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CONTROL THEORY PRACTICES APPLIED TO TEACHING PRACTICAL CONTROL THEORY

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ABSTRACT

Control theory is useful in a broad range of diverse applications that include mechanical, electrical and chemical systems. This work extends the application of control theory from achieving a desired technical outcome to achieving a desired pedagogical outcome. In this paper, the desired outcome is the teaching and learning of applied control systems theory. In the proposed model, the student is the plant, their skill set is the set point, the instructor is the controller, and either an exam or a project-based-learning (PBL) course is the sensor. The PBL course is used to evaluate the actual skill set of the students and the difference between the actual and desired skill set (error signal) is fed back to the professor to initiate curricular changes. This model is shown to be applicable at various levels. At the micro level, examinations within a course are used to optimize that course. At the intermediate level, a PBL course is used as the sensor for a conventional lecture-based course. At the macro level, the departmental program as a whole is matched to the needs of industry in pursuit of a 100% employment rate of its students.

NOMENCLATURE

DOF	degrees-of-freedom
ECE	Electrical & Computer Engineering
EC	Electrically Commutated
EE	Electrical Engineering
EEDS	Electrical Engineering Design Studio
ELEC-341	ECE Control Systems Course
ELEC-391	ECE EEDS Course
FDM	fused deposition modeling (3D printing)
LCR	inductance / capacitance / resistance
LTI	linear time invariant
OPDCA	Observe / Plan / Do / Check / Adjust
PA	practical ability
PBL	project-based learning
PID	proportional, integral, derivative
PLA	polylactic acid (FDM material)
RCG	requirements, constraints and goals
TA	teaching assistant
TK	theoretical knowledge
UBC	University of British Columbia

INTRODUCTION

Project-Based-Learning (PBL) has been shown to be an effective means of improving post-secondary education [7] by combining realistic, clear goals with formative assessments. In engineering, PBL is a popular alternative to traditional lecture-based approaches [12] that enhances both learning outcomes and student interest [11] while providing a better understanding of goals, progress and weaknesses [5]. PBL simultaneously teaches applied skills while it reinforces existing theoretical knowledge [18]. It is well suited to mainstream engineering courses such as applied control theory [4] by highlighting both excellence and deficiencies in student capabilities. By adopting a system-thinking approach [2], PBL courses are a powerful tool for evaluating non-PBL courses by answering the question: "did the student attain the desired competence?".

However, students may not demonstrate their full potential in a PBL environment unless sufficient guidance, support and resources [9] are provided. Frequent formative assessments, not just end-of-term summative assessments [3, 20], in conjunction with technology [1, 10, 14, 15] and/or resource-optimization strategies [6, 16] are all necessary ingredients for successful implementation of PBL [17].

In [19], it is suggested that technology provides the feedback in the closed loop system which describes the evolution from a 20th to 21st century skill set. Here, this idea is formalized and extended to the educational system to show how institutions can obtain convergence between the desired and actual skill sets demonstrated by students. In the context of a professional program such as Electrical Engineering, the governing intent is to fulfill the career goals of students and satisfy industry demands.

An analogy is drawn between pedagogy and a formal feedback control loop. This allows fundamental control theory techniques to be used to draw conclusions about the relationship between specific changes and pedagogical efficacy. Some background is provided on two courses that are used to demonstrate the concepts and some specific examples show how a desired outcome is achieved in a 3rd year Electrical Engineering program. The results are reported based on both statistical and circumstantial evidence.

BACKGROUND

Feedback control is a widely adopted topic that is taught in various engineering disciples. On the one hand, it is the natural phenomenon that causes bicycles to remain upright and motors to accelerate to a particular speed when a voltage is applied. On the other hand, it is the technique that is used to balance power loads in transmission systems, make complex electro-mechanical systems (robots) follow prescribed paths, and forms the basis of the OPDCA (Observe / Plan / Do / Check / Adjust) continuous improvement model used in manufacturing and education [13]. Its versatility transcends any one engineering discipline because it is a fundamental problem-solving technique that is adopted by both humankind and nature. It may be summarized as follows.

- Perturb a system
- Measure the result
- Compare the measured result to the desired result
- Adjust the perturbation accordingly
- Repeat

Any feedback control system comprises the fundamental components shown in Fig. 1. A Controller applies a signal *x* to a System to produce a Result. That result is measured by a Sensor and an error signal *e*, which is the difference between the Measured and Desired result, is used by the controller to adjust the control signal such that the error is reduced. The purpose of controller design theory is often to minimize the error as much and/or as quickly as possible so that the system produces a result that maximally resembles the desired result, while avoiding instability.

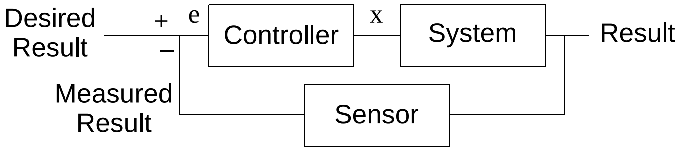

Fig. 1: Control system components

Consider a conventional example that involves controlling the speed of a DC motor using the feedback control system shown in Fig. 2. A PID controller applies a voltage *v* to a DC motor. The motor rotates at a speed *ω* which is measured by an Encoder, subtracted from the desired speed, and fed back to the PID controller. A micro-controller is typically used to read the measured speed, subtract it from a pre-programmed desired speed, and apply the PID control gains to output a voltage *v* to the motor.

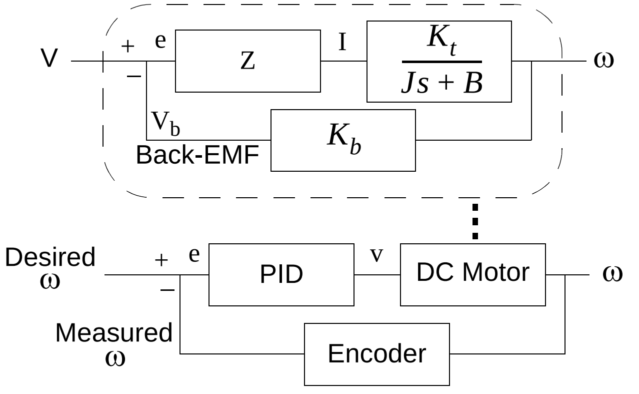

Fig. 2: Nested DC motor feedback loops

It is common in complex systems for multiple feedback loops to be nested. In the above example, the DC motor is itself an implementation of the feedback loop, as indicated in Fig. 2. The error voltage e appears across the windings which have impedance Z and results in the current I. The current causes the motor to accelerate according to the motor torque constant K_t, the motor inertia J and the motor friction B. The speed constant of the motor K_b develops a back-emf V_b according to the speed of the motor ω which subtracts from the applied voltage V to produce the error voltage e.

This fundamental representation of feedback may be used to model how a course is developed and optimized, ironically, even a course in control theory itself. ELEC-341 is a required 3rd year course on Systems & Control in the Electrical Engineering (EE) program in the Department of Electrical and Computer Engineering (ECE) at the University of British Columbia (UBC). The theoretical content includes system modeling in the complex frequency domain, system response, stability analysis and controller design topics which includes root locus, PID control and Nyquist criterion. The feedback control loop in Fig. 3 describes the activity of the professor who uses the past performance and observed responses from students to optimize the course content and delivery. The underlying goal is to impart sufficient Theoretical Knowledge (TK) onto the students such that they are capable of scoring 100% on the exams.

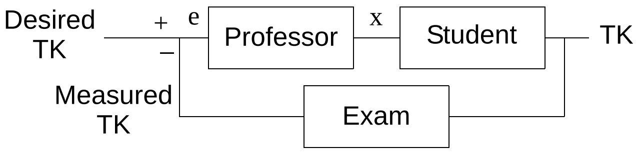

Fig. 3: Theoretical Knowledge (TK) control system

The process of imparting theoretical knowledge may be described as follows. The controller is the Professor who develops and adjusts the lecture material x based on the difference between the desired and measured TK, as determined by the results of midterm and final examinations. The control signal x is the lectures themselves, and the system is the student whose theoretical knowledge is affected by the lecture material and delivery.

A secondary goal of ELEC-341 is to provide the students with sufficient experience in practical PID controller design that they can model a realistic electro-mechanical system and design a controller that meets a pre-defined performance specification, given a prescribed task. This is accomplished by a Simulink based project that makes up a substantial portion of the ELEC-341 course grade.

This parallel task of imparting Practical Ability (PA) onto the students may be represented by the control system depicted in Fig. 4. The controller is the Professor who develops and adjusts the project definition based on the difference between the desired and measured PA, as determined by the results of the project evaluation mechanism. The control signal x is the project definition, and the system is the student whose practical ability is affected by the project they are assigned and the experience it instigates.

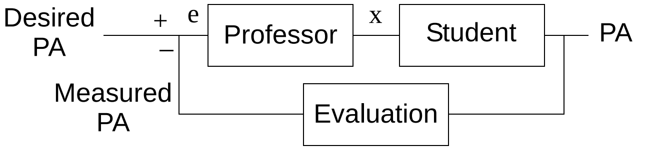

Fig. 4: Practical Ability (PA) control loop

The systems shown in Fig. 3 and Fig. 4 each represent sub-components of ELEC-341 which is designed to provide students an integrated knowledge and ability to use control theory tools to solve practical problems in actual physical systems. Evaluation of the success of this higher level task is accomplished by an independent course. The Electrical Engineering Design Studio (EEDS) course (ELEC-391) is shown as the sensor in Fig. 5.

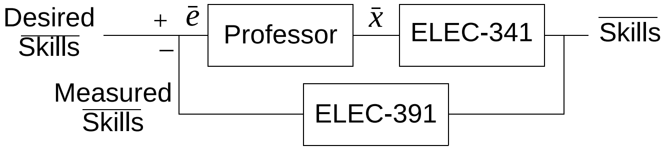

Fig. 5: Intermediate-level pedagogical control loop

In Fig. 5, the desired, actual and measured skills include both theoretical knowledge and practical abilities so all signals are represented as vectors. The control signal x corresponds to integrated abilities that are evaluated by ELEC-391.

ELEC-391 is a course with an average of 2 lecture hours per week which are primarily devoted to hands-on skills. The theoretical knowledge that is necessary to complete the project is assumed to have been mastered in pre-requisite courses. The projects are designed to include as much breadth and encompass as much of the 3rd year Electrical Engineering curriculum material as possible. This includes digital, analog and power electronics, electronic devices, real-time programming, feedback control, machine design and electro-magnetics. In addition, the electro-mechanical nature of the projects provides an opportunity to instruct students on a diverse range of hands-on prototyping skills in both the electrical and mechanical domains. Consequently, the control loop depicted in Fig. 5 is used as a means of optimizing multiple lecture courses, not only ELEC-341, such as the 3rd year machines course as well as the 3rd year semiconductor devices course.

One fundamental element of control theory is the ability to evaluate the sensitivity of the system to changes in any component in the system. For example, the control system in Fig. 3 may be re-represented in the standard analytic form shown in Fig. 6 where the Professor is the controller (K), the Student is the plant (G) and the Exam is the feedback path (H).

The sensitivity of the transfer function (1) to changes in K are derived by (2). The magnitude of K (gain of the Professor)

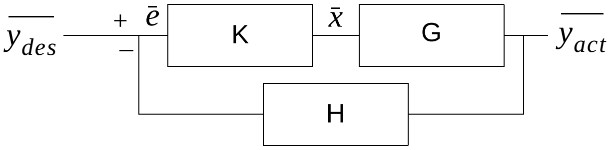

Fig. 6: Analytic control loop

corresponds to the magnitude of the changes they are inclined to make to the course delivery in response to an error signal. The magnitude of *G* (gain of the Student) corresponds to their ability to convert course delivery into theoretical knowledge and retain it. The magnitude of *H* (gain of the Exam) corresponds to the effectiveness of the exam to assess the student's knowledge, with a value of "*1*" corresponding to an ideal evaluation.

$$T = \frac{\overline{y_{act}}}{\overline{y_{des}}} = \frac{KG}{1 + KGH} \tag{1}$$

$$S_K^T = \frac{K}{T}\,\frac{\partial T}{\partial K} = -\frac{1 + 2KGH}{1 + KGH} \tag{2}$$

Equation (2) has a maximum amplitude of *2* when *KGH>>1*. This suggests that sensitivity depends on the path gain *KGH* and does not favour any one parameter. In other words, the gains of the professor, student and exam all contribute equally to the ability of the professor to affect change. This is intuitively satisfying since disengaged students or erroneous examination results neutralize any efforts made by a professor to reduce the difference between the knowledge demonstrated by their students and the knowledge they are hoped to acquire. It is, therefore, just as important for a professor to keep the class interested and participating and to evaluate them in a meaningful way, as it is to improve course content, delivery and assignments.

MICRO-LEVEL FEEDBACK LOOP

At the micro-level, the feedback path (the sensor in Fig. 3) may be any student evaluation that takes place in the course which may not necessarily be a conventional graded exam. In ELEC-391, a student survey is conducted that is not graded to avoid influencing the responses, but instead penalizes non-participation to get a 100% response rate. One survey question asked students to estimate the week in which they began performing the skill that was the subject of each lecture. The week when the lecture material was presented is shown in Table 1 for each year, and is plotted in Fig. 7 where the technical topics are labeled A-I and an 'x' indicates when each skill was first used by the students.

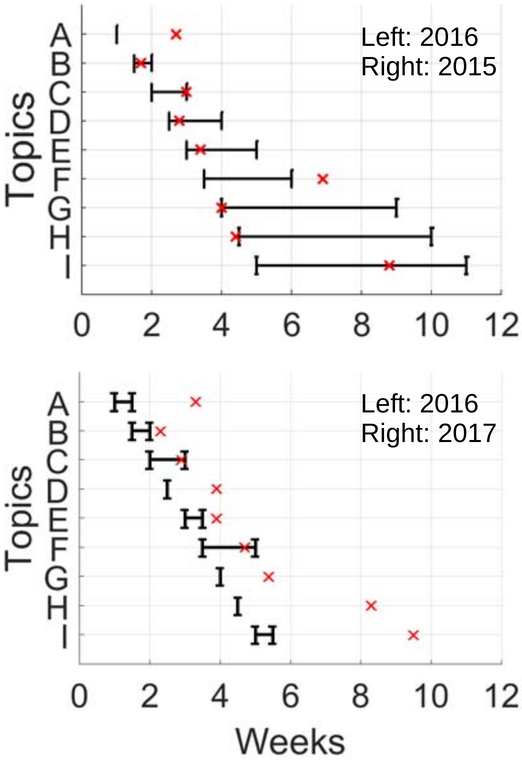

Fig. 7: Graphic comparison of topic delivery dates

	Topic	2015	2016	2017
	Overhead: Course info	1	1a	1b
A	Design & RCGs	1	1a	1b
B	How to get started	2	1b	2a
C	3D printing & waterjet	3	2a	3a
D	SolidWorks I: Solid & Sheet	4	2b	2b
E	Electrical Prototyping	5	3a	3b
F	Altium I: Circuit Design & Sim	6	3b	5a
	Overhead: Progress	n/a	5	5
	Overhead: Component Demo	8	10	10
G	Mechanical Prototyping	9	4a	4a
H	SolidWorks II: Assemblies	10	4b	4b
I	Altium II: PCB Layout	11	5a	5b
	PCB Production	12	11a	11a
	Overhead: Final Demo	14	14	14

Tab. 1: Spring 2015 - 2017 lecture schedule

In 2015, only 2 lecture hours were scheduled per week. In 2016, an additional 2-hour time slot is added to each of the first 6 weeks of the course in exchange for cancelling some of the later lectures. This change is shown in Fig. 7 to be beneficial for all but two (A and F) lecture topics that were used by students in 2016 weeks before they had been presented in 2015.

However, further improvement appears possible since topics G and H were used earlier but presented later than topic F. In

2017, topic F was delayed until after topics G and H but was only used marginally earlier than topic G. Since topic F is an introduction to circuit design software, it is reasoned that students were familiar with this software from previous projects and did not require the lecture to feel qualified to use it.

The student use of topic H (PCB Layout) was delayed by 3 weeks in 2017 which is likely because PCBs were not required until Demo 3 so they were not started until after preparations for Demo 2 had been completed. Regardless, the order of the lectures now closely resembles the order in which the skills are first used, and in most cases the lectures precede student usage. The only apparent opportunity for future improvement is topic A which consistently does not get used until week 3.

The evaluation of the project is divided into two components. The motor and the control system are developed independently by pairs of students and are evaluated part way through the course. Those components are then integrated by the entire team into a working system which is evaluated at the end of the course. In 2015, **24**% of students received a failing grade in the component evaluation (see Table 2). It is assumed that they had underestimated the magnitude of the project and were unable to recover in time for the system level evaluation which had a similar failure rate of **23**%.

The desired failure rate of **0**% is far from the measured failure rate of **23**% so a substantial change is implemented in 2016. An early formative assessment is added which is a progress review. It takes place in the 5th week and holds a relatively low grade percentage but was observed to produce the following side-effects.

- Unsolicited feedback was provided and underestimated tasks were pointed out in time for students to react.
- Students were motivated to have something substantial to demonstrate early in the term, motivating them to set aggressive milestones.

The second hybrid formative/summative assessment is a component evaluation that takes place in the 10th week. Each group is graded individually on their sub-component. This evaluation was observed to produce the following side-effects.

- A milestone was set that required two independent student groups to be simultaneously ready for integration.
- Proper design processes such as defining requirements, constraints and goals were defined to coordinate the activities of the two groups which ultimately have a common end-goal.

The third summative assessment is an integrated system evaluation that takes place in the 14th and final week. Each team is graded as a unit. The formal evaluation was observed to produce the following side-effects.

- Student groups reorganized and converged to function as a cohesive unit.
- Students learned to appreciate the magnitude of a system integration task.

Evaluation	2015	2016	2017
Demo #1 - Progress	n/a	16%	18%
Demo #2 - Component	24%	8%	5%
Demo #3 - System	23%	0%	1%

Tab. 2: Failure rate

As a result of the improved assessment method, failure rates of the Component evaluation dropped from 24% in 2015 to 5-8% in 2016/2017. Feedback that was provided during the Progress evaluation came early enough to avoid 50-72% of the failures. A consistent reduction in failures with each demo results in a statistically insignificant number of failures in the System demo and the desired goal of **0**% failure is achieved.

The average number of hours spent per 4-student team, as reported by the survey, are shown in Fig. 8 where each demo week is indicated by a red line and the desired trajectory is indicated by a dotted line. It is hoped that students begin working hard early, with the amount of effort increasing smoothly as the term progresses and as the project gains inertia.

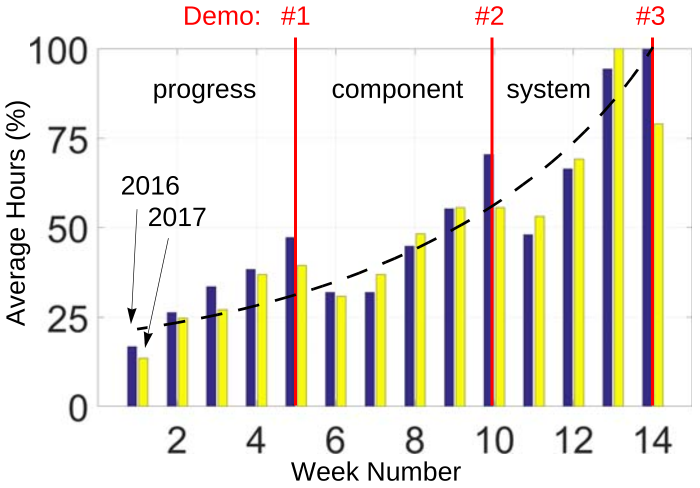

Fig. 8: Normalized average hours spent per student team

The numbers of hours are normalized as a percentage of the maximum average number of hours, to account for discrepancies between the estimates reported by students in the two years. Consistently, an effort spike occurs prior to each demo, with the average overall effort increasing as the term progresses. Also, a significant number of hours are being invested in week 1 so minimal procrastination is taking place, unlike what was observed in 2015 when there was a much higher failure rate. The periodic demos motivate an early start, continual progress, and large, concerted efforts just before the demos take place. Anecdotally, one team suggested that additional demos would be beneficial due to the unifying effect that they have on team dynamics. In other words, the demos act as a damping mechanism that smooths out peaks in the under-damped trajectory that describes the amount of student effort devoted to the project over the course of the term.

Recall from equation (2) that meaningful evaluation is as important as an engaged student or an effective teacher and that for an evaluation to be meaningful, adequate resources must be provided [9]. To help identify whether adequate resources were provided in ELEC-391, budgetary expenditures were tracked and correlated to the final grade for each group in 2016 and 2017. This data is shown in the scatter-plot in Fig. 9 with the average grade for each $100 increment plotted as a solid line. There is no identifiable association between grade and expenditure. The averages are nearly flat, with a slightly negative slope in both years. Both the highest (>95%) and the lowest (<70%) are achieved with between 60% to 100% of the allotted budget. It is concluded that budgetary constraints are not impacting grade and that increasing the budget is unlikely to improve the result.

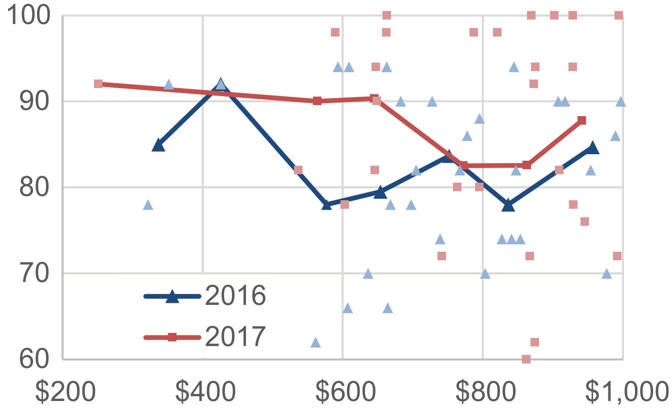

Fig. 9: Project grade vs budgetary expenditure

A resource that was identified in 2016 [17] to be in high enough demand to impact the result was access to 3D printers. In 2016, 5 FDM printers were made available for student use during lab hours (30 hrs / week). In 2017 these printers were replaced by 3 FDM printers that were installed right in the lab for 24/7 access. As a result of this change, the amount of PLA (FDM material) usage rose in 2017 by 50% (13.2 Kg in 2016 vs. 19.75 Kg in 2017) and the number of requests for outsourced (performed by a UBC technician) FDM printing dropped by 51% (86 in 2016 vs. 42 in 2017).

The simultaneous increase in material usage and decrease in outsourcing indicates that additional access did in fact reduce a resource constraint. Incidentally, the cost of the additional 6.55 Kg of material was trivial in comparison to the cost of the technician time that was freed up by this change. Not only did it improve the student evaluation process, but it also reduced the cost to the department. Since it is shown that printer-related delays are reduced by additional 3D printer access, but it is not yet shown that these delays have been eliminated altogether, a fourth printer is allocated to be added to the lab for the 2018 offering of ELEC-391.

INTERMEDIATE-LEVEL FEEDBACK LOOP

The intermediate-level feedback path is shown in Fig. 5. Its plant is one 3rd year course (ELEC-341) and its sensor is a different 3rd year course (ELEC-391). Each iteration of the control loop requires a calendar year, assuming that the two courses are offered out of phase (in different terms). In addition, to close the loop, the instruction of these two coursed must be a coordinated effort. At UBC, ELEC-341 is offered in the winter and spring terms and ELEC-391 is offered in the spring and summer terms. The winter offering of ELEC-341 and the spring offering of ELEC-391 are delivered by a common instructor (the author) so there is perfect coordination between these two processes. The following discussion describes the control loop iteration depicted by Fig. 10 where the spring 2016 ELEC-391 measurement motivated changes to the winter 2017 ELEC-341 delivery which were subsequently measured by the spring 2017 ELEC-391 measurement.

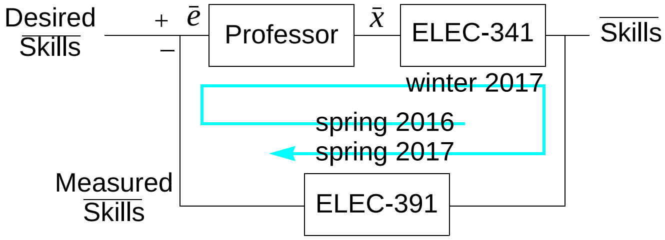

Fig. 10: Pedagogical control loop iteration

The spring 2016 ELEC-391 project involved an electronically commutated DC (EC-DC) motor which was designed, constructed, and used to actuate the main rotor of a semi-constrained 2-DOF helicopter. The system had to be modeled and simulated as a preliminary step toward designing a PID controller which controlled the helicopter height and yaw. It was noted that students had difficulty simulating the motor since they had designed it themselves so it did not come with a data sheet. They struggled with the task of system identification, particularly the physical parameters that are not easily measured such as inertia and friction.

The ability to perform system identification that was measured in spring 2016 ELEC-391 differed from the desired ability so a change was made to the design project ($\bar{x}$) that was assigned in winter 2017 ELEC-341. This affected the skill set of the students which was subsequently measured in spring 2017 ELEC-391.

The change to the ELEC-341 design project was to incorporate an actuator for which physical parameters were not known. Instead, a vector of practical data was provided which provided the impulse response of the actuator (see Fig. 11). Students were obliged to infer from the impulse response the associated physical parameters. It was expected that this experience would have a dual effect on students. First, they would have first-hand experience with extracting physical parameters from an impulse response. Second, they would realize that an impulse response, which is easily obtained experimentally, can be used to quantify unknown and difficult to measure physical parameters.

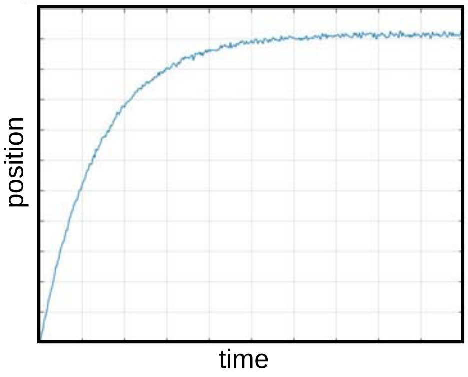

Fig. 11: Impulse response

The spring 2017 ELEC-391 project involved a linear DC motor which was designed, constructed, and used to actuate a 2-DOF haptic interface. The linear motor, just like the 2016 EC-DC motor, lacks a data sheet and any information about its associated physical parameters.

Fig. 12 is a bar chart showing the percentage of student groups that provided some justification for the motor simulation included in their project report (A), the percentage that performed physical measurements to derive some of the associated model parameters (B), and the percentage that used an impulse response to determine the unmeasurable parameters (C).

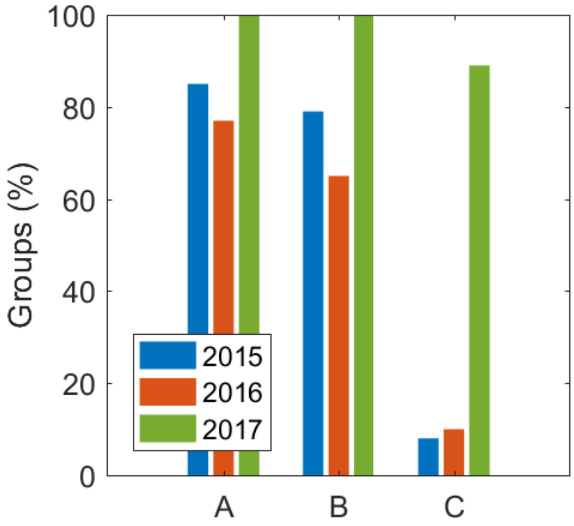

Fig. 12: Actuator model derivation

The use of an impulse response rose from no more than 10% in 2015 and 2016 to 89% in 2017. In addition, 100% of students provided an explanation for their model and measured some of the parameters, which was not the case in previous years. This accounts for an elimination of almost the entire error signal which corresponds to student teams that either did not explain, measure or evaluate their motor using an impulse response.

The elimination of unexplained and unmeasured model parameters may be further explained by an additional change that was made to the ELEC-341 project. In 2016, both the ELEC-341 project and the ELEC-391 project were a 2-DOF helicopter. Consequently, the Simulink model that was provided by the instructor for the ELEC-341 project was recycled in the ELEC-391 project with parametric changes to account for the different electro-mechanical properties. In 2017, the ELEC-341 project was a serial robotic paint booth while the ELEC-391 project was a parallel haptic interface. The Simulink model could not be recycled and had to be generated from scratch by the students in ELEC-391. It is proposed that this led to a greater understanding of the model and the more complete descriptions that were provided in the reports.

For the next iteration of improvements to ELEC-341, the PID tuning method that was used by students is evaluated. Fig. 13 is a stacked bar chart showing the percentage of students that performed model-based tuning such as a root-locus method (A), the percentage that performed cook-book tuning such as Ziegler-Nichols (B), and the percentage that used trial and error (C). The remainder of the students did not specify a tuning method.

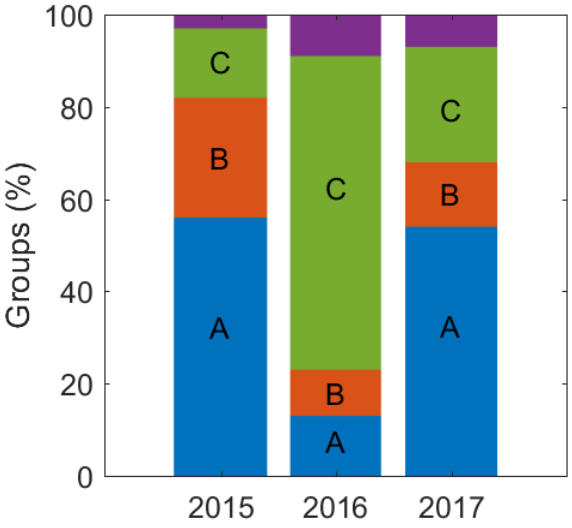

Fig. 13: Controller tuning method

It is desired that all students perform model-based tuning. However, Fig. 13 indicates that, at best, little more than 50-60% of students do, with the remaining using cook-book methods or trial and error. A root-locus method is introduced in ELEC-341 but it is not uniformly adopted when confronted with a practical problem. This indicates a need for a change to the delivery of

ELEC-341 to place greater emphasis on the root locus method, with the hope that a reduction in this error will be observed in 2018 ELEC-391.

CONCLUSION

It is concluded that the error signal that represents the difference between the desired and actual skill sets of a 3rd year Electrical Engineering student at UBC is reducing drastically during each control cycle (academic year). This is illustrated in Fig. 14 which shows an example of what one student team delivered during subsequent ELEC-391 demos in 2017. Many desired outcomes are clearly present which include the following.

- A substantial amount of progress has been made by Demo #1 indicating that significant effort had been devoted right from the start of the project.
- The level of quality improved and additional components (x-y table) were added in Demo #2 indicating that continued, increasing effort had been devoted throughout the project. A new motor concept is present and the proof-of-concept motors from Demo #1 are retired.
- A polished, high quality standard is maintained in Demo #3. All components are optimized and nicely packaged for a professional appearance and high reliability. The (red) motor is essentially unchanged from Demo #2 and a second copy (blue motor) has been produced, indicating that the Demo #2 motor was in fact a finished product.
- It is not apparent from Fig. 14 but the system delivered a convincing sensation of haptic feedback and effectively demonstrated both hard contact and damping.

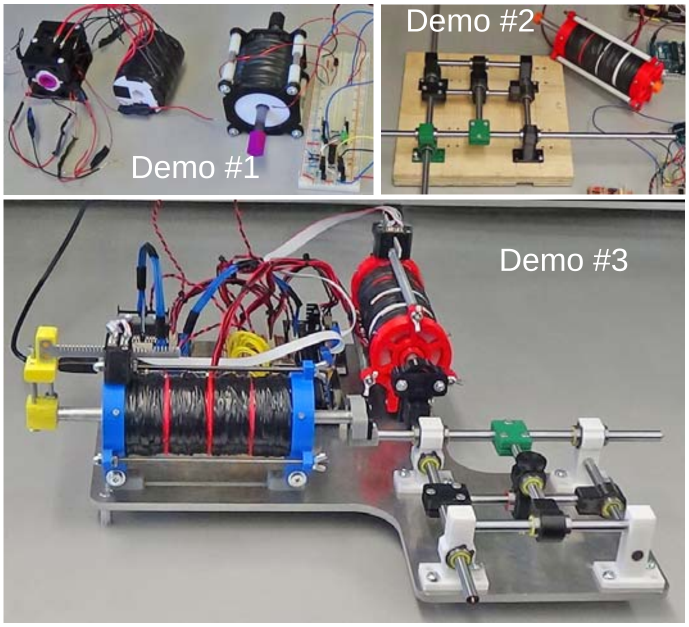

Fig. 14: Student work sample - demos 1, 2 & 3

The average grade for all students was 76% in 2015, 83% in 2016, and 81% in 2017. A 5-7% increase corresponds to almost an entire letter grade of improvement. The lab space, faculty and staff were approximately consistent in all years. The fundamental changes were the ones described here which focused on program delivery, evaluation, and resources.

The projects also remained fundamentally consistent but each had different specifications. In all three years the project involved designing a motor, a sensor, a controller, a current driver, and a 2-DOF robotic mechanism. The style of the motor rotated between a mechanically commutated DC motor (2015), an electrically commutated DC motor (2016), and a linear motor (2017). In 2015, the robot was a position controlled robot that could be specified by the students in an open-ended fashion. In 2016 the robot was a velocity controlled helicopter which mimicked the prior ELEC-341 project. In 2017 the robot was a force controlled haptic interface which is an application that the students were not familiar with. In addition it was mandatory for both motors to be custom made since commercial linear motors were not available. In previous years, students could opt to use one commercial motor and sensor in their mechanisms. Although the project remained more or less consistent, it became progressively more challenging from 2015 to 2017 so the substantial increase in the average grade symbolizes an even more substantial improvement in student accomplishment.

It has been shown that the same feedback control loop that is used to solve engineering design problems may be used at both the course (micro) and year (intermediate) levels to optimize student learning in engineering, or any other educational activity. In fact this same technique may be applied at the program (macro) level as depicted in Fig. 15. The controller is the entire faculty who determine the program content x, based on the difference between the desired 100% employment rate and the actual employment, as determined by Industry.

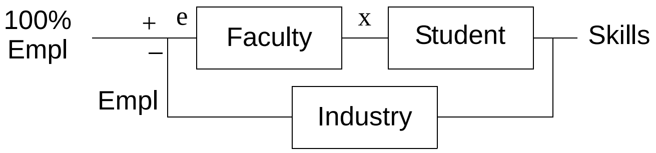

Fig. 15: Program level control loop

The main challenge in Fig. 15 is in achieving a high controller gain so that the error signal is minimized rapidly. The controller gain corresponds to communication among faculty so that measurements made in one course are reflected in the changes made to subsequent courses, just as it has been demonstrated here in Fig. 10.

Here, a common professor was responsible for delivering both ELEC-341 and ELEC-391 so there was no lack of communication. At the program level, this is impractical. The ECE department at UBC comprises over 50 professors so coordination and communication are a necessity to close the feedback loop and achieve the department mandate of satisfying both the career aspirations of students and the evolving demands of industry.

It has been shown that fundamental control theory principles which are normally applied to mathematically represented control systems may also be applied to less formally represented pedagogical control systems. For example, sensitivity theory (1,2) is used to draw conclusions about the relevance of the student, professor and evaluation mechanism with respect to the ability of the professor to affect positive change. In addition, other control theory fundamentals are also inferred.

- The control frequency is shown to improve error convergence. Increasing the frequency of evaluations effectively increases student outcomes at the course (micro) level.
- The controllability of a system assesses the ability of each input to control all outputs (states) of the system. When a common professor delivers multiple courses, the controllability is high. At the program level, it is reduced unless there is strong communication and coordination between faculty members.
- Many theorems have a requirement for the controlled system to be LTI (linear time invariant). Time invariance, or consistency, is impacted by many human factors which include subjectivity as well as staffing changes.

In the future, the Time Invariance criteria will be more closely considered and addressed. In particular, variations in the sensor (testing criteria) are observed due to a number of human factors. In order to reduce subjectivity, all evaluations are performed by the same team of evaluators so evaluations must be performed sequentially. With large class sizes, evaluations may span many days, or even an entire week. The difficulty associated with recalling the grade that was assigned to different sets of accomplishments compounds the already subjective nature of evaluating an open-ended design project. New tools and techniques are being formulated to maximize objectivity, consistency and therefore, time invariance to an intrinsically non-linear system in an effort to increase observability, controllability and error convergence with an ultimate goal of 100% employment of all UBC ECE graduates.

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