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Introducing the Guided Design Experience in Control Engineering Education*

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The design skills of engineering students can be best achieved using an integrated learning approach which consists of a sequence of structured, guided, and open-ended design experiences throughout the undergraduate curriculum. This paper presents the implementation of the guided design experience through an introductory core course in the area of control engineering at the undergraduate level in the department of electrical engineering at the American University of Sharjah. The objective and implementation mechanism of the delivery of guided design experience is demonstrated through a class project in this course at the junior level. The effectiveness of the teaching methodology is assessed for a group of students by conducting a survey before and after the execution of the course project. The survey results show that the control class project is very successful in enhancing the critical thinking of students, developing students confidence in their design skills, and preparing them for the open ended design experience.

Keywords: engineering education; design skills; control systems; integrated approach

1. Introduction

The initiation of the design experience in the senior year is inadequate to prepare the students for the engineering industry after graduation. Development of design skills requires continuous exposure to design experiences throughout the engineering curriculum. Traditionally, design skills are incorporated within a curriculum in a scattered manner [1, 12], resulting in a limited exposure to design practice [8]. The work done in [1, 2] elaborates freshman year courses while, [3, 5] discuss the development of individual courses in the forthcoming years of engineering education. An effort has been made in [6, 7] to cover more than one course instead of working on a single course to make a better connection between the courses. The problem with all these efforts [1, 7] is that their main focus is not the students' design skills development but the contents of courses. The work presented in [8, 9] attempts to develop the progressive and cooperative design skills while teaching the courses of embedded systems and applied electronics respectively. The capstone project [10, 12] is the ultimate exposure of students to the design experience. However, the incorporation of design skills in a scattered manner at the earlier stages of engineering education results in a limited exposure to the design practice [8] and students are not adequately prepared to take up the open ended design problem and thus don't perform well while executing the capstone project.

Introduction of design skills in an integrated sequence at the junior and senior years [13] has been made to overcome the above mentioned limitations; however, these changes do not provide an overall vision and lack strategy to cover and distribute the required design skills in a comprehensive manner throughout the entire curriculum. Therefore, a strategic integrated learning approach consisting of three stages of design experience has recently been introduced [14]. These stages are: (1) structured design experience, (2) guided design experience, and (3) open-ended design experience. This integrated process allows the development of design skills in engineering students in a homogeneously distributed manner, where students continuously experience design practice and gain design skills at an involvement and complexity level compatible with their study year. The proposed strategy [14] suggests to carefully distribute the design stages when developing the curriculum, such that students gain a solid base in each stage while having a smooth transition from one stage to another. Therefore, some of the courses fundamentally serve one single stage, while others serve as transitional courses from one stage to the other.

In terms of study years, it is suggested that freshman courses should primarily focus on the structured design experience, whereas the sophomore year courses provide either purely structured design experience or a transition from structured to guided design experience. Similarly, junior year courses deliver purely guided design experience, while senior year courses may have the transitional phase from guided to open ended or only open ended design experience. Lastly, capstone courses should be developed to deliver the open ended design experience. The instructors can use these guidelines and check how well various aspects of

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design experience are being covered in different courses making sure that the students achieve the necessary skills by the time they finish their undergraduate studies. A cooperative and progressive design experience has been described in [8] and a progressive project based learning approach to enhance the students' design skills has been presented in [9]. However, the delivery of design experience in the engineering education without an integrated approach will affect the learning abilities of the students and will leave them unprepared for the open ended capstone design projects which represent the major initiation to the real industrial environment. It has been well documented in the literature [8] that senior students usually start to work on their first open ended capstone project without being well prepared for it. The integrated approach [14] enables the educators to overcome this problem and helps them introduce and develop the needed skills by taking students through the stages of structured, guided, and open ended design experience.

This paper puts the first course in control systems in a proper perspective for students' design skills development and presents the delivery of guided design experience during the junior year of studies through a class project in the control systems course. Control engineering is one of the major areas of electrical engineering which plays a pivotal role in the students' design skills development, and requires therefore, a special attention. In the past, most of the work done in this field [6, 7] did not adequately focus on design skills development in a systematic way. Therefore, the work presented in this paper will make a meaningful contribution by giving a direct demonstration of students' design skills development in the area of control engineering and will draw the attention of control engineering academician to benefit from the proposed integrated approach [14]. The guided design experience prepares students very well for the open ended design experience that the students have to exercise during the senior year's capstone projects.

2. The integrated learning approach

This section presents a description of the integrated approach for the development of design skills and other attributes that would ensure that skilled graduates are well prepared for further education as well as for industry. This strategy initially introduces the design process and shows how the design skills are to be developed during the engineering education. The integrated approach is elaborated in [14] in detail. Here the core of the proposed approach is included for the sake of completeness to provide a ready reference for the readers.

2.1 Stage 1: Structured design (SD) experience

The main objective of the structured design experience is to bring students' attention to the concept and practice of engineering design at the early stage of freshman and sophomore level courses. Thus, the delivery of the structured design experience should be limited to motivate and excite students' interest in the design practice of the engineering profession. The main components of the design skills are introduced to the students by taking them through the design steps to accomplish the assigned tasks.

The implementation mechanism of this stage utilizes comprehensive and well defined step-by-step procedures and instructions, which are delivered through carefully developed hands-on tasks and experiments. These tasks span a wide range of topics determined by the course material and include, but are not limited to, the concepts of measurement, calibration, application of knowledge, system characterization, and utilization of design tools.

The main outcome of this stage is the realization of the engineering design practice through hands-on experiments and simulations. The development of teamwork and communication skills are other important outcomes of this stage, thus, all communication modes i.e., written, verbal, and visual communication are exercised through written reports, oral presentations, and visual aids. The detailed implementation of the structured design experience has been demonstrated via two freshmen lab courses in [15].

2.2 Stage 2: Guided design (GD) experience

The main objective of the guided design experience is to get students start exercising the design skills by themselves in contrast to the structured design experience where they were given the complete step by step procedure to accomplish the required tasks and the objective was a mere realization of the design steps and the process.

The implementation mechanism of this stage is realized by carefully guided design activities to perform the specified design objectives. The instructor does provide limited guidance but not the step by step procedure to accomplish the desired tasks. Care must be exercised at this stage, as the course progresses the level of guidance from the instructor should be reduced. This gradual confidence building process should make students more and more independent in accomplishing their design tasks. The complexity of the assignments at this stage is from low to moderate. The design activities are performed in a team environment where each member has to work on his subsystem. These subsystems are finally integrated together thus experiencing the cooperative design experience. The design tools selected at this stage and the next stage (open ended design experience) are the ones that are mostly utilized by industry.

The main outcome of this stage is confidence building and making students more independent while accomplishing the assigned design objectives with as little guidance as possible. Also, cooperative design experience is realized at this stage as well. This stage will prepare students better for the open ended design experience and will improve both the quality and the level of exposure to the engineering design experience.

The main objective of this paper is to demonstrate how the guided design experience is introduced and implemented in the engineering education through a class project in the first linear control systems course.

2.3 Stage 3: Open ended (OE) design experience

This is the third and ultimate level of design experience in the engineering education, which is exercised through the senior and capstone courses. A number of capstone projects are expected to originate from industry exposing students to the real engineering problems. The main objective of this stage is to make students completely independent in taking all the design process decisions by themselves with almost no guidance.

The implementation mechanism of this stage engages students in the open ended learning while working in a cooperative learning environment. The students are to start from the design specifications, think and outline the design steps to execute the complete design, decide on the tools that are needed, distribute the design assignments among the team, and finally integrate the overall system and test it for the design validation. The guidance from instructor is very much limited and students learn to rely on themselves. In this implementation process the instructor becomes just a team member not the team leader any more. The author at this stage has many times dared to tell students 'well this is just my opinion, or may be one way or my way of solving this problem. I am sure that you can come up with another better solution'. Once the students reach this stage, the objectives of teaching design skills to the engineering students are achieved. The main outcomes of this stage are: students' resistance fades, their confidence to rely on themselves is built, and lifelong learning skills are honed.

3. Case study: Implementation of guided design experience in control systems

This class project demonstrates how the guided design experience is introduced in the area of control engineering. The same methodology can be applied to other courses that are targeted for introducing such design experience at the junior year level. Through this project students are to develop a magnetic coil levitation system which illustrates the linear control system design process. In their first course with a semester-long project, students work in groups of three. The class project actually involves the development of a working prototype requiring the background knowledge of a broad range of concepts in electronics and circuits analysis. The class project demonstrates key issues by focusing on the linear systems concepts from modeling to analysis and design. Some performance measures such as response time, overshoot, damping and stability are also addressed. Students can learn a great deal from a relatively simple example by focusing on one subsystem of the overall complex nonlinear system. This project is carefully designed such that it starts with a guided design methodology by providing students information about the different stages of the overall system and then gradually leads students through the guided design experience at each stage.

The proposed approach helps students to form a good basis for the design experience that they are expected to gain in more advanced control systems courses [2, 4]. The advanced control system courses should focus on either a transition from guided to open ended or open ended design experience only.

The magnetic levitation system consists of an electromagnet, a steel ball, sensors, a power amplifier, and a controller. The conceptual schematic diagram is shown in Fig. 1. The electromagnet provides the force necessary to lift the ball when supplied with the required current to generate the needed force and counteract gravity. When exposed to this problem, students can easily see that the magnetic field strength and therefore, the force strength depends directly on the amount of current flowing through the coil; i.e. maintaining the ball suspended in air requires the judicial control of the force and hence current. This gives a good motivation to introduce students to the concept of feedback control and the need for sensors.

The search for needed sensors such as optical sensors to measure the ball position, or a current sensor to measure the electromagnetic force is a good exercise to motivate the development of closed loop control system architecture. The relationship between force and current is nonlinear, therefore students are advised to first focus on the relationship between voltage and current supplied to the coil and how current can be controlled by dealing only with a linear system.

The objective is to build student's confidence in design through some guidance and to help them

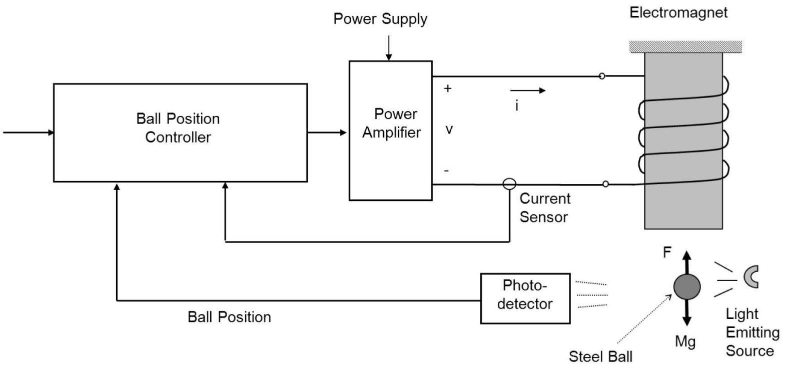

Fig. 1. Magnetic levitation system.

acquire the needed experience to tackle more complex projects in future courses which are more of open ended nature. Therefore, two levels of guidance are availed to the students. The first level is to split the class project into four different stages which follow the general process of any control system design. These stages include building a prototype system, designing the hardware and interface circuitry, system modeling and identification, and control system design. An assignment is next formulated for each stage. Therefore, students should understand that they have to achieve the specific deliverables for each assignment before being able to move to the next stage. The details of the project assignments are listed in Appendix A.

The second level of guidance is the amount of information given to students at each stage to help them achieve the needed objectives of each assignment. As the students move from one assignment to the next, the complexity of the tasks needed to fulfill the project requirements increases, while the guidance is reduced. This is needed to prepare students for more autonomy and critical thinking.

In the first part of the project, for example, students are asked to build an electromagnet as a prototype. Only general information on the expected size and shape is given. Students have to search the internet and figure out material needed for the coil, the wire size, the number of turns, and the impact of these parameters on the effectiveness of the coil in providing the required force to levitate a steel ball. This exercise in itself is a good introduction for students' confidence building and lifelong learning.

The guidance given in the second assignment mainly consists of student introduction to operational amplifiers and power amplifiers for hardware interfacing. It is expected that students have covered this topic in the electronics course which is planned to be taken in the semester preceding the control system course. Students are then required to select the needed resistors to get the required amplification gain. The use of a shunt resistance for current sensing is also challenging since they have to search and pick the correct value with the required power rating.

In the third assignment, students are asked to design the experiments needed to identify the system parameters such as the coil inductance and resistance which are needed to build the system transfer function. The only guidance given to students at this stage is that they are advised to use the concepts learned in class related to first order systems, transient response characteristics, and block diagram representation.

The goal of the fourth assignment is to design and study the performances of an analog controller for the magnetic levitation system. A typical circuit, shown in Fig. A4, is given to students as an example for controller implementation using analog operational amplifiers. The students are to derive the controller transfer function described by Eq. 1.

$$K(s) = K_p + \frac{K_i}{s} = \frac{R_4}{R_3}\left(\frac{R_2}{R_1} + \frac{1}{R_1 C s}\right) \quad (1)$$

Students are to use MATLAB to design the controller gains based on the Root Locus design method. They have to pick the correct values for the resistors and the capacitor to get the suitable PI controller gains for implementation.

At the end, students will demonstrate the system functionality and check the design specifications through simulation and through experiments. Figs. 2–4 show the students work and the results obtained. Fig. 4 shows the performance of the current control system obtained by one of the students' group. Students successfully demonstrated the achievement of the desired specifications in term of current overshoot, steady state error, and settling time.

It is evident from different assignments that the amount of guidance given to students is adequate to enable them to have a good overall view of the

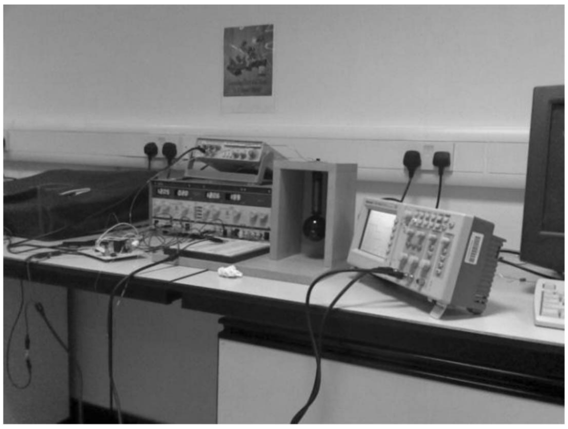

Fig. 2. Experimental setup built by students showing the magnetic levitation system, control board and instrumentation equipment.

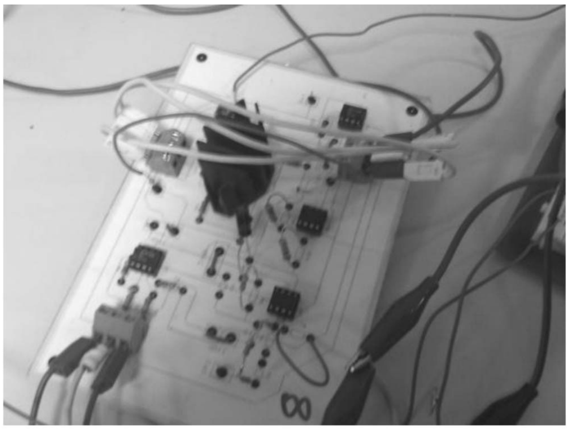

Fig. 3. Prototyping control board including the power amplifier and analog PI controller.

project while having some autonomy in performing the details of each assignment.

4. Student assessment

Thirty students were enrolled in the Control Systems course (ELE 353) during the fall semester offering. At the beginning of the semester, the students were first polled to check their skills levels in engineering design. Twenty six students answered the first survey. At the end of the class project students were once again asked to assess their design abilities and the impact of the control project on their design skills. Twenty nine students answered the second survey. Different scales were used to assess the students' responses such as the scale of 'Significantly Improved' to 'Not Improved' and the scale of 'Extremely valuable' to 'Not valuable'.

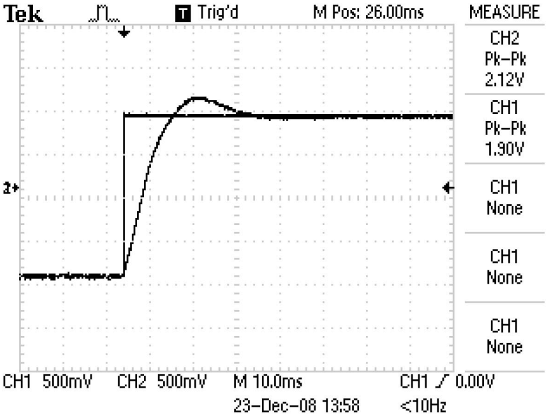

Fig. 4. Experimental results showing the performance of the current control system. Current reference = ±0.95A, overshoot = 11.58%, settling time = 26 ms.

Table 1 shows a major improvement in the students' confidence level after going through the proposed design experience. Most of the students after taking this course have shifted from no or little level of confidence to moderately confident level. Only one student has shown very little confidence and no student has shown lack of confidence. We can notice also that there is no major shift to very confident level which is as expected since the focus of the design methodology is the delivery of guided design experience. Students are expected to become very confident in the following elective courses where the open ended design experience is delivered.

Table 2 and 3 show the students' assessment of

Table 1. How confident you are to design an engineering project almost independently?

	Very confident		Moderately confident		Little confident		Not confident	
Before taking the class project	1	3.8%	15	57.7%	8	30.8%	2	7.7%
After completing the class project	3	10.3%	25	86.2%	1	3.5%	0	0

Table 2. Indicate your abilities in the design process (Survey before taking this course)

Ability	Very good		Good		Average		Below average	
Develop specifications and problem statements	1	3.8%	19	73.1%	6	23.1%		
Divide tasks and work in a team	9	34.6%	14	53.9%	2	7.7%	1	3.8%
Use hardware and software tools to design and analyze a system	2	7.7%	8	30.8%	14	53.8%	2	7.7%
Find alternative solutions for a problem and select the optimum solution	1	3.8%	14	53.9%	8	30.8%	3	11.5%

Table 3. Indicate your abilities in the design process (Survey upon completion of the course)

Ability	Significantly Improved		Moderately Improved		Not Improved	
Develop specifications and problem statements	15	51.7%	14	48.3%		
Divide tasks and work in a team	17	58.6%	10	34.5%	2	6.9%
Use hardware and software tools to design and analyze a system	14	48.3%	13	44.8%	2	6.9%
Find alternative solutions for a problem and select the optimum solution	10	34.5%	17	58.6%	2	6.9%

Table 4. Rate the value of this control class project from the following perspectives

Area	Extremely Valuable		Moderately Valuable		Not Valuable	
Preparation for and completion of senior design project	15	51.7%	12	41.4%	2	6.9%
Appreciation of the complexity of real problems	17	58.6%	11	37.9%	1	3.5%
Confidence in building and analyzing real engineering problems	16	55.2%	12	41.4%	1	1.4%
Education as an electrical engineer	22	75.9%	7	24.1%		

some of the abilities required in the design process before and after taking this class project. About 50% of the students indicate a significant improvement and 40% indicate a moderate improvement in the design attributes of specifications development, teaming, and use of hardware and software tools for designing and analyzing the system. This represents quite a good achievement which is in line with this stage of guided design experience within the proposed integrated approach.

The design attribute of finding alternative solutions and choosing an optimum solution show a relatively lower improvement, i.e. about 35% of students indicated significant improvement while about 60% felt moderate improvement. This is an expected finding because the design attribute of finding alternative solutions and choosing an optimum one is an objective of the open ended design experience for which students are being prepared for at this stage.

Finally, analysis of the students' survey in Table 4 indicates that 50–60% of students rate this design experience extremely valuable for the completion of their capstone project, appreciation of the complexity of real life problem, and for building confidence in real engineering problem. Almost 40% ranked the design experience as moderately valuable for the same attributes. However, 75% of students felt this project is extremely valuable for their education as electrical engineers. This shows the need and verifies the success of the proposed integrated design strategy in which student are taken through the confidence building in a systematic way while going through various stages of the design experience.

5. Conclusion

This paper focuses on the guided design experience which is one of the three stages of design skills development i.e. structured design experience, guided design experience and open ended design experience. The work presented in this paper demonstrates how students are trained to be independent while working on a project in the area of control engineering. The paper also described how the guided design experience is useful for developing confidence in the students design skills and preparing them for the open ended design experience which they are to exercise in the elective courses and the capstone project in the final year of study.

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Appendix A

A1. Class project: Modeling and control of a magnetic ball levitation system

Objectives:

- Design and implementation of a closed loop current controller for a magnetic ball levitation system.
- Study the performance of analog PI controllers using operational amplifiers.

Design Specifications:

The closed loop system with the analog PI controller should meet the following design specifications.

- Zero steady state error for a step input.
- Maximum overshoot less than 10%.
- Settling time less than 0.1 sec.

A2. Assignment 1

This first part of the project involves the design of the electromagnet and the support structure as illustrated in Fig. 1 (section 3 of the paper).

A magnetic coil is to be designed to levitate a magnetic ball when supplied with a current control system. The coil will be wound on a steel rod or a ferromagnetic material. The number of turns can be made on multi layers to maximize the value of the inductance. The structure holding the electromagnet can be made by wooden legs or cut in a wooden box. Keep the dimensions of the whole system within 20 cm height, 15 cm width, and 15 cm depth.

Calculate the inductance of the designed coil and measure its resistance. Students may search the internet for similar design projects.

A3. Assignment 2

This second part of the project involves the design of a power amplifier, a current sensor and testing of operational amplifiers on the controller board. Fig. A2 shows the circuit diagram of the electromagnet coil supplied through a power amplifier. The current sensor is designed to give a voltage reading v_m (Volts/Amp).

Students should select the required components and test the circuit using a prototype board. Students may also apply DC and AC analysis to measure the resistance and inductance of the coil.

Explain in your report the design procedure details and tabulate the results.

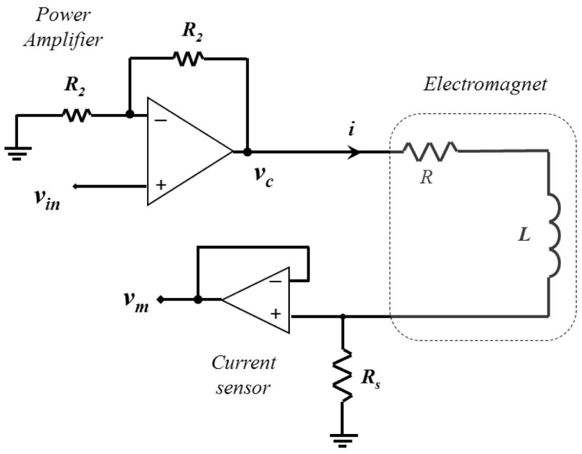

Fig. A2. Electromagnet system.

A4. Assignment 3

This part of the project deals with the transient response analysis and the parameters identification of the electromagnet. The magnetic coil should be supplied with a square wave voltage and the step response of the system is to be recorded. The time constant and the inductance of the coil will be determined from the current waveform. Measure the response of the system for a square wave input voltage and display the transient and steady state value of the current waveform.

Finally, identify the system parameters from the measured step response of the system.

A5. Assignment 4

This assignment involves the current control system design for the magnetic levitation system. The block diagram of the closed loop system is shown in Fig. A3 and the implementation of a PI controller using operational amplifiers is shown in Fig. A4. The students are to pick the correct values for the resistors and capacitor to get the suitable PI controller gains.

Students will derive the controller transfer function and will design the controller gains based on the Root Locus method. After the design is made, students will demonstrate the functionality of the system and check the design specifications through simulation and experiments.

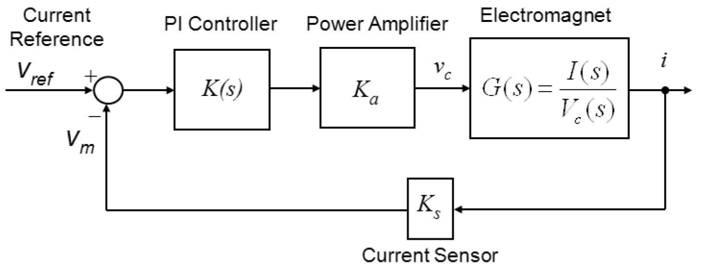

Fig. A3. Closed loop current control system.

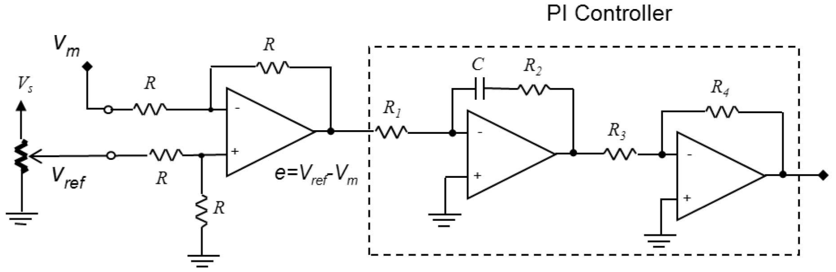

Fig. A4. Analog implementation of the PI controller.

Demo:

Each group should arrange a meeting with the instructor in the Control Lab to show a demo of the working project.

Rached Dhaouadi received his Ph.D. in Electrical Engineering from the University of Minnesota in 1990. From 1990 to 1994 he worked as a Visiting Researcher with the Hitachi Research Laboratory, Japan, in the design and development of motor drive systems for rolling mills. From 1994 to 2000 he was with the Polytechnic School of Tunisia, University of Tunis. He also held Visiting Scholar positions at Trondheim Institute of Technology, Norway, and at Rice University, USA. He is currently a Professor of Electrical Engineering at the American University of Sharjah, UAE. His research interests are in the areas of motor drives, and intelligent motion control systems, with applications to rolling mill drives and mobile robots. Dr. Dhaouadi is a senior member of the IEEE and a member of the Industrial Electronics Society.

Yousef Al-Assaf completed his BS degree from Sussex University in the UK in 1984 and his PhD from Oxford University in 1988. His research focuses on using soft computing to model and control various industrial and medical systems including materials modeling and classification, prostheses control, industrial quality control and optimization. His industrial experiences are in the areas industrial instrumentation and control (PLC, SCADA, DCS, microprocessor and PC-based controllers). He designed and developed various automated control systems for various industries including fertilizer, textile and sheet-cutting establishments. Dr. Al-Assaf has given various in-house and general workshops in PLC and computer industrial process control for practicing engineers. Dr. Al-Assaf was a founding member and chair of the industrial engineering department at University of Jordan and worked as the outreach manager at University of Jordan. He was a founding member of the electrical engineering and computer engineering programs at the American University of Sharjah (AUS). He is currently the Dean of the College of Engineering at AUS. Dr. Al-Assaf has various contributions in the development initiatives and strategies of engineering education and outreach. He was the regional manager for one of the European Commission projects with the Mediterranean region (Euro-Mediterranean partnership). The aim of the project was to develop 'a generic interactive package for systems engineering courses and applications.'

Habib-ur Rehman received his B.Sc. degree in electrical engineering from the University of Engineering and Technology Lahore, Pakistan, in 1990. He received M.S. and Ph.D. degrees, both in electrical engineering, from the Ohio State University, Columbus, Ohio, in 1995 and 2001 respectively. He has a wide experience in the area of power electronics and motor drives in industry and academia. From July 1998 to December 1999, he worked as a design engineer in the Ecostar Electric Drives and Ford Research Laboratory, where he was a member of the Electric, Hybrid, and Fuel Cell vehicles development programs. From 2001 to 2006 he worked in the department of electrical engineering at the United Arab Emirates (UAE) University, Al-Ain, U.A.E., as an Assistant Professor. In 2006, he joined the department of electrical engineering at the American University of Sharjah where he is currently working as an Associate Professor. Dr. Rehman is the recipient of Best Teacher Award from the College of Engineering, UAE University for the academic year 2002/2003. His primary research interests are in the areas of microprocessor/digital signal processor based adjustable-speed drives, power electronics, alternative energy vehicles and renewable energy systems. Currently, he is also investigating effective delivery of design skills in engineering education specifically in the field of electrical engineering.