal Journey," *IEEE Control Systems Magazine*, vol. 18, no. 2, pp. 81-88, 1998.

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