From Technology Elaboration Toward Application Innovation: An Instructional Transformation in a Project-oriented Capstone Course of Dynamic Control Systems

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From technology elaboration toward application innovation: An instructional transformation in a project-oriented capstone course of Dynamic Control Systems

1. Introduction: Case study on capstone transformation of System Engineering Education

Many courses in engineering programs have long been offered with a primary focus on basic knowledge or skills. Such courses are characterized by lectures (direct teaching) and homework assignments taken from textbooks. This context is deteriorated by the fact that top universities in Taiwan have been emphasizing on research to some extent of overlooking the prominence of instructions. The major stakeholders of engineering education, therefore, have stated major concerns. For example, the government urges to promote economic growth through new and innovative model of high technology business; the employers demands the need for a new set of competences (ie. creativity, leadership and collaboration); college students regard their learning as rich but yet listless, lacking a sense of humanity and meaning. Therefore, a national policy to renew Engineer education was launched by the State Department and financial grants of engineering education reformation [1]. Following this trend, a three-year pioneer curriculum transformation in System Engineering (SE) has been implemented in many research universities. A subprogram within the electrical engineering field is related to system engineering. Its emphasis is attached to the use of system theory in electronic applications, e.g., autonomous vehicles. In fact, electrical engineering related system engineering tends to emphasize control techniques, which are often software-intensive. Managing complexity is an important component of many courses taught within the SE program. Modeling, simulation, reliability, and safety analysis of complex systems are considered to be essential parts of the training required for a successful system engineer.

The goal of this transformation was to shift the primary focus of SE programs on "technology elaboration" to strengthening "application innovation" in respond to the requests of the stakeholders. This study adopts the in-depth case study to describe a 3-round evolution process in transforming the Dynamic Control Systems course (DCS) from a standard college engineering course toward capstone.

A cross-discipline pedagogical team (CDPed team, thereinafter), composed of professors and doctoral/master students from engineering and education, was built to tackle issues arose during curriculum transformation. Previous research [2] has stated that there is no single course structure or instructional strategy that would be effective for all engineering programs. Therefore, this transformation was conducted with careful design decisions and followed by a self-improvement cycle (see figure 1). In

higher education, capstone courses offer senior undergraduate students the opportunity to summarize, evaluate, and integrate some or all of their college experience [3]. The professors in the CDPed teams set the learning objectives for the System Engineering capstone course in helping students to better synthesize and integrate skills and knowledge acquired from the SE related courses; a significant project-based experience where teamwork, creative thinking and written-oral communication were also the key components of that experience.

In general, the transformation took three school years, starting from 2013 to 2016. In the 3 transformation rounds, it has established a practical framework to share with engineering educators. The goal of this case study is to illustrate how initial plan of capstone transformation containing only partial perspective has been challenged. Through various self-improvement mechanisms (illustrated in Figure 1), challenges have been overcome and the capstone course gradually evolved toward comprehension and optimization from 2013 to 2016.
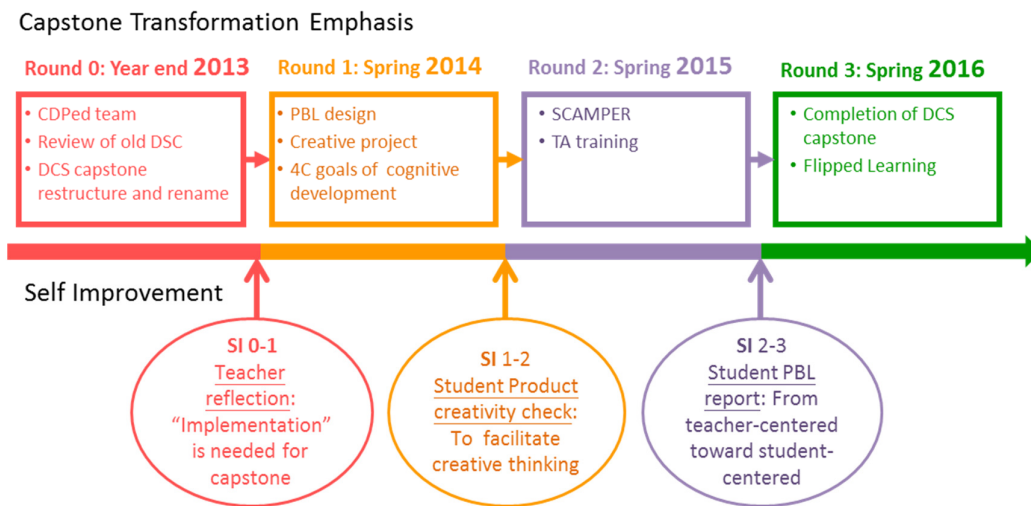

Figure 1: The evolution process (rounds 0-3) in Dynamic Control System capstone transformation from 2013 to 2016 in the current case study. The transformation emphases are illustrated in the colored boxes. The colored circles signified the methods and decisions of self improvements (SI0-1, SI1-2, and SI2-3). Various self-improvement methods (teacher reflection, product creativity check, and PBL experience student report) were adopted in each round (text underlined). The major decisions of self-improvement are provided in the colored circle.

This paper is structured as a case study to explain the transformation process listed in Figure 1, including working emphases, self-improvement methods and sequential transformation decisions for the DCS capstone course. Figure 1 shows the timeline of capstone transformation (rounds 0 to 3) and self-improvement cycles from 0-1, 1-2, and 2-3.

In the following, Session 2 describes "***Round 0: DCS capstone curriculum structure and goal***" (left red box in Figure 1) with a description of self-improvement 0-1 through teacher reflection (left red circle in Figure 1). Then we provide details of "***Round 1: Design of DCS capstone projects and development of students' cognitive competencies***" (orange box in Figure 1) with details of self-improvement 1-2 through product creativity check (orange circle in Figure 1). Third, "***Round 2: Development of SCAMPER and TA training***" (violet box in Figure 1) is introduced with self-improvement 2-3 of examining students experiences in project-based capstone process (violet circle). Because PBL encourages learners to construct their own knowledge, it is expected students to perceive the course as more student-centered. Finally, "***Round 3: Completion of DCS capstone structure and Flipped learning***" (right green box in Figure 1) is described.

2. Round 0: Dynamic Control Systems capstone curriculum structure and goal

Previous studies [4-7] have found convincing evidences that indicate the effectiveness of the capstone course. The capstone course allowed students to integrate the learning experiences acquired from their academic disciplines and made sure they were able to demonstrate the competences aligned with the department learning objectives. This gave students a chance to clarify what they've acquired and to reflect on their own growth over time. It invited students to extend their knowledge, work independently and collaboratively with peers under minimal faculty supervision. From a curriculum perspective, the benefits of a capstone course include a curriculum planning so that faculty of the 100-, to 300-levels know what students will accomplish at the end of the course. In addition, the records gathered from a capstone course can aggregate information about students' performance, which can serve as an evaluative feedback to the departments on the strengths and gaps within their curricula.

In Electrical Engineering (EE), students are required to gain sound theoretical analysis and design skills for a variety of practical systems that makes the significance of Systems Engineering in professional training. From this course, the students can learn more about system verification and applications. Several EE professors had agreed upon a System Engineering curriculum scheme (See Figure 2). At the yearend of 2013, the capstone DCS then was renamed as "Dynamic System Simulation and Implementation (DSSI)." DSSI aimed to help students synthesize and integrate skills and knowledge acquired throughout the SE course.
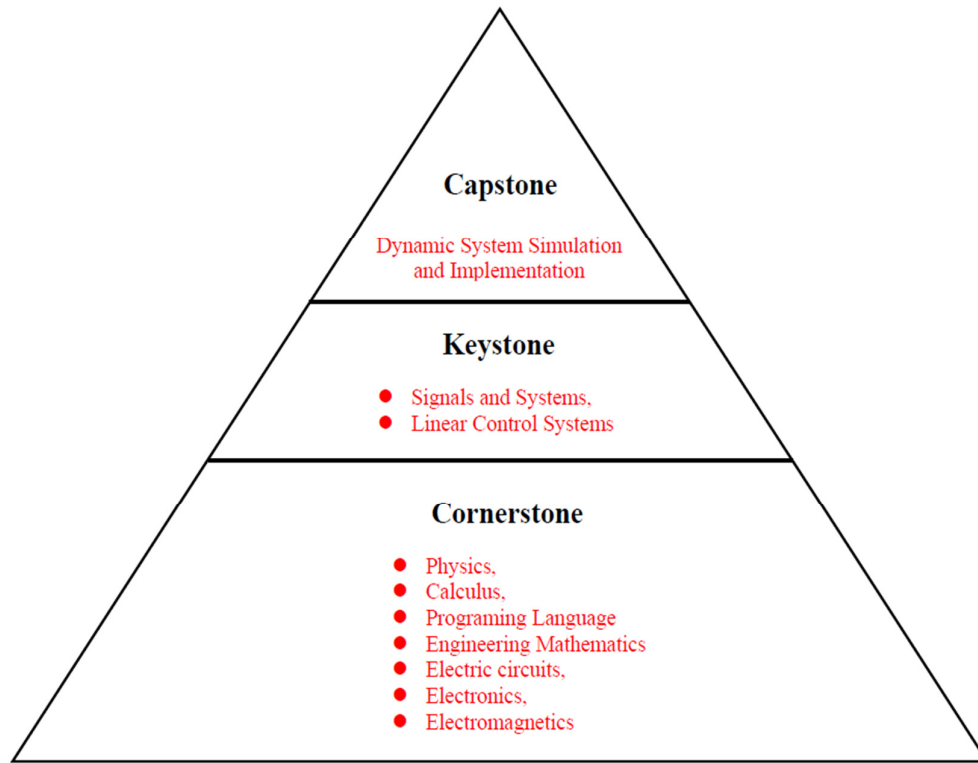
Figure 2: An illustration (at round 0) of System Engineering curriculum scheme that categorizes 100-300 courses into cornerstone, keystone and capstone, respectively.

Self-improvement from round 0 to round 1

From round 0 to round 1, the DCS professor decided to do self-reflection on previous SC syllabus and examination of System Engineering course structure. Figure 3 lists four standard steps in system engineering design shown in syllabus: (1) mathematical modeling, (2) controller design, (3) system simulation and (4) system implementation. Previously, the Dynamic Control Systems (DCS) [8-9] course was coined as "Dynamic System Analysis and Simulation (DSAS)" and the instructor (the second author of this study) edited the teaching material to include the first three standard steps of system engineering design: "Mathematical modelling", "Controller design" and "System simulation." However, an actual system could be transferred to a dynamic mathematical model by building a mathematical model, designing controllers and verifying the controller by numerical simulation in order to measure up to the required specifications. For the implementation of controller to be completed, the controller design needs to be tested for its feasibility by numerical simulation and hands-on experience to demonstrate creative thinking. The first transformation decision was then to include hands-on experience by introducing step (4) "system implementation" in the right box of Figure 3.
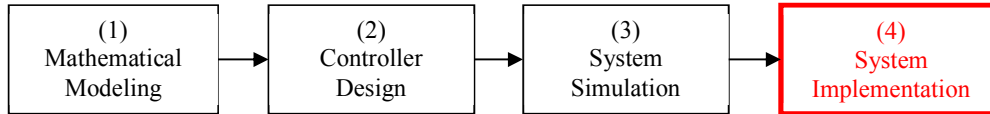
Figure 3: "Dynamic Control Systems" capstone course must include 4 standard steps of system engineering design. Red box indicates the major decision of the capstone transformation from round 0 to round 1.

Mathematical modelling

In order to lay a solid mathematics foundation for students, "Calculus" and "Engineering mathematics" are usually incorporated into required courses specified for freshmen and sophomore. "Engineering mathematics" can be differentiated into four courses: "Linear algebra", "Differential equations", "Complex variables" and "Probability". Electric Circuits and Electronics are the introductory courses that teach circuit design and electronic components. Students not only learn fundamental technical knowledge, but practical skills like (1) how to transfer the circuits to mathematical models, (2) how to solve problems with mathematical tools, and (3) how to interpret the performance results of the electric circuits.

Controller design

After engineering students have understood the necessity of "Mathematical modelling," a course on "Systems and signals" would proceed to introduce "Controller design" with regards to the characteristics, principles and skills of signal processing. "Linear control system" course [10-13] teaches students the knowledge and techniques of linear system controller design including basic control laboratory.

System simulation

In the capstone, students are taught to use MATLAB/SIMULINK for constructing numerical simulation programs.

System implementation

In previous DSAS course, students could clarify confused theories and concepts by conducting "System simulation," but students still lacked actual hands-on experience with practical system identification and verification [14]. To compensate for this, "Dynamic System Simulation and Implementation (DSSI)" included a project of "System implementation" emphasizing creative thinking on top of the 4 complete standard steps of system engineering design.

3. Round 1: Design of project-based DCS capstone course and development of students' cognitive competencies

Project-based Learning

Through the first self-improvement at yearend of 2013, the first capstone transformation decision was to adopt project-based learning (PBL) as the major instructional strategy. This decision was based on the goal of capstone transformation highlighting experiential learning and 4Cs cognitive development (introduced in the following). Project-based learning [15-19] is a comprehensive approach to the process of teaching and learning that engages students in the investigation of real-life problems. While lecturers provide guidance to students during their project work, students become active learners and participants in hands-on activities. Educators who adopt PBL are likely to stand against the traditional teacher-centered approach, characterized by lectures and rote memorization. On the contrary, PBL encourages learners to construct their own knowledge in making learning meaningful. PBL also promotes a repertoire of skill sets, such as teamwork, creative thinking as well as written-oral communication. In other words, "projects are the curriculum". Students learn to research and define the problem, explore the solution space for more than a single solution, and learn to iterate and improve their designs in arriving at an appropriate solution that meets the objectives. Specific end products are clearly defined, while the steps taken to achieve them can vary. The end products serve as the basis for discussion, feedback, and revision.

Starting from 2014, two team projects of practical dynamic systems were designed for DSSI course, (1) DC motor system and (2) Rotary Inverted Pendulum system (See Figure 4) [20-23]. DC motor is a typical example of linear system, while Rotary Inverted Pendulum system is a type of nonlinear system. Through hands-on group works, students may acquire the differences of system verification and control with two different types of practical systems. Project 1 (system parameters identification, speed and position control of DC motor) and Project 2 (system parameters identification, speed and position control of rotary inverted pendulum) require 4 standard steps of system engineering design in Figure 3.
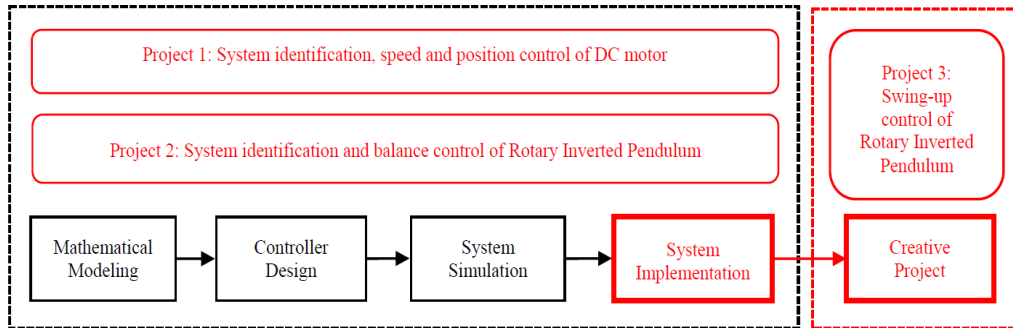
Figure 4: Curriculum redesign in Round 2 (spring 2014): Project design and standard steps of systems engineering design. Red box indicates the major decision of the capstone transformation at round 1.

In addition to the basic training through projects 1 and 2, the design of Project 3 (swing-up control of rotary inverted pendulum) allow students the opportunity to generate more than a single solution (See Figure 5).
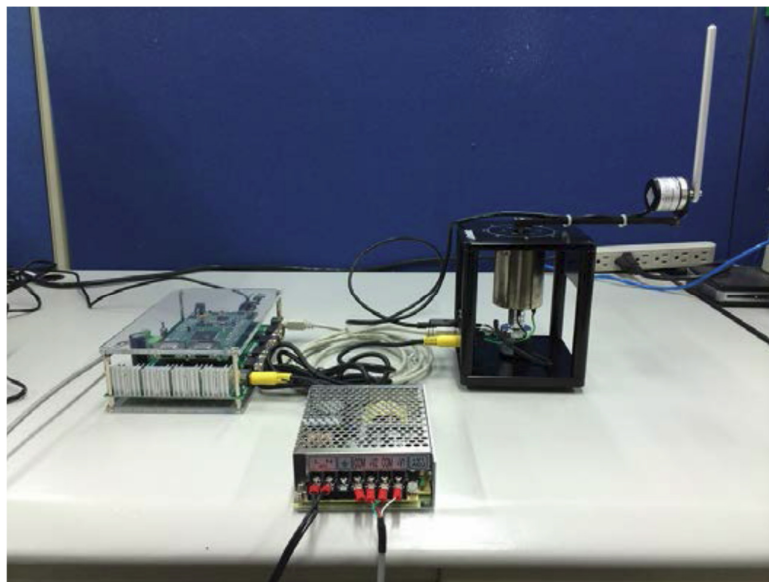

Figure 5: Rotary inverted pendulum system driven by DC motor

Students' cognitive competencies: 4Cs

Through project experience in DSSI capstone course, we hope students can develop four cognitive competences (coined as 4Cs).

(1) *Complex integration of System Engineering - fundamental knowledge*: referring to the 1st and 2nd standard steps, Mathematical modelling and Controller Design, in System Engineering design (See Figure 3). Students have to integrate their prior knowledge: Linear algebra, Differential equation, Electrical circuit theorem and Signals and systems.

(2) *Collaborative System Engineering simulation and experimentation*: referring to the 3rd and 4th standard steps, System Simulation and System Experimentation, in

System Engineering design (See Figure 3).

(3) *Communication to the public orally and visually*: referring to group discussion with TA and final presentation for project 3.

(4) *Creative thinking*: Since project 3 encourages students to generate ideas, to predict through simulation, to form hypotheses, to devise alternative scenarios and solutions, and to explore options, we regard it as a project that promotes creativity and innovation.

Self-improvement from round 1 to round 2: Assessing creativity level of project product

The creativity projects (project 3), swing-up and balance control of Rotary Inverted Pendulum in free style, were assessed by a panel of SE experts using Creative Product Semantic Scale developed by O'Quin and Besemer [24]. Three creativity dimensions of products are evaluated: (1) novelty (e.g., the product is unique), (2) professional level of solution (e.g., the product is designed properly using Control theory), and (3) synthesis style (e.g., the product demonstrates good sense of System Engineering design). The final project presentations were all recorded and can be retrieved at NCTU OpenCourseWare (OCW) (http://ocw.nctu.edu.tw/course_detail-v.php?bgid=8&gid=0&nid=509&v5=YTBqLt4oW1U). Figure 6 is an example screen of final presentation (the design of Rotary inverted pendulum system driven by DC motor of group 7th) and Figure 7 is the product implemented by the group.

Unfortunately, the levels of product creativity in round 1 were about medium. The CDPed team thus decided to introduce a simple technique, SCAMPER, to help develop creative thinking. In addition, because the team of teaching assistant reflected that they were not familiar with the features of capstone course nor creative thinking skills, the CDPed team decided to provide TA training during round 2 of curriculum transformation.

Figure 6: An example screen of final presentation (group 7)

Figure 7: Power-point file description about the product implemented by group 7

4. Round 2: Development of SCAMPER and TA training

Tailor SCAMPER for System Engineering

Creative thinking is essential in the design process that could turn ordinary ideas into

innovation. However, it is often difficult to break the thinking barriers because rigid mindset (the routine of thinking) could limit a person's brain broadband. One of the effective methods used to enhance the likelihood of creative thinking is the SCAMPER technique [25]. SCAMPER is an acronym for seven subskills: (S) substitute, (C) combine, (A) adapt, (M) modify, (P) put to another use, (E) eliminate and (R) reverse. Each keyword represents a set of questions that could be addressed during the project process to encourage creative thinking. Following SCAMPER flow, individuals could intentionally broaden their viewpoint without being caught up in their mindset.

Because Project 3 (swing-up and balance control of Rotary Inverted Pendulum in free style) is where we encourage students to show creativity, in Round 2 (year 2015) the CDPed team tailored SCAMPER to fit the requirement of Mathematical Modeling and Controller design (1st and 2nd steps of System Engineering Design). Specifically, the order of SCAMPER is modified (S-C-E-R-M-A-P) according to the ease for use in DSSI projects. The resulting SCAMPER (Table 1) has been introduced to students during the first stage of system engineering design when they were working on "Mathematical Modeling" and "Controller design", because the initial idea generation period is the key time point for common ideas to turn into creativity.

Table 1: SCAMPER worksheet with Project 3 (swing-up and balance control of Rotary Inverted Pendulum in free style) for use in "Mathematical Modeling" and "Controller design", stage 1 in the system engineering design process. The order has been changed into S-C-E-R-M-A-P.

Thinking skills For Project 3	Application: After you come out the initial model, you need to modify the initial model using the steps (as many as possible) in the following.
1.(S) Substitute	Can you replace the parts in your initial mathematical model with another? Do as many replacements as you can and select the best one.
2.(C) Combine	Can you analyze the possibility of merging two parts into a single more efficient/strong component? Do as many merging as you can and select the best one.
3.(E) Eliminate	Can you identify the parts of your mathematical model that can be eliminated to improve a critical feature (e.g., speed, position…)? Try as many as possible to see what is unnecessary.
4.(R) Rearrange	Can you change the order of components in the mathematical model to further improve it? Try as many combinations as possible to see what would happen.
5. (M) Modification	Reflect on previous 1-4 (S)(C)(E)(R) to make further modification on the mathematical model

(M) = Integration of (S)(C)(E)(R) or bigger change	Can you make a bigger adjustment rather than slightly adjusting parts of the controller design? Please focus on the overall process.
6. (A) Adapt	Reflect on 5 (M) and see what else you can do to make improvement on the mathematical model?
(A)= Further adjustment on the controller of 5. (M)	If you change the constant of the model, what would happen?
7. (P) Put to another use	Review 1-6 and see if there are alternative functions to your mathematical model and controller design. Can this model be innovatively applied (What product, where, when, and how to use?)
(P) = Other use of the controller	Turn your swing-up and balance control of Rotary Inverted Pendulum into a distinctive product.

Teaching Assistant Training

In Round 1 of curriculum transformation, the DSSI course has been changed into capstone and hands-on project experience was emphasized. However, the examination of creativity level for end products of project 3 that aimed at brainstorming and innovation showed unsatisfactory results. Most students reported that they adopted a play-it-safe strategy in conducting the final project (swing-up and balance control of Rotary Inverted Pendulum in free style).

In response to this, the self-improvement meeting of CDPed team decided to offer Teaching Assistant (TA) professional Training workshops. The TA training focused on 2 aspects: (1) the principles underlying capstone course and (2) creative thinking skills (the modified SCAMPER, Table 1).

Self-improvement from round 2 to round 3: Student experiences in Project-Based Learning capstone

In round 2, 5 repeated investigations were held across a semester to examine students' learning experiences through the instructional process of PBL capstone. The 5 time-points were selected during (1) base knowledge introduction, (2) SCAMPER introduction, (3) Midterm, (4) Projects 1-2, and (5) Final presentation of Project 3. Because PBL encourages learners to construct their own knowledge in making learning meaningful and to promote a repertoire of skill sets, such as teamwork, creative thinking as well as written-oral communication, it is expected students to perceive DSSI as more student-centered.

Figure 8 shows the investigation results along the 5 time points. Students were asked "Who did you worked with in DSSI class?" In general, the results show that the DSSI

course gradually shifted from being teacher-centered to student-centered. At Time 1 (the beginning of the semester) when teacher taught base knowledge of DCS, 61% students reported that they learned with the teacher; 26% stated that they learned with peers and only 13% studied alone. At Time 2, when SCAMPER was introduced, students' report was as it was in Time 1; mainly, students worked with the teacher. However, when it came to the midterm week, 92% of the students took the exam alone, 8% with the teacher, while none reported to be with peers. When projects 1 and 2 began, more students reported to have worked with peers (54%) than with the teacher (38%). At the final presentation, they collaboratively presented their outcomes to the teacher (38% with peers and 62% with teacher).
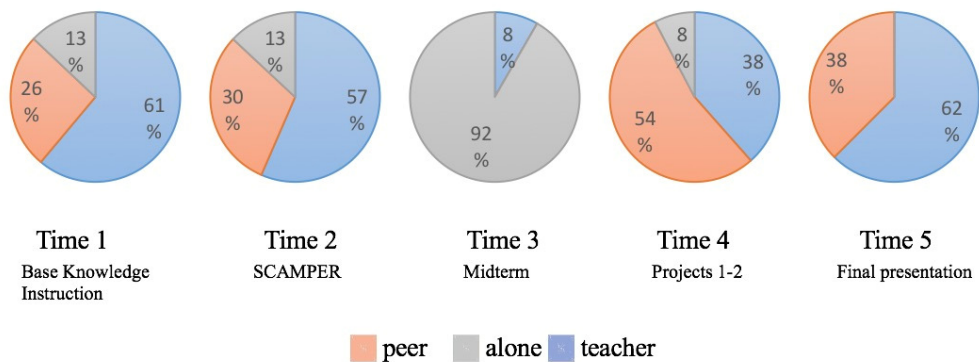

Figure 8: 5 repeated investigations were held across a semester to examine DSSI students' experiences along the instructional process of PBL capstone. Students were asked to report "whom they worked with in DSSI class?"

5. Round 3: Completion of capstone structure of System Engineering and Flipped learning

DSSI Course description

With three rounds of curriculum improvement, the final structure of capstone course of Dynamic System Simulation and Implementation (DSSI) was completed. Table 2 shows the syllabus and Table 3 shows the lecture topics of capstone DSSI course.

Table 2: Syllabus of capstone DSSI course

Week	Classroom		Laboratory	
	Topics	Lectures	Lab	Project
1	Introduction to dynamic systems	1	Lab1: System identification of DC motor	
2	Modeling of DC motor	2		
3		2		
4		3		
5	Introduction of system	4	Lab2: Position and	

6	simulation by MATLAB/SIMULINK	5	speed control of DC motor	
7	PID controller design	6		SCAMPER
8		6		
9	Midterm exam		Lab3: System identification of Rotary inverted pendulum	Creative project: Swing-up control and balance control of Rotary inverted pendulum
10	Modelling of dynamic mechanical systems	7		
11		8		
12		9		
13	Modelling of Rotary inverted pendulum	10		
14		10	Lab4: Control of Rotary inverted pendulum	
15	State-feedback controller design	11		
16		12		
17	Computer-based exam	13		
18	Project oral and presentation:			
Teaching methods	Constructive teaching			
	Flipped learning		Project based learning	

Table 3: Lectures of capstone DSSI course

	Lectures	Course materials
Introduction to dynamic systems	1	1. Introduction to dynamic systems
Control of DC motor	2	2. Modeling of DC Motor
	3	3. Simulation of DC Motor
	4	4. Runge-Kutta Formula for Differential Equations
	5	5. Identification of Dynamic Systems
	6	6. Controller Design of DC Motor
	E1	Project 1. Experiment of DC Motor Control (system implementation)
Control of Rotary Inverted Pendulum	7	7. Lagrangian Equations
	8	8. Modeling of Rotary Inverted Pendulum
	9	9. Model Linearization of Rotary Inverted Pendulum
	10	10. State-Feedback Control of LTI Systems
	E2	Project 2. Experiment of Rotary Inverted Pendulum Control
Creative project	CP	Project 3. Swing-up and balance control of Rotary Inverted Pendulum

In Round 3, flipped classroom/learning was adopted as the major instructional strategy that sought to break the mode of traditional teaching and learning by

delivering online distance education. It rearranges learning activities, such as allowing assignments (traditionally known as homework) to be worked on during class. In a flipped classroom, students view online lectures, participate in online discussions, or carry out study at home and engage in hands-on activities in the classroom with guidance from the instructor and TAs. The idea of "flipped classroom" wasn't new. Video-taped lectures assigned as homework can be traced back to history.
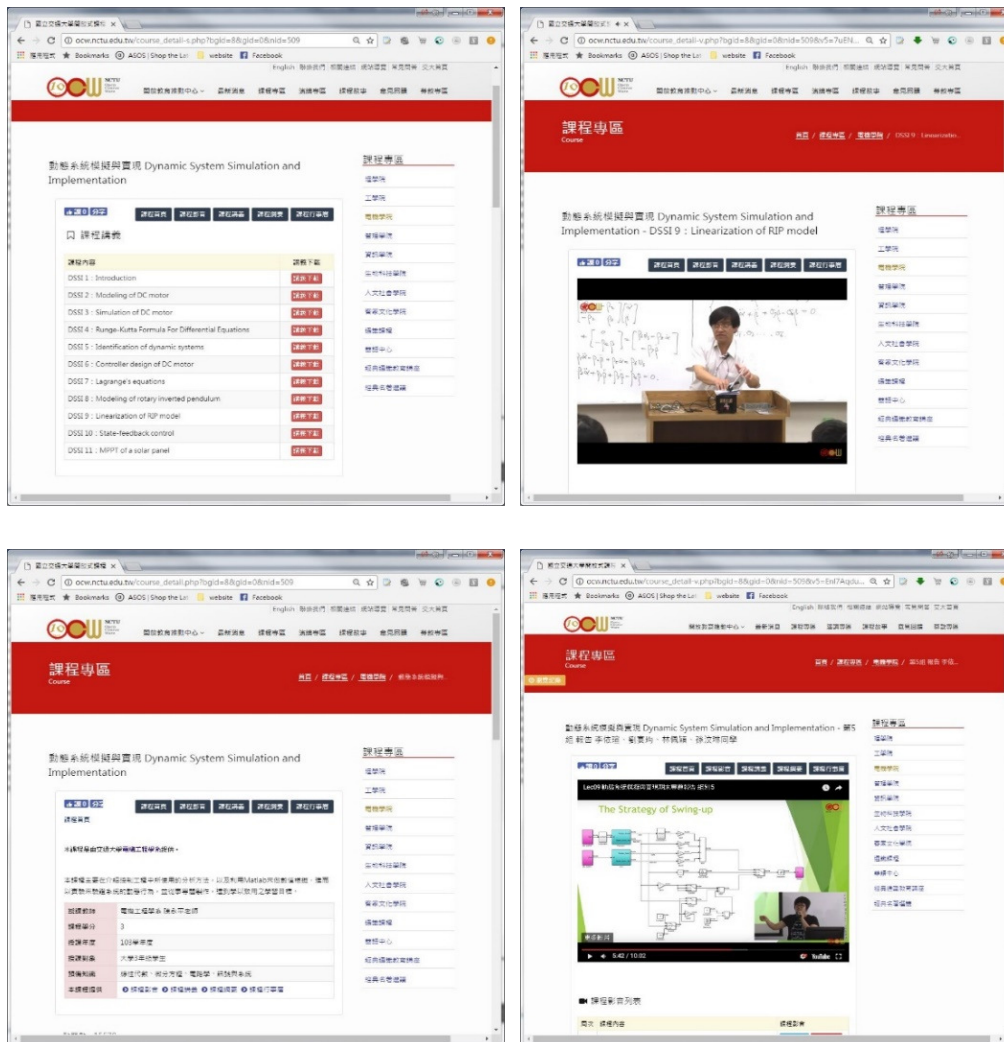

Figure 9: Sample screens of online video-taped lectures for DSSI capstone course

Instructors of DSSI have recorded lectures using OpenCourseWare (OCW) in his university. The video-taped lecture series can be accessed at: (http://ocw.nctu.edu.tw/course_detail.php?bgid=8&gid=0&nid=509&page=2). Some sample screens are demonstrated in Figure 9.

6. Conclusion

Completion of capstone structure of System Engineering

The current study launched a project-oriented capstone course, in the Department of Electrical and Computer Engineering, titled "Dynamic System Simulation and Implementation". The course employed a project-based learning approach, where all lectures, assignments, experimentations and creative projects were held to help students integrate System Engineering fundamental knowledge in Dynamic Control Systems. The whole capstone structure is shown in Table 4. The complete framework of System Engineering Capstone course entails the following: Goal, course structure, Cornerstone/Keystone courses, SE project, SE process, students' Cognitive process, the instructor's instructional strategy, and TAs' training. In sum, the underlying the framework included the interactive dimensions of (1) capstone curriculum structure and its goal, (2) the design characteristics of capstone project, (3) goals about student cognitive development, (4) alternative instructional strategies and (5) the training of teaching assistants (TAs). In addition, (6) the evaluation method and outcomes used to guide self-improvement was also reported.

Table 4: Curriculum redesign Round 3 and the complete framework at the end of the transformation

Capstone course goal	1. Course Goal: "Dynamic Control Systems" is designed as a capstone course. The goal is to offer undergraduate EE students nearing graduation the opportunity to summarize, evaluate, and integrate the core learning experience of System Engineering. 2. Course structure: Integration = Cornerstone + Keystone + Projects to enhance creativity			
Cornerstone and Keystone course base	1. Cornerstone: Physics, Calculus, Programing Language, Engineering Mathematics, Electric Circuit, Electronics, Electromagnetics. 2. Keystone: Signals and Systems, Linear Control Systems			
Capstone projects to integrate experience of System Engineering	1. Base: System identification, speed and position control of DC motor 2. Advance: System identification and balance of rotary inverted pendulum 3. Integration: Swing-up and balance control of rotary inverted pendulum			
Realization process of System Engineering	1. Mathematic modeling	2. Controller design	3. System simulation	4. System experimentation
Target cognitive competencies of students:4C	1. Complex integration	2. Collaborative simulation/ experimentation	3. Communication orally/visually	4. Creative thinking
Instructional strategy	Flipped learning: concept ● Before class(individual) = OCW + assignment(simulation) ● Class(group) = discussion + Quiz		2. Project-based learning: Hands-on ● Group = SCAMPER + simulation/experimentation	
TA training	SE knowledge base, Lecture skill, Assessment skill		Project implementation and assessment	

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