Control Education

As preparations start in August for a new academic year, this is a good time to reflect on educational best practices and the extent to which they can be embedded into the courses that you are teaching. This is especially true when (as I will be this year) you are teaching a new course at a level (sophomore) that is one year younger than you have ever taught before. As such, the report from the IEEE Control Systems Society Technical Committee on Control Education (TC-CE) (see page 20) is particularly timely, and it includes references to two very interesting papers [1], [2].

Reference [1] reminds teachers to reflect on 1) the teaching outcomes of a course (what you want the students to be able to do and why), 2) how you can, as the teacher, best help them achieve that, and 3) what effective good practice there is. The types of best practices examined include a discussion of teaching style, the use of software for assessment, utilizing online and shared teaching resources, and embedding either local or remote laboratories into the systems and control course materials.

The discussion on teaching also includes the reminder of the common knowledge that student engagement drops off after more than 15 min of didactic presentation and, thus, encourages that more active learning scenarios be utilized for the lectures (see [3] for examples). Note that while sources, such as [4], support this 15-min claim, there are some opposing views in the literature [5], [6].

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The teaching process as a feedback control system is discussed in [1], with the lecturer providing the information/measurement and the students acting as the control law [7]. In [7, Ch. 8], this point is expanded further with the idea that

> the closed-loop lecturing mode implies taking and providing frequent formative assessments alongside the course progress and continuously facilitating students' feedback and reflection. In the closed-loop lecturing mode, it is made clear to students that they have to practice [sic] and that they are knowledge constructers [sic], while the teacher's role is to coordinate their learning process.

Control systems courses often have many details to cover, so lectures of some sort will typically be required. Thus, [1] provides some key insights on presenting good lectures:

- Carefully walk through solutions on the blackboard using the correct language to explain it to help the students connect the two concepts.
- Avoid screen dumps: present the material at about the pace that a student can write it and process it (this helps students become active and not passive).
- Talk to the students, not the blackboard!

I agree with these ideas and have certainly found that the pace of my teaching has intentionally slowed quite dramatically throughout the years.

Other best practices that are popular and effective [1] include *lecture flipping* (that is, utilizing online video recordings and other materials as preclass preparation and then using the in-class time to focus on problem solving or reinforcement of the material). This contrasts with the standard technique of just covering the material in lectures and having the students work with it while doing their homework. I have colleagues that have adopted this approach for their course, but I have not yet taken the full leap.

I did arrange to convert one of three lectures in a junior-level course into a recitation/experiment period. As such, there were often two lectures and two recitations per week, which provided plenty of opportunities to work with the students on problems directly related to the material covered in class the day before. These sessions would help me identify misconceptions that could then be cleared up in real time or revisited in the next lecture. The tradeoff is that I had to rescope to approximately three-quarters of the amount of material to fit in the fewer

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lectures. The trade here is between less material covered and (hopefully) more of it better learned. Similar to the prior discussion on teaching pace, I have found that, typically, less is more when it comes to teaching and learning.

The switch to a fully flipped class would place a lot of burden on the out-of-class preparation, and past experience has shown that there are a lot of factors (such as homework deadlines for other classes) competing for the students' time. For similar reasons, I have stopped having required reading in textbooks (which are very expensive) and have just provided course handouts as reference guides. I would be interested in how others have motivated the students to increase the relative importance of this before-class preparation (or after-class reading) time to enable a fully flipped set of lectures on control systems.

Allowing the use of software in exams would dramatically open up the space of interesting problems that can be considered.

EXPERIMENTS

Also discussed in [1] is the key role of experiments in student learning for control systems courses. The section on experiments (both real and virtual/remote [2]) is very helpful, as I was not aware of the online repository of interactive laboratories [8]. I agree with the importance of the reduced cost of parts, enabling students in the class to buy their own laboratory testbed. However, I was intrigued by the statement in [1] about the take-home helicopter experiment:

> The system is dynamically rich, containing a mixture of continuous and discrete-time dynamics. It is nonlinear and displays significant dynamic coupling between the inputs to each fan and each of the measured linkage angles. The system provides students with a challenging control problem, requiring mastery of techniques such as modeling, state-estimation, and multivariable control.

The text suggests that the testbed is very useful for advanced courses, but it might present many challenges to students just starting to learn about control. Specifically, it might provide lessons on what makes control synthesis difficult for real systems before they really have the tools available to address them.

To address this, I tried to develop a similar platform (see Figure 1), which is essentially a quadrotor folded in half and, thus, dynamically interesting for students in an aerospace program. The arm pivot is on bearings and adds only a small amount of damping (mostly from the centrally mounted wires). Obviously, the pendulum can be oriented vertically (leading to both stable and unstable dynamics), which enables challenging control problems to be addressed later in the semester.

For design simplicity, we use only the inertial measurement unit that was already integrated with the onboard processor to obtain an estimate of the pendulum angle. The students must design the proportional-integral-derivative (PID) gains (which can be changed in real time on the desktop computer linked to the arm) of the attitude control loop that sends commands to the two opposing propellers. This onboard computer system was custom-made for research reasons. However, several similar hardware configurations are now available with much better interfaces, such as Matlab.

The design has its limitations (the system dynamics are third order, not second, and the attitude estimate tends to drift with time). Overall, the system is easy to use and very inexpensive to build. It is not, however, robust enough for the students to carry it around in a backpack, which was our original objective.

An important consideration is that cheap testbeds can be helpful due to the increased access that they provide. However, it is also possible that they increase the students' frustration due to all of the complicating factors. As a

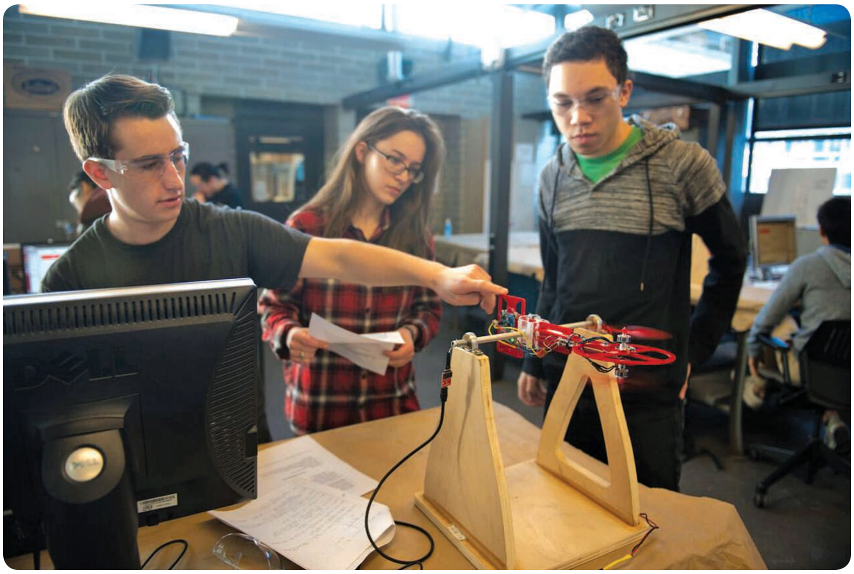

FIGURE 1 As part of course 16.06 at the Massachusetts Institute of Technology, students implement a proportional-integral-derivative controller on a pendulum that is stabilized using hardware similar to that found onboard a quadrotor (autopilot with tunable gains and propellers). (Photo courtesy of Bill Litant.)

Jonathan How with Gokhan Inalhan during Inalhan's recent visit to the Massachusetts Institute of Technology, Cambridge.

result, the students might ultimately end up learning the wrong lessons about control—that it is just about twiddling PID knobs in the lab until something works, for example.

COURSE MATERIAL

Another challenge I find in teaching control systems courses at the undergraduate level is deciding what material to cover. My department offers three courses in the area, the first two of which are required for most students. The sophomore-level course focuses on the standard signals/systems material with an emphasis on transforms, increasing mathematical maturity in control-relevant topics (such as algebra and differential equations), and introducing feedback control.

The second (junior-level) course is the last control system subject that most of the students will ever take. Thus, when I teach that course, I try to focus on the concept of using feedback to modify the system dynamics to achieve some specified performance goals. I mostly cover classical control (PID) rather than rush through that material to include state-space techniques. This is, in part, because we have a third course that covers the state-space material for the students interested in control systems but also because the state-space material has much algebra background that must be covered to obtain a useful result [such as the dynamic output feedback controller (DOFB)].

I agree that full-state feedback can be presented relatively easily. However, I am unsure that that material alone adds much to the students' understanding of how a control system works. This belief builds from my undergraduate experience, which included a first control course that covered state-space techniques (including full-state feedback and some optimal control) rather than classical control. As a result, I felt that I was at a distinct disadvantage in graduate school when we studied the DOFB algorithms in detail: I lacked the background to understand and interpret what those DOFB controllers were trying to accomplish and whether it made sense.

With the increased performance of computational and plotting tools, such as Matlab, there are also questions about what aspects of classical control must be taught now. For example, how much time/effort should be invested to learn the sketching rules for Bode or root-locus plots? Arguments are often made for retaining sketching skills. However, given that few designs are ever done that way, are those the right skills to be learning? I am much less convinced of their importance than I was before. The report from TC-CE indicates that there will soon be a survey to establish which topics should be prioritized in these control courses, and I look forward to seeing the results.

The role of using software to assess control skills is also discussed in [1]. Anyone creating many exam questions quickly realizes the limitations of working with only the first- or second-order systems that students can handle by hand. Allowing the use of software in exams would dramatically open up the space of interesting problems that can be considered, and both the knowledge and desired coding skills would actually be tested. There are many factors to be considered in choices such as this. However, as indicated earlier, I think it is important to keep abreast of the best practices in the educational field and try new components in the curriculum.

Good luck with the new teaching year, and, as always, I look forward to your feedback and insights on best practices.

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