Improved Learning Through Collaborative, Scenario-based Quizzes in an Undergraduate Control Theory Course

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Abstract

A significant challenge for many students in introductory control theory courses is the abstract mathematical concepts, as well as application of those concepts to engineering problems. When students are overwhelmed with the material, they often aim for rote application of mathematical formulas, without attempting higher-level critical thinking (e.g., evaluation, comparison, design). We constructed a series of five in-class scenario-based quizzes, implemented in lieu of standard lectures, to facilitate higher levels of understanding. Students worked in teams of three to solve multiple-choice and short-answer problems designed around a specific scenario. For example, one scenario involved analysis of transient properties (e.g., settling time, percent overshoot) of a teleoperation system for robotic surgery, and prompted students to weigh trade-offs between responsiveness and excessive motion. In order to assess the value of collaboration in these quizzes, we contrast student gains on one scenario-based quiz completed individually to those completed collaboratively. We evaluated pre-test performance and conceptual growth using a validated concept inventory [1]. Students also completed a pre/post measure of their abilities to co-regulate their work as members of a group. We found that students showed improved co-regulation abilities, performed lowest on the individually completed quiz, and that the students who began with the lowest scores on the concept inventory had comparable outcomes to their higher-scoring peers. Collaborative quizzes are well aligned to active learning approaches to teaching and have potential to improve understanding of math-intensive engineering concepts, as well as further develop students' ability to apply these concepts to actual engineering analysis and design problems.

Introduction and research purpose

Students in introductory control theory courses tend to struggle with the abstract mathematical concepts as well as application of those concepts to engineering problems. When students are overwhelmed with the material, they often aim for rote application of mathematical formulas, without attempting higher-level critical thinking (e.g., evaluation, comparison, design).

As in other STEM domains, efforts to improve student learning outcomes have turned toward a range of learner-centered pedagogical approaches. As engineering professors seek to improve teaching practices and student learning outcomes, they have focused on more student-centered and context-rich learning experiences, and using assessment to better understand both what their students know and how their instructional innovations impact student learning. One of the major on-going shifts in engineering education is the incorporation of more research-based strategies, including inquiry-based and student-centered approaches, providing more real-world context in problems, and providing increased opportunities for collaborative learning and teamwork [2].

A major component to understanding what students know and whether an instructional innovation was successful is assessment [3], and a common approach to this is designing concept inventories that are intended to assess students' conceptual understandings and misunderstandings [4, 5].

Our purpose in this paper is to investigate an instructional innovation—collaborative quizzes—and understand its role in supporting student development and learning. We detail our reason for designing a collaborative assessment—as a means to align assessment to other socio-constructivist learning approaches already adopted. Although others have previously studied forms of collaborative assessment, we contribute research on a less studied form, and additionally provide a stronger theoretical backing for the approach: co-regulation.

Learning is a fundamentally social process

Research on how people learn has made clear that learning is a fundamentally social, interactional process [6-9]. As such, many engineering educators have sought to incorporate social, collaborative, and team-based strategies into their teaching.

Recommendations for supporting collaborative and team-based learning have long been available, and include providing an adequately complex task that actually requires multiple people to solve it, mutual accountability and interdependence, opportunities to work and discuss ideas together, and deploying team skills [10]. A common failing in collaborative and team-based learning is providing a task that is too simple to warrant collaborative effort.

As a result, many of the exemplars of collaborative and team-based engineering learning come from extended design projects. For instance, incorporating teamwork into early engineering coursework has been cited as a means to enhance retention [11]. Research on team-based learning has focused on a range of topics, from developing project management skills, to supporting interdisciplinary collaboration, to developing shared understanding of problems [12].

For our focus, research on collaborative learning is more relevant, as we sought to understand short-duration collaborative work in an assessment context. Across contexts, collaborative learning has generally been shown to better support learning, compared to individual approaches [13-15]. In engineering specifically, collaborative learning has been shown to be accepted and viewed as effective by learners [16, 17], to support a sense of belonging or connectedness [18], to support conceptual change [19] and to be superior to individual approaches [20]. In collaborative engineering learning, some have focused on how and when collaboration might contribute to learning [21]. For instance, students resist collaboration in competitive environments in which a single correct answer exists [22].

Student learning in introductory control theory courses

Much of the work on student learning in undergraduate control theory courses has sought to improve student outcomes through development of software or hardware tools and platforms. A variety of graphical user interfaces and other interactive simulation and analysis tools have been developed [23-30]. Researchers have long called for standardization and shared resources [31]. For control system courses that include a laboratory component, several laboratory exercises [32, 33] and laboratory kits [34-36] have been developed to facilitate learning through a mix of hands-on and theoretical approaches [37, 38]. Some experimental platforms have even been employed in distance learning [39, 40]. Many of these tools are driven not only by the desire to improve student learning, but also by the need for reusability and customization without complete redesign.

Researchers have explored blended learning [41] and flipped classrooms [42] in control theory courses. For example, researchers used an adaptive online system to tailor workload in response to student participation—assessed through time spent on online modules, and student performance—assessed through scores on online quizzes or exercises, then explored system identification methods [43] to help predict student performance and improve performance of the adaptive system. Mason and colleagues [42] conducted a rigorous two-year study to evaluate the effectiveness of a flipped classroom. They implemented a variety of assessments, including student surveys, student discussions, as well as standard graded work. They showed improvement in student understanding of open-loop systems, root locus design, Bode design, and design problems in general, but not on other topics. More material was covered in the interactive version of the course as compared to the traditional lecture version, and interestingly, students believed that they spent less time studying in the interactive course as compared to the traditional lecture version.

Assessing student understanding

One of the challenges of understanding the impact of a curricular innovation is identifying the right measures to detect changes, assuming they are present. Common approaches include surveying students about their perceptions of their learning and their acceptance of the innovation and using concept inventories. While understanding student acceptance is relevant and useful, research suggests that students may not be able to judge accurately when something supports their learning [44].

Concept inventories are multiple choice tests used to identify the concepts students hold at a given time, and are commonly used as a pre-course assessment to plan instruction, and as a pre/post measure to assess the effectiveness of instruction [45-48].

Traditionally, concept inventories are guided by the notion of the *assessment triangle*, a conceptual framework that includes cognition—what students know; observation—what evidence we seek about their knowledge; and interpretation—how we interpret the evidence about their knowledge. Others expanded this notion into an *assessment square* focused on clearly defining the construct of interest, the means to assess the construct, the observation or evidence collected through that means, and the interpretation of the evidence collected [49, 50]. The *assessment square* therefore expands the construct of interest beyond the cognitive domain and more clearly differentiates between the means to measure and the evidence accrued via a measurement.

Developing concept inventory assessments is a labor intensive process of first understanding students' alternative conceptions through interviews with students and constructed responses to open ended items, then turning those into incorrect answers in multiple choice questions [4, 5, 45].

Compared to the sciences, there are fewer concept inventories available in engineering [51], though many have been developed in the past few years. For instance, concept inventories now exist for statics [52], thermodynamics [53], thermal and transport science [5], circuits and systems [54], and other areas [55].

A control systems concept inventory was proposed for students in mechanical engineering and in mechatronics [1], and has been validated [1, 56, 57]. The authors of the inventory evaluated data from 135 students who completed the inventory as both a pre-test and post-test, along with data from students' course scores. They assessed the efficacy of individual questions on the inventory, as well as the inventory as a whole, through a variety of metrics, including ability to discriminate between high-scoring and low-scoring students, internal consistency (through Crohn's alpha coefficient), and statistical correlations with exam and course scores. The concept inventory was used to evaluate the effectiveness of a newly developed active-learning centered classroom setup [56]; the "normalized gain," the percentage of questions answered correctly in the post-test but not in the pre-test, from 22 mechanical engineering students was comparable to that reported for mechanical engineering students in another study [1]. The inventory was used to assess the effect of inexpensive laboratory kits on student learning in a course that focused on both mechanical and electrical systems, finding that students using the inexpensive version performed comparably to those who used traditional equipment; however, the authors cautioned that there sample size was too small to draw strong conclusions about their ongoing work [57].

Collaborative quizzes to support learning

Past research has shown that testing can enhance learning and retention [58-60], though this phenomenon has largely been studied in laboratory settings and with rote memorization. Despite this, researchers have made recommendations about using quizzes and cumulative exams to better support retention [61], and also to consider multiple forms of assessment [62].

One approach to assessments that support learning that has been well-studied in classrooms is the two-stage collaborative model. Researchers have extensively studied this two-stage collaborative model in medical education, engineering, computer science and the natural sciences. In this model, students complete a quiz individually, then complete the same quiz as a team. In this approach, students discuss their ideas and learn from their peers [63], scoring significantly higher on collaborative quizzes than on individually-completed quizzes [64-67], and in some cases score significantly higher on delayed post-tests of retention [68-70], but not in others [71-73]. Findings from one study suggest that the effect may be short lived, with significantly higher retention over short (1-2 week) time spans only [72, 74].

Students typically appreciate this approach [75-77]. They report that such approaches enhance their understanding, provide opportunities to develop relationships with their peers [78], and reduce stress [79]. While this approach benefits all students[80], low-performing students sometimes see a larger benefit [81, 82]. However, video analysis of students during a collaborative exam suggests that while students tend to spend time discussing items that at least one member got wrong on the individually-completed stage, students who answered incorrectly tended to participate less and ultimately saw less benefit [83]. This finding suggests that low-performing students who don't participate in the collaborative portion may miss out on opportunities for learning, and this may explain why some studies have not reported a benefit for low-performing students.

While collaborative approaches to quizzes appear to be well received by learners, and to generally support learning, we note a lack of theoretical backing for this approach. We propose co-regulation as a means to provide this backing.

Co-regulation as a theoretical framework for collaborative assessment

Co-regulation is defined as "a group process whereby multiple members dynamically plan, monitor, and evaluate their shared understanding of the joint problem space and the solution in an ill-structured problem-solving process" [84]. To put this into simpler language and in context, this means that engineering students working collaboratively to solve a challenging problem are also working on a range of collaboration activities, and this will look different across differently functioning groups. For instance, group that is co-regulating well will plan (and revise their plan) for how they will accomplish their collaborative work. As they work, they will monitor how each person participates, making sure that everyone has a shared understanding of the problem and the ways they are working to solve the problem. Of course, not all groups function in this manner, so understanding the kinds of activities that improve co-regulation is of interest to researchers and instructors.

Co-regulation is an extension of a large body of work investigating self-regulation [85-87]. Self-regulation involves setting learning goals, monitoring learning processes and outcomes, and reflecting on learning outcomes; generally, when students are adept at self-regulating their learning, they learn more [88-90]. Expanding self-regulation to collaborative settings has helped researchers understand how students learn from one another, as well as why they sometimes don't do so effectively.

Just as the literature suggests that self-regulation skills support individual learning, co-regulation also supports collaborative learning [85, 86]. For example, Zheng & Huang found the use of co-regulation strategies enhanced group performance in problem-solving tasks [91]. Co-regulation involves cognitive processing [92] and awareness of how the collaborative work is progressing [93], meaning it has both individual cognitive aspects and group, social components [87]. Researchers have delineated four dimensions components of co-regulation: clarification & resolution, elaboration, refuting, and summarization, and use these to measure student progress on co-regulation [94].

Gaps identified and research questions

A great deal of research has focused on two-stage collaborative assessment, in which both stages are completed in class. Our study expands on this by investigating a new approach, in which students complete individual work prior to class, the complete the remainder collaboratively. This differs from the two stage model in three primary ways: first, although many students do work individually on the pre-class portion, others work collaboratively. Second, this approach allows us to use more authentic and complex scenarios that truly require collaborative effort to solve. Third, the pre-class portion is not identical to the in-class collaborative portion, but instead provides a foundation for their in-class portion. The current study investigates whether collaborative assessment positively impacts student learning.

Additionally, while research has focused on student acceptance and perceptions of collaborative assessment, this area remains undertheorized, leaving open questions about other impacts collaborative assessment might have on learners. The current study addresses this gap by incorporating research on co-regulation.

We sought to answer the following research questions:

- To what extent do collaborative quizzes support student concept development, as measured by a concept inventory test?
- To what extent do collaborative quizzes enhance students' co-regulation skills?
- To what extent do collaborative quizzes support student learning, as measured by students' performance on an individual versus a collaborative quiz?
- Does initial performance on concept inventory test (high versus low) predict student learning outcomes, as measured by the final exam score?

Methods

Study design

In order to assess the value of collaboration, we contrast student gains on one scenario-based quiz completed individually to those completed collaboratively.

Participants and Setting

Participants included students enrolled in an introductory control theory course (28 students provided consent, one student did not complete the course and was dropped from the data set, N=27). Thirteen students were mechanical engineering (ME) majors and 14 students were electrical and computer engineering (ECE) majors.

Course description

The course is required for students in EE and ME programs. Enrollment is typically split nearly equally between the two disciplines. The course covers mathematical modeling through transfer functions and state-space representations, Laplace transforms, step response properties of second-order systems, internal and bounded-input bounded-output stability, root locus, Bode diagrams, and Nyquist diagrams. No lab component is conducted in conjunction with the course. The course met twice per week for 1 hour and 15 minutes each class, for a total of 13 weeks.

The course was structured to include quizzes and homeworks on alternate weeks, for a total of five quizzes and five homeworks. Students completed two midterm exams and one final exam. Lastly, a small participation grade was allotted, based on completion of the two concept inventories, participation in the class (including the collaborative quizzes as well as other think-pair-share activities during regular lectures), and completion of the University-required course survey at the end of the course.

Materials and intervention

We constructed a series of five in-class scenario-based quizzes, implemented in lieu of standard lectures, to facilitate higher levels of understanding (see Appendix A). Students completed four of these collaboratively, and one (quiz number 3) individually. Students completed an initial ungraded "practice" quiz, so they could acclimate to the timing and difficulty of the exercises, as well as to the dynamic of working in groups. Students had access to the entire quiz several days before the in-class component, and were instructed to complete a preliminary section individually before the class. The in-class, collaborative portion was designed to rely upon answers from the preliminary work, and there was not enough time to do both the preliminary and in-class work during class, so there was clear incentive to complete the individually completed work ahead of time.

Students worked in teams of three to solve multiple-choice and short-answer problems designed around a specific scenario. Students self-selected into groups of three for each collaborative quiz. While students were allowed to pick different groups, most groups were consistent over the entire semester. Past research on collaborative quizzes has generally sought experimental control and used random group assignment. However, in one study that contrasted random versus self-selected assignment, students in self-selected groups reported lower rates of conflict and stress, compared to their randomly assigned peers [95]. In a similar study, students who self-selected tended to report greater agreement that this approach improved their individual learning, whereas those randomly assigned tended to report greater agreement that the approach improved their collaboration skills [96].

Measures

We evaluated students' initial conceptual understanding and growth using a validated concept inventory [1] as a pre- and post-test. The inventory is self-contained, in that it contains "mini-tutorials" needed to probe questions that rely on concepts that are completely new to students at the beginning of the course. Because this course includes both ECE and ME students, and the inventory focuses primarily on mechanical applications, we modified one of the problems on the inventory to show an RLC circuit in lieu of a spring-mass-damper system (but the underlying equation as well as all of the questions were unchanged); this same approach has been used elsewhere [57]. Students had 50 minutes to complete the inventory, and were encouraged to select the 'I don't know' option when available, rather than guess. The inventory was given as a pre-test during the second class of the semester, and as a post-test at the second-to-last class of the semester.

We also used student performance on the individually-completed final exam as a holistic measure of performance, and used rubrics to score student work on the quizzes (see Appendix B).

To measure students' initial co-regulation skills and growth in these skills, we gave students a previously used co-regulation survey [94]. The survey measured our dimensions components of co-regulation: clarification & resolution, elaboration, refuting, and summarization (See Appendix C). Students completed this survey at the beginning and end of the course.

Analysis

We selected quiz number 3 as a good target for evaluating the impact of collaboration on conceptual growth because students performed very poorly or poorly on related items on the concept inventory pretest. This was also the case for items related to quiz numbers 2 and 4. We hoped that this choice would allow us the best opportunity to observe conceptual growth.

We grouped items on the concept inventory into four sets linked to the four graded quizzes. This resulted in four pre-test and four post-test variables measuring student conceptual understanding of modeling, transient response characteristics, stability and feedback, and steady state response. We aggregated students' scores on these items on the pre- and post-test.

To answer our research questions, we conducted repeated measures ANOVAs to evaluate progress on concepts related to each quiz, to compare quiz performance, and to evaluate progress on co-regulation. We sought correlations between various measures. We ran a linear regression to determine whether students who began with low scores on the concept inventory performed worse in the course.

Results

Our first research question focused whether collaborative quizzes support student concept development, as measured by a concept inventory. To answer this question, we conducted a repeated measures ANOVA for the four main concepts on the quizzes, modeling, transient response characteristics, stability and feedback, and steady state response to compare students' concept inventory scores before and after the collaborative quizzes. The repeated measures results showed that students did not perform significantly better in the concept inventory tests in all four areas ($p>0.05$).

We followed up the analysis to examine how the concept inventory test compared to the other assessments such as the non-collaborative quiz, the problem sets, and subsets of related questions on the final examination. We ran this comparison using bivariate correlations. We found that the concept test results did not significantly correlate to student performance on many of the other measures, including the (non)collaborative quizzes, the problem sets, or subsets of exam scores ($p>0.05$).

Our second research question focused on whether collaborative quizzes might enhance students' co-regulation skills. To examine this question, we conducted a repeated measures ANOVA to compare students' co-regulation scores before and after the collaborative quizzes. The repeated measures results showed growth in students' ability to coregulate after the collaborative quizzes (($F(1,22)=18.733$, $p < 0.01$; $\eta^2=0.460$). The strong effect size suggested that the collaborative quizzes could help learners to regulate their collaborative learning processes.

Our third research question focused on whether collaborative quizzes support student learning, as measured by students' performance on an individual versus a collaborative quiz. To examine this question, we conducted a repeated measures ANOVA to compare the scores of individual and collaborative quizzes. The results suggested there was a significant difference among the five quizzes (($F(4,21)=18.733$, $p < 0.01$; $\eta^2=0.885$). Specifically, students performed significantly worse in the individual quiz compared to the other four collaborative quizzes ($p<0.01$). The mean score on the non-collaborative quiz was 0.73 and the mean scores on the collaborative quizzes ranged from 0.88 to 0.98 (see Figure 1).

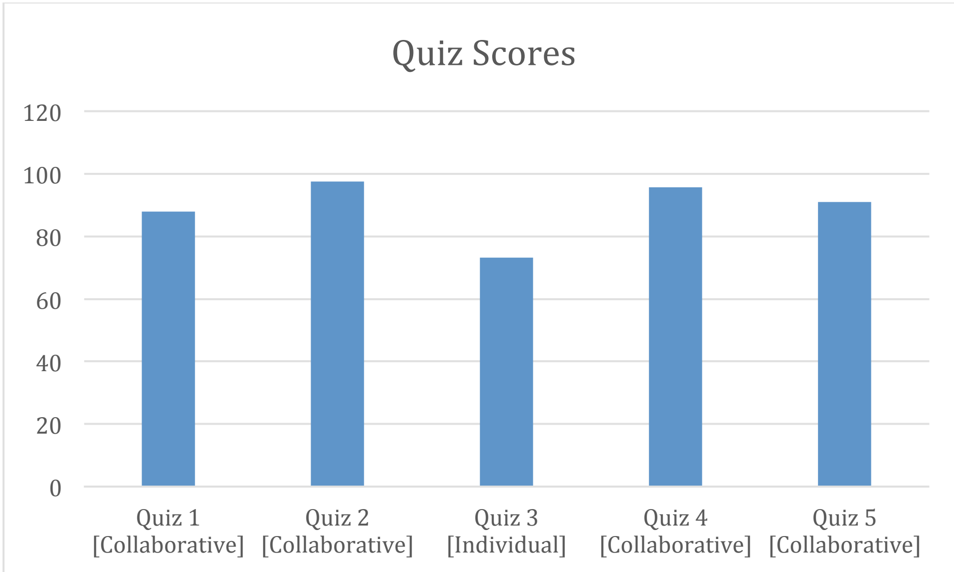

Figure 1: Mean value of quiz scores of the individual and collaborative quizzes

Our fourth research question focused on whether initial conceptual understanding predicted student learning outcomes, as measured by the final exam score. We used the initial concept inventory score as an indicator for students' prior knowledge, We split the class into two groups—high initial knowledge and low initial knowledge—based on their scores on the concept inventory pre-test. We ran a linear regression to compare the two groups of students against their final exam scores. Interestingly, we found that the students with high initial knowledge scored two percent lower on the final exam than the students with low initial knowledge did, even though the differences were not significant ($M_{high\_Initial\_knowledge} = 87.2\%$; $SD_{high\_Initial\_knowledge} = 11.1\%$, $M_{Low\_Initial\_knowledge} = 89.5\%$, $M_{Low\_Initial\_knowledge} = 5.9\%$, $p>0.05$).

Discussion and implications

As others have noted, concept inventories seem to function best when used holistically [97] and to compare rather large changes to entire courses, such as comparing a traditional (lecture) format to active learning formats. One challenge with concept inventories is that they can sometimes appear holistically reliable, yet lack reliability at the item level [97]. Likewise, others have found that concept inventories do not reliably identify specific misconceptions [98]. In our case, we aimed to use the concept inventory diagnostically, to find a more fine-grained change. We did not find this tool to be appropriate to this task. Concept inventories appear to be too blunt an instrument to detect such fine grained changes. Others have cautioned that while they may be useful for making programmatic changes, they lack the fidelity needed to make refinements to a course, especially one that already includes numerous active learning strategies, as was the case in our study.

A challenge for developers of concept inventories is that while it is relatively straightforward to develop items for lower-level, simpler concepts, it can be challenging to develop items for higher level concepts [51]. One reason for this is that upper division courses are often not as standardized in content across universities, and may include interdisciplinary approaches, suggesting the need for a broader range and up-to-date set of items [48]. This relates to one of our findings—that the concept inventory items correlated to few of our other variables.

Research in both science and engineering education has shown that even carefully crafted multiple choice questions can sometimes misrepresent students' understanding [99, 100]. Further, students can sometimes simultaneously hold conflicting ideas and deploy these in different contexts [101]. Another concern that has been raised about concept inventories is that, despite efforts to validate them, they are not always equitable. For example, gender gaps are commonly found for concept inventories, and appear to be at least partially a product of item wording [102], though they are also likely a product of differences in experience [103, 104]. In contrast, in constructed response items gender gaps are less commonly observed [105], suggesting that future work could include a mix of multiple choice and constructed response items. Similar to differences based on gender, research with concept inventories has found that some questions appear to disadvantage students who are blind, based on their experiences [106]. Across disciplines, it is clear that prior experiences matter and can misrepresent student understanding [107].

Because of these concerns, some have argued that instructors should use a mix of multiple choice and constructed response items, in part because these offer different insights into students' understanding and opportunities to write can help students gain a "richer understanding of technical concepts" [100]. Similar to our findings, others have observed differences in gains by assessment type [108]; one study showed that students in a studio course made larger conceptual gains on a concept inventory, but made smaller gains on final exam problem solving questions, compared to a traditional classroom.

Overall, we see the collaborative quizzes as a well-aligned assessment tool for the active learning classroom. This approach fostered improved co-regulation skills, and students who started with the lowest levels of conceptual knowledge had similar course outcomes to those who began with higher scores.

In reflecting on our observations of the course, we also feel the collaborative quizzes were well-received. The majority of students participated fully and were engaged with the materials. It was not uncommon to hear students in extended discussions, particularly about the latter questions in the quizzes, which tended to focus on interpretation of the mathematical concepts. For example, for the quiz on surgical robot manipulators, most groups worked quickly through the first four problems, then spent considerable time arguing about e.g., the role of settling time and overshoot in design of an effective surgical robot manipulator (Appendix A). Some students, in an effort to reconcile their physical interpretations with the mathematical descriptions, challenged their own answers to earlier questions and revisited their answers. Students were often overheard explaining course concepts to their fellow group members and, in general, took an inclusive approach when fellow students lagged. This helpful behavior was also evident at times across groups, perhaps due to the classroom setup (three groups at a table meant that other groups would overhear discussions within a given group, and give rise to inter-group discussions). These observations provide a real-world check on the students' scores on co-regulation.

In a typical class, students in one or two groups (usually at separate tables) would spend much of the time working individually and would intermittently compare their work. Sometimes this seemed to be due to a lack of understanding amongst the group members as to how to proceed with the problem. The instructor encouraged closer collaboration in these groups by posing carefully worded questions that suggested relationships between the problem and material covered in course lectures, or soliciting their comments on various aspects of the problem. For students who seemed to have trouble with the problem, the instructor tasked the students with addressing a simpler problem that would help them solve the quiz problem, then return 5-10 minutes later to evaluate students' progress and provide additional guidance as necessary.

While the pre-class work was not graded or checked for completion, no instances were observed of students completing pre-class work during class. In addition to the dependence of the in-class work on the answers to the pre-class work, as well as the limited time available during class, the grading structure may also have encouraged adherence to the prescribed guidelines, since all students in the same group received the same grade. If anything, the observable trend was for some groups to work ahead on the in-class work before coming to class. Those groups who had this habit typically arrived at the start of class with several questions prepared in advance for the instructor, and spent the remainder of the in-class period discussing ramifications to their answers on the quiz.

In comparison to more traditional lecture formats, students appeared to have a much more meaningful understanding of the course concepts. This had the additional benefit that students were also more willing to ask questions during class, in part because they were attempting to relate new concepts to ones they visited during the scenario-based quizzes. They were invested in solving applied engineering problems, as opposed to purely mathematical problems.

The course evaluation administered during the last two weeks of class (with participation points awarded for completion), showed the students' positive assessment of the collaborative quizzes. Indeed, one student explained:

> "I learned a lot on collaborative quizzes. I have never encountered this type of activity and I think that it was very educational. So during these quizzes I have been explaining lots of things and I think that these are the things which I remember very well now. By the way I did not see any point in quiz we did by ourselves. It was like a take home exam."

When asked on the course evaluation what features of the course and of the instructor's teaching contributed most to their learning, 58% of responding students mentioned the collaborative quizzes.

Overall, we see collaborative quizzes as a helpful tool for supporting learning, especially in classrooms already employing other active learning techniques.

Acknowledgements

This material is based upon work supported by the National Science Foundation. Oishi was supported under Grant Numbers CMMI-1254990 (CAREER, Oishi), CNS-1329878, and CMMI-1335038. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Appendix A: Collaborative Quiz

ECE 345 / ME 380: Introduction to Control Systems
Collaborative Quiz #2

Dr. Oishi

Due Thursday, September 29, 2016 at the end of class

1 Introduction

Surgical robots provide a means for the surgeon to manipulate tissue remotely, often in a minimally invasive fashion. The surgeon retains control of the task, and the robot manipulator acts to extend the "reach" of the surgeon when direct access is not preferable. Such a system needs to be accurate, versatile, and fast for effective manipulation.

Figure 1: Robot assisted surgery. Image from `https://www.asme.org/engineering-topics/articles/robotics/robo-doctor-will-see-you-now`, courtesy Intuitive Surgical Systems.

We approximate the actuator dynamics of the manipulator through the transfer function

$$G(s) = \frac{K}{s^2 + 40s + K} \tag{1}$$

The input $r(t)$ to the system is the position dictated by the surgeon's hand. The output $y(t)$ of the system is the position of the manipulator in the workspace. We wish to design the parameter K to achieve a fast response that does not cause excessive overshoot. The ideal system response would have overshoot less than or equal to 5% and settling time that is less than or equal to 0.1 seconds. We presume that K is positive.

The goal of this exercise is to design the gain K to achieve desired performance characteristics.

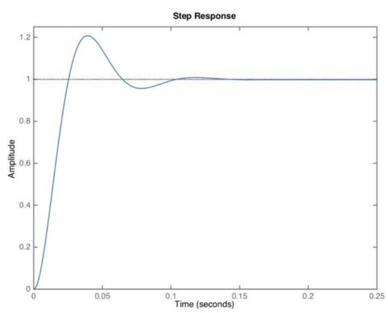
2 Questions to be completed before class

Complete the following in preparation for the work to be done during class. *Your answers to these questions do not need to be handed in.*

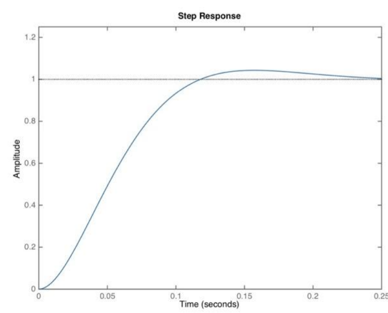
1. Find the natural frequency ω_n, the damping ratio ζ, and the decay rate $\zeta\omega_n$ for the system (1) in terms of the parameter K (if applicable).
2. What is the steady-state response of the system (1) to a unit step input?
3. For a damping ratio of $1/\sqrt{2} \approx 0.707$, what is the corresponding percent overshoot?

3 Questions to be completed in class, in groups

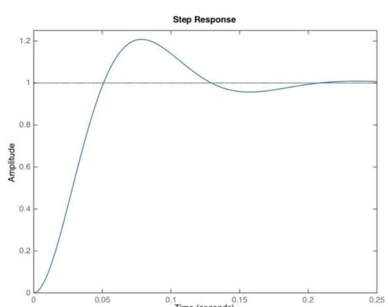
1. Which of the following step responses meets the desired specifications? *More than one answer may be correct.*



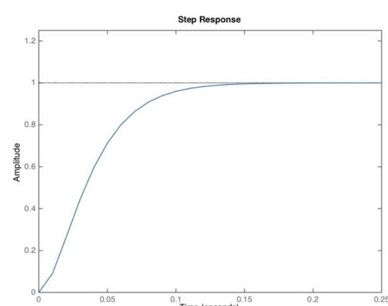
(a)



(b)



(c)



(d)

Now that we have established desired behavior of the system, consider the performance we can accomplish through choice of the value of K.

2. We wish to tune K to meet specifications on both damping ratio and settling time. Which of the following describes the effect of K on settling time for the system (1)?
   (a) Settling time is inversely proportional to $\sqrt{K - 400}$.
   (b) Settling time is 0.01 seconds, irrespective of the value of K.
   (c) Settling time is 0.1 seconds, irrespective of the value of K.
   (d) Settling time is 0.2 seconds, irrespective of the value of K.
3. To achieve a damping ratio of $\zeta = 1\sqrt{2}$, we must have $K = 800$. In this case, which of the following is true?
   (a) The overshoot criterion is not satisfied because the system is overdamped.
   (b) The overshoot criterion is satisfied even though the system is underdamped.
   (c) The overshoot criterion is irrelevant because the system is undamped.
   (d) The overshoot criterion is satisfied because the system is critically damped.
4. Which of the following most accurately describes the system response when K is increased to be as high as physically possible?
   (a) Settling time will decrease, but overshoot will exceed 5%.
   (b) Settling time will increase, and overshoot will decrease below 5%.
   (c) Settling time will remain constant, and overshoot will increase.
   (d) Settling time will remain constant, and overshoot will approach infinity.
5. Imagine that you are a control engineer at a surgical robotics company. After completing the above analysis, you are offered the choice of proceeding with the current design, and manipulating K in whatever fashion you deem appropriate, or introducing a additional controller, which results in the modified system $G(s) = \frac{K}{s^2+(40+L)s+K}$ that can be tuned by altering both K and L. The new controller will incur significant expense, due to new safety certifications that must be obtained. Would you recommend the original or the modified control system? Why? Clearly justify your response in 1-2 sentences.

If your group finishes early

Consider the following points.

- Describe in your own words the difference between peak time and settling time. Give an example of a system with a fast peak time but slow settling time, and vice versa.
- Sketch in the complex plane the locations of poles of (1) as K increases from 0 to ∞. (This is a variant of a *root locus* plot.)

- One way of achieving improved performance is by "closing the loop" (which we will discuss in coming chapters). By incorporating proportional feedback, we can change the transfer function from $G(s)$ to $\frac{KG(s)}{1+KG(s)}$. Would closing the loop enable the system to obtain the desired settling time? Why or why not?
- The steady-state error is defined as the difference between the reference input and the actual output. Will increasing K reduce the steady-state error when the reference input is a unit step? Why or why not?
- Why is it important to have a robotic manipulation system that is significantly faster than typical human response (approximately 0.3 seconds)?

Appendix B: Example rubric for scoring

M. Qi
ECE 345/ME380
Fall 2016.

Grading Rubric

Midterm #2.

[1]

1. 5 points each for (a), (b), (c).

   -1 to 3 for algebra error(s)

   -2 for extra K in ess formula.

2. 5 pts for T_p formula

   5 pts for inequality in terms of K.

   -2 for algebra error(s).

3. 5 pts for response consistent w/ answers to (1) + (2).

4. 5 pts each for (a), (b), (c).

   -1 to 3 pts for algebra error(s)

   -2 pts for not using criteria stated at top of problem in (c).

\

12

1. - significant Evidence of knowing how block diagram algebra works, but wrong answer: + 6 pts.

   - No or little evidence of block diagram algebra, + 2 pts

2. use asymptotic stability to prove: + 7 - + 10 pts (algebra errors)

   use test signal to disprove: + 2 - + 4 pts.

3

1. Algebra error(s), -3 pts.

2. (b) should be consistent w/ polynomial found in (a) for full credit for (b).

   Algebra error(s) -3 pts.

   For (b), +5 pts each for correctly computing Routh table + for interpretation of sign changes in 1st column.

Appendix C: Co-Regulation Instrument

1. When I did not understand my peers' understanding of the problem, I asked them to clarify it.

2. When I did not understand my peers' perspectives, I asked them to clarify their perspectives.

3. I summarized the group's understanding of the problem to understand the problem better.

4. I refuted some of my peers' solution alternative(s).

5. When my peers explained their understanding of the problem, I elaborated on their understanding.

6. When there was a misunderstanding to the solution alternatives among the team members, I tried to resolve the issue.

7. When my peers stated possible problem constraints, I elaborated on their understanding.

8. When I solved the problem, I described the relationships between stakeholders and the problem to my peers.

9. When I saw a misunderstanding of the problem among the team members, I tried to resolve the issues.

10. When I did not understand my peers' solution alternatives, I asked them to clarify it.

11. I refuted my peers' understanding(s) of the problem.

12. After my peers explained their solution alternatives, I shared my understanding with them.

13. When solving the problem as a group, I explained the possible solution alternative(s) to my peers.

14. When my peers suggested a solution, I elaborated on their understanding.

15. I summarized the input of our team to come up with a solution.