REMOTE LABS AND GAME-BASED LEARNING FOR PROCESS CONTROL

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Remote laboratories appeared in higher education almost two decades ago. Since then, the infrastructure for building remote laboratories has come a long way and stand-alone and commercial tools such as MATLAB and LabVIEW are easily integrated with off-the-shelf learning management systems (LMS) to build comprehensive remote-laboratory learning environments.[1-3] Shared social networking platforms such as Facebook have a potential to take remote laboratories to yet another level. A recent survey shows that a significant amount of research in remote laboratories has focused on comparing remote laboratories against hands-on and virtual laboratories.[4] For example, Tzafestas et al.[5] show a comparison between students trained in a traditional way on robots as opposed to using a virtual laboratory or a remote laboratory, and observed no statistical differences in performance due to the modality of delivery. Each modality tends to emphasize different educational objectives.[4] In addition to conceptual understanding, hands-on laboratories have historically emphasized design, professional, and social skills. Virtual laboratories, on the other hand, have focused primarily on professional and conceptual skills while remote laboratories have mostly addressed professional skills and conceptual understanding.

In some sense, prior research on remote laboratories has centered on the amplification and attenuation effects of introducing the remote laboratory technology.[6] The amplification effect is represented by positive impacts of this technology such as round-the-clock remote access. For example, surveys in specific fields such as RF have been conducted recently to identify scarce laboratory equipment most suited for such amplification.[7] The attenuation effects, on the other hand, represent negative impacts of introducing this technology. For example, the slow response time is one such attenuation effect mediated by using high-speed Internet to provide real-time video from a remote laboratory.[8] The predominance of these two factors is also reflected in assessments models. For example, Nickerson et al.[9] present a detailed model for comparing hands-on laboratories, remote laboratories, and simulated laboratories. This model contains criteria such as purpose of the experiment, the experimental and the coordination interface, and laboratory frame and technology. The only pedagogically related criterion in this model, however, is the individual differences between learners. This paper takes the view that remote laboratories are more than simple surrogates for real or virtual laboratories and can be used to explore forward-looking learning designs such as game-based learning. The rest of the paper is organized as follows. First, a brief introduction to game-based and mobile learning (m-learning) is presented. This is followed by a description of a learning problem in chemical engineering. A game-based remote laboratory to address this learning problem is presented next. This is followed by a pilot study to validate the learning design.

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GAME-BASED LEARNING

What constitutes a game has many definitions. For example, Prensky[10] defines game as organized play. After analyzing many definitions of a game, Salen and Zimmerman[11] define a game to be "a system in which players engage in artificial conflict, defined by rules, that results in a quantifiable outcome," (pp. 80). We extend this definition to define instructional games to be a system where learners engage in artificial conflict, defined by rules, that results in quantifiable outcome and enhances learning.

While Aldrich[12] and Gibson et al.[13] have outlined various principles of digital game-based learning, recent studies[14] have shown that game-based learning actually improved student motivation as well as performance. There is also emerging evidence[15] that when using game-based learning as opposed to self-learning, the students not only thought that the game was the preferred method and was more enjoyable, but also they showed willingness to continue to use this method of learning. Tuzun et al.[16] show that not only did children do better while using game-based learning, but playing games also developed them as independent learners. Game-based learning has also been used successfully in higher education. For example, Ebner and Holzinger[17] show that performance of students using game-based learning was better than the control group in the context of civil engineering.

M-learning has also received much attention recently.[18,19] For example, Akkerman et al.[20] show that students learned history by walking around with their mobile phones and by sharing information about what they saw in the city. There are also efforts to move existing gaming platforms to m-learning platforms[21] Mobile game-based learning has also been used in the context of providing mass learning in developing countries.[22] M-learning, to extend a traditional LMS, also received a positive response from college students.[23] Podcasting was also found to be more effective for revision of lectures than notes or other conventional means.[24] M-learning has also been shown to significantly increase environmental awareness.[25] A framework for designing m-learning games has been proposed.[26] Specific criteria for assessing the quality of learning games have also been proposed.[27] Issues addressing the quality of m-learning are also outlined in Gafni.[28]

Alternative pedagogical approaches including using competition games have been recently used to teach robotics in remote laboratories.[29] Using a gaming engine as an interface to a remote laboratory in a conventional pedagogical context has also been explored.[30] Such studies are more an exception than a rule, however. The relative absence of game-

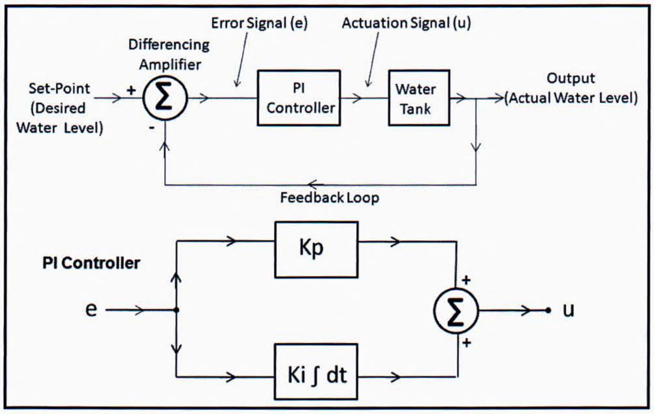

Figure 1. Block diagram for PI controller for a water tank.

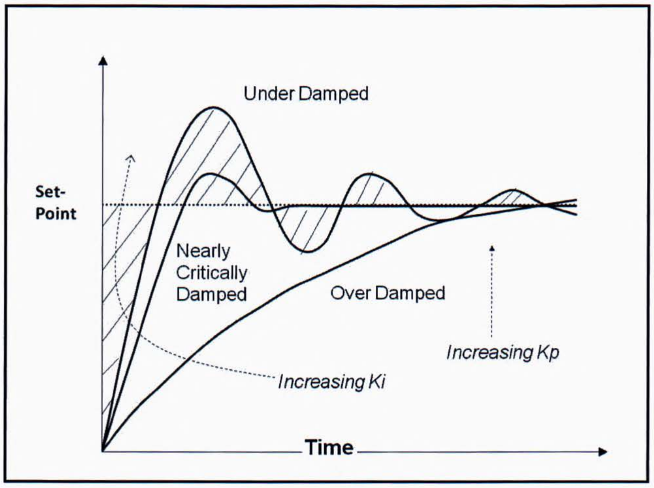

Figure 2. General effect of K_p and K_i on the setpoint.

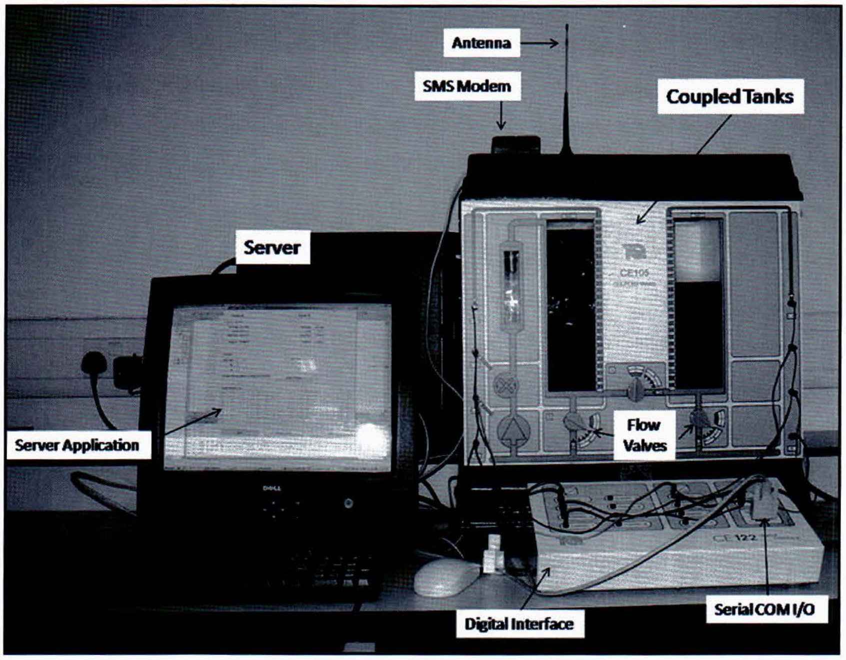

Figure 3. Physical setup for the remote lab game.

based learning in remote laboratories can be attributed to the fact that infrastructure is a pre-requisite for experimentation with novel pedagogical paradigms like game-based learning. Since such infrastructure is now widely available or easy to build, another explanation can perhaps be that most teachers and researchers are digital immigrants who did not grow up with the Internet and gaming technologies and consequently hold a completely different viewpoint, while most students are digital natives of the gaming generation.[10]

THE LEARNING PROBLEM

The learning problem being addressed in this paper is how to teach proportional integral (PI) controllers in an undergraduate chemical engineering course on control systems. Using remote laboratories to teach control applications is not new.[31,32] The water tank equipment has been typically used to demonstrate a PI controller. This equipment consists of a tank of water that is connected to a water reservoir. There is a constant drainage of water from the tank into the reservoir. The control problem is to maintain a constant water level in the tank by continuously pumping water back into the tank from the same reservoir. This is done by providing a square-wave input to a controller that sends a voltage signal to an electric pump to maintain a particular level of water. Figure 1 shows a PI controller for the water tank equipment. Setpoint represents a desired water level in the water tank. Actuator signal is the voltage applied to the water pump. The output process variable is the actual water level. Difference between the desired and actual water level is represented by an error signal. The error signal is fed into the PI controller to continuously calculate the voltage being applied to the pump. A PI controller does so by multiplying the error with a constant proportional constant (K_p) and with an integral term represented by the sum of error accumulated so far multiplied with an integral constant (K_I). The control loop in Figure 1 can be described by a transfer function, and a time-domain solution can be derived as shown in Eq. (1).

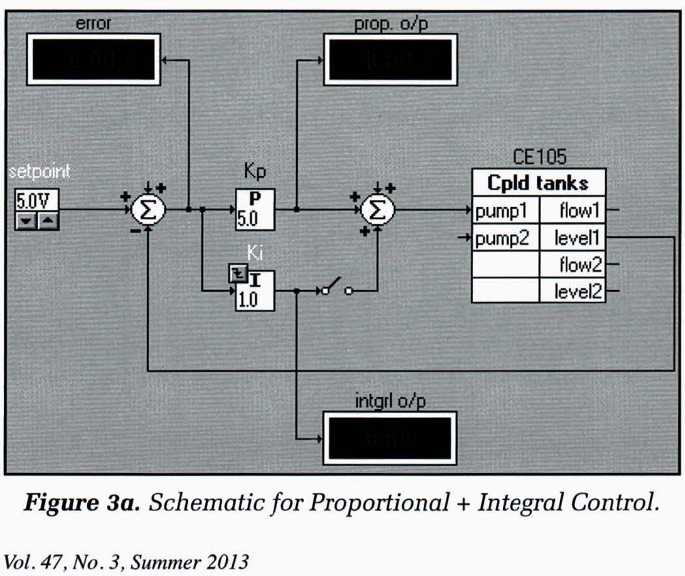

***Figure 3a.** Schematic for Proportional + Integral Control.*

$$h'(t) = \frac{K_3}{\tau_3\sqrt{1-\zeta_3^2}} e^{\frac{-\zeta_3 t}{\tau_3}} \sin\left[\sqrt{1-\zeta_3^2}\,\frac{t}{\tau_3}\right] * \left[\frac{C}{2} - C\,S(t-t_w) + C\,S(t-2t_w) - CS(T-3t_w) + \cdots\right] \quad (1)$$

C and t_w are the height and width of the input square wave, respectively. Also,

$$K_3 = \frac{K_I}{K_p K_I} \quad (2)$$

$$\zeta_3 = \frac{1}{2}\left(\frac{1+K_p K}{K_p K}\right)\sqrt{\frac{K_I}{\tau}} \quad (3)$$

$$\tau_3 = \sqrt{\frac{K_I \tau}{K K_p}} \quad (4)$$

where K_p is the controller gain and K_I is the integral or reset time. K and K_I are constants that include the process gain, the gain on the valve, and the gain on the measurement sensor. The values of K_p and K_I determine an appropriate behavior for the closed-loop system. As Figure 2 shows, an ideal behavior for the water level is represented by the near critically damped curve where the water level oscillates initially but settles down to the setpoint quickly. An under-damped behavior means that the water level will fluctuate around the desired level and take a long time to settle down. Finally, as Figure 2 shows, when the system is over-damped, it takes a long time to reach the desired water level. The area under each curve on both sides of the setpoint represents the total accumulated error. A smaller error typically corresponds to a better controller.

THE REMOTE LABORATORY GAME

A key consideration in the design of any control system is to quickly bring the system to the desired setpoint and to maintain it there. This remote laboratory game has two learning goals or objectives. The first goal is to learn how to throw a system into oscillations and the second goal is to stabilize or tune the system and bring it back to the setpoint.

Architecture

Figure 3 shows the physical setup for the remote laboratory game and Figure 3a shows the schematic of our process. The water tank equipment (CE105 from QT- Quasar Technologies, Oslo, Norway) consists of two identical water tanks with the corresponding water pumps and a reservoir. Each tank has a flow valve that can adjust the amount of water draining into the reservoir. The pump for each tank is controlled through a voltage provided through the digital interface. The digital interface is connected to a personal computer (PC) through a serial port. Figure 4 (next page) shows the software architecture. A java program (1180 lines of Java code) was written to communicate with the microcontroller in the digital interface

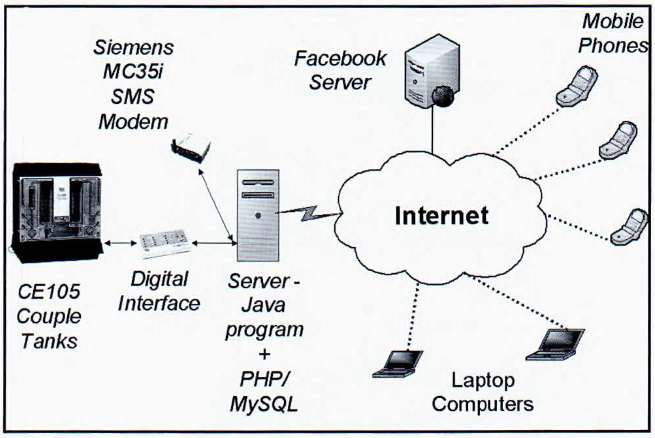

Figure 4. *Software architecture for the remote lab game.*

Figure 5. *The Mobile User Interface.*

through the serial port and to implement the PI-controller on the PC. In addition, the same Java program also communicates with an Apache server-based PHP/MySQL application (1487 lines of PHP code) that implements a game interface by communicating with the popular Facebook social networking site through the Internet. The Java application is also able to send SMS messages through a Siemens MC-35 SMS modem connected to another serial port on the PC. The Java server consists of various classes providing interfaces to each of the hardware components. For example, *CTHardwareInterface* class implements the binary communication protocol between the PC and the digital controller running over the serial port. Similarly, the *HTTPInterface* class is responsible for processing new inputs from Facebook that come through the Apache HTTP server and forwarding these control parameters to the equipment using an instance of the *CTHardwareInterface* class. The *HTTPInterface* class is also responsible for retrieving the current values of various tank parameters (such as the water level) using the *CTHardwareInterface* class and updating these in the MySQL database. The *SMSSender* class communicates with a Siemens MC35i SMS modem to send alerts to the game players. A *ControlPanel* class provides a user-friendly GUI for the server and allows a user to start and stop the server and to display the current readings of the equipment for diagnostic purposes. Instances of each class run concurrently using Java's native multi-threading capabilities. For example, instances of *SMSSender* and *HTTPInterface* class each run in their own thread. Since the architecture uses Apache server's native HTTP concurrency-handling mechanism in addition to Java threads, the number of concurrent players at one point is limited only by the memory and processing limitations of the Apache server and the Java virtual machine. The MySQL database records the complete history of all the changes made by each team along with time stamps.

A learner who wishes to play the remote laboratory game can access the game by logging into Facebook. It is possible to create a new game tied to a particular water tank or to join an existing game. Two roles are provided to a player. A player can either join as an invader or as a defender. The objective of a defender is to change the values of K_I and K_p to bring the water level in the tank to a particular setpoint. An invader, on the other hand, tries to destabilize the system by throwing the system into oscillations. The game continues until the person who created the game decides to stop it.

Typically, two teams play the game. One team is charged with defending one tank and attacking the other. Another team does the converse; attacking the tank being defended by the first team, and defending the tank being attacked by the first team. Each player is allocated a fixed number of changes to either of the two parameters (K_I and K_p) after which they are not able to make any changes until the end of the game. Within these limitations, each player is allowed to make changes at any time. This means that players can request changes to the parameters of any tank in a concurrent fashion; the requested changes are queued and are actually applied to the system in a first-come-first-served fashion. Each player can view the behavior of the system the player is attacking or defending in the form of a visual display. In addition, each player sees the total error the player has accumulated on a particular system indicating whether the player is winning or losing the game.

The computer connected to the water-column instrument runs a customized Java-based web-server (using server sockets) that allows the Facebook web application to connect as a socket client. This server uses Java's native multi-threading and synchronizing mechanism to ensure that only one client has access to one water column at a time. A single thread is spawned for each socket connection from the Facebook application, and the request to make changes to each water column is queued on the semaphore being used to access each water column. The change request is automatically processed once the water column is released by another client's request (if any).

Each player can access the game using his or her mobile phone or through a normal browser on the Internet. The user interface (UI) for the game is specifically designed using the Facebook mobile interface to accommodate small mobile devices. The UI has been deliberately kept simple and functional. For example, as Figure 5 shows, in addition to showing that the team is supposed to invade Tank #1 as opposed to defending it, the UI also details the desired setpoint, the number of changes allowed, a graphical representation of how the water level has changed over time and the total system error accumulated so far. Figure 5 shows how another team can use the simple UI to change the K_p and the K_I of a tank they are defending or invading; they are only allowed to change one parameter at a time. A team member can quickly scroll up and down to view the same information about each tank the team is either attacking or defending in a consistent manner.

If the user leaves the game and significant changes appear in the behavior of either tank, they receive an SMS warning that a change has occurred. One important aspect of the system is its ability to capture and show the actions of any player in real time. Such information can also be used in the post-analysis of any game to pinpoint conceptual gaps of the students.

Finally, it should be noted that some parameter changes can take a long time to manifest in the behavior of the system. This is part of learning how a PI controller may behave in the real world. Consequently, the game is designed to be played over a few hours. A limited number of changes force the players to be deliberate about their choices, however.

Game rule design

The main objective of the game is to teach chemical engineering seniors the principles of proportional integral control including the objective of feedback, the basic equations of proportional and integral controllers, the key concepts behind both proportional and integral control, the general purpose behind the two controllers, how K_p and K_I respond to a process disturbance, and in addition the disadvantages of proportional and integral control.

The game rules and regulations were:

1) *The period of the contest was 3 hours.*
2) *Each team consisted of 2 members.*
3) *12 students constituted the "control" group.*
4) *12 students constituted the "gaming" group.*
5) *The "control" group consisted of the students who did not play the game but ran a simple level-control experiment with one tank. The "control" group was then asked to take the quiz before and after they ran their experiment.*
6) *The "gaming" group was divided into 6 teams (two members in each group). The teams were randomly selected and named (Team A, Team B, Team C, Team D, Team E, and Team F).*
7) *The teams were randomized to see who played who.*
8) *Each team member needed a mobile phone with SMS capability.*
9) *The objective of the game was to minimize the Standard Square of Error (SSE) between the setpoint and the control variable over a 3-hour period.*
10) *The offensive and defensive teams had different objectives. The offensive teams were trying to maximize the SSE in their opponents' tank. The defensive teams were trying to minimize the SSE for their own tanks.*
11) *The teams could control the level by changing K_p or K_I.*
12) *Each team could change K_p or K_I 12 times in the 3-hour period (6 changes to fix their tank and 6 changes to disturb the other team's tank).*
13) *The 12 changes allowed the students to change either K_I or K_p.*
14) *The minimum and maximum values for K_p were 1 and 10, respectively.*
15) *The minimum and maximum values for K_I were 0 and 1.0, respectively.*
16) *The setpoint change was a square wave input.*

Typically any game contains three levels of rules.[11] Operational rules are rules that come with a game as a set of instructions. Constitutive rules define the underlying formal structure below the surface of a game. These structures can be mathematical or logical. Finally, implicit rules are unwritten rules of the game and are concerned with etiquette and good sportsmanship. These rules can change from game to game. For example, a child playing chess may be allowed to take back a move while an adult might not. Table 1 shows the three types of rules for this game.

TABLE 1
Three Levels of Game Rules

Nature of Rules	Rules
Operational Rules	• Each team acts as an invader for one tank and a defender for another. • Each member of the team gets a fixed number of tries at changing the parameters of a tank as a defender or an invader. • Only one parameter can be changed at a time. • The team whose total error for the tank they are invading is more than the one they are defending wins. • The game ends in fixed amount of time.
Constitutive Rules	These rules are governed by the transfer function of a PI system which determines the error that will be accumulated.
Implicit Rules	The players will not abandon the game; the players will not cheat or collaborate; etc.

TABLE 2
Effectiveness of Game Design

Criteria	Comment
Challenge: There should be multiple ways to win the game, vary the difficulty of the game, sufficient randomness, and constant feedback about performance.	There are multiple ways to win the game by varying K_p and K_I differently. Constant feedback in the form of the total accumulated error and its profile is provided.
Curiosity: The activity should offer sensory stimulation and novelty to stay in the game.	Since the competing team is constantly reacting, there is enough novelty and the error curve provides sensory stimulation.
Control: The player should feel control over the activity and witness the effects of making choices.	This is clearly provided when every change to K_p or K_I results in an immediately different response from the system.
Fantasy: The player should feel involved in the game.	Although the game does not have a "surface story," since there is a real chemical process that needs attention, the players should feel involved.
Interpersonal Motivation: The players meet and play with others and earn respect among peers for performance.	This is a team-based game and in addition pits students' knowledge of control systems against each other.

Effectiveness

Malone and Lepper[34] define five criteria for evaluating the effectiveness of a game. Table 2 shows how each of these criteria is incorporated in the game design. For example, the curiosity criterion is satisfied in two ways. First, the team is left to wonder which parameter the opposite team changed to explain the current behavior. Secondly, the team is curious about what impact changing a particular parameter will have on the system. In either case, the response is novel because it depends on the current as well as previous states of the system. Similarly, Dondi and Moretti[27] define four classes of criteria to evaluate a learning game. Pedagogical and context criteria include target groups, learning objectives, context of usage, didactic strategy, communication and media, and evaluation activities. Each of these criteria has been considered in designing the game. For example, the target groups have been clearly identified as the chemical engineering students taking the control course. In addition, the two learning objectives have been formally specified. The instructions for playing the game are clear and the game is clearly related to the working context because both system tuning and trying to determine the causes of a system destabilization are important professional activities for control engineers. The didactic strategy has clearly defined roles for attackers and defenders; the rules are clear and there is a clear coherence between the rules and the consequences of actions that a learner makes. The user interface of the game has been kept minimal and simple and leads to a good quality of interaction between the user and the game. The evaluation is inherently built into the game in term of the accumulated error. In other words, if a student can minimize the error, this is a direct measure of their understanding of how to tune the system. Content criteria include properties of content such as obsolescence and balance for the target group. In this game, content only consists of game instructions and as such does not play a major role. Technical criteria include credits, conformance to standards, and technical quality issues. The game is robust because it has been tested for many hours without any errors. In addition, it conforms to the Internet standards which mean that any standard browser on a mobile phone or a laptop can be used to play the game. The user interface is minimal and functional and the images of the graph are clear even on small mobile screens. Finally, for the information-produced category, the game uses Facebook as the underlying platform, and all passwords and user information are safely maintained through Facebook. In addition, the game also saves all the activities including each action of each player as a history. These reports can easily be printed by the instructor as desired.

Game design and outcome criteria

It is also instructive to evaluate game design from a preparation for lifelong learning perspective. The ABET organization provides one set of criteria that graduating chemical engineering students must meet on their graduation day. Table 3 shows how each of these criteria is addressed by the game. As Table 3 shows, the game directly addresses criteria (a)-(e), (g), and (k).

EVALUATION

A pilot study was conducted to evaluate the remote laboratory game. The pilot study had two objectives. The first objective was to gain an insight into whether the students would like playing the game. A second objective was to see if playing the game would make a quantitative difference in student performance. Unlike previous remote laboratory studies that have compared a remote laboratory to a virtual or hands-on laboratory, the objective here was to compare game-based remote laboratories treatment against a control group represented by students who had no exposure to this game.

Pilot study design

Students currently taking the CHE 421 - Chemical Process Dynamics and Control class at the American University of Sharjah were recruited to evaluate the game. The students had been exposed to the proportional and integral control loop in classroom lectures before their participation. Twelve students were chosen at random as the control group while another 12 volunteered to play. There was no statistical difference between the mean GPA of the control and treatment groups. The control group had seven women while the treatment group had five women. The 12 volunteers were randomly divided into six teams of two students each. Each of the six teams was

TABLE 3 ABET Outcome Criteria and Game Design	
ABET Criteria	**Game Design**
(a) an ability to apply knowledge of mathematics, science, and engineering	The game requires a mathematical interpretation of the transfer functions.
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	The students need to conduct mini-experiments to verify their assumptions about the parameters of the system being attacked or defended.
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	Tuning or destabilizing the system is a parameter design problem.
(d) an ability to function on multidisciplinary teams	Since control is taught in many engineering disciplines, the game can be played by a multidisciplinary team.
(e) an ability to identify, formulate, and solve engineering problems in engineering practice.	System tuning is an engineering problem and is regularly practiced in many engineering contexts.
(f) an understanding of professional and ethical responsibility	Not directly addressed in the game.
(g) an ability to communicate effectively	Team members are playing from remote locations and therefore require an effective communication strategy.
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	Not directly addressed in the game.
(i) a recognition of the need for, and an ability to engage in life-long learning	Not directly addressed in the game.
(j) a knowledge of contemporary issues	Not directly addressed in the game.
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	To compete successfully, the students need to use the mathematical knowledge and tools often used in engineering practice for control engineers.

randomly assigned a competing team. This resulted in three gaming contests each consisting of two teams of two students each. Each contest was run for a total of three hours. All students took a pre-quiz on PI controllers before the contests. Similarly, all students took a post-quiz on PI control after the contests. One day before the contests, the students playing the game were invited to the laboratory where they were shown the laboratory equipment and given explanation of how it worked. Twelve hours before the game, each team was e-mailed a copy of game instructions that included a description of the operational rules of the game. The students were given the option of either playing the game on their mobile phone or on their laptop computers using wireless LAN. After playing the game, each student was asked to individually fill out a survey to evaluate various aspects of the game.

Results

Post-game survey

Table 4 shows the post-game survey questions. Table 5 (next page) shows the results from the survey including a weighted average (WA) for each question, where 1 means strongly agree and 5 means strongly disagree. Results in Table 5 indicate that more than 10 out of 12 students either agreed or strongly agreed that the game helped with the learning objectives (WA = 1.33). Most students enjoyed playing the game (WA = 1.13) and felt that the game was immersive (WA=1.27).

In addition, most students indicated that they would recommend this game to a friend (WA = 1.27). Half the students felt that the game motivated them to learn more about control systems while the other half were not so sure (WA = 1.6). None disagreed with the assertion, however. Out of 12 students, four were not sure if the game was addictive (WA = 1.67). In summary, the students generally thought that it helped them learn the material and was enjoyable.

None of the students noticed the unusual behavior caused by opening the flow valve. Many students carried the control textbook with them. In addition, in two out of three contests, students continued to play with the system even after they had won the game. When asked about the reason, they typically indicated that they were curious about how the system would behave under certain conditions.

Performance

Playing the game once did not have an impact on performance of the students. An analysis of variance to compare the test results from before and after the game for both control

TABLE 4 Post-Game Survey Questions	
No.	**Post-Game Survey Questions**
Q1.	Playing the game improved my understanding of how to tune proportional-integral control systems.
Q2.	Playing the game improved my understanding of how to destabilize proportional-integral control systems.
Q3.	I felt immersed in the game.
Q4.	I enjoyed playing the game.
Q5.	The game motivated me to learn about control systems.
Q6.	I would recommend this game to a friend.
Q7.	The game was addictive.

TABLE 5 Post-Game Survey Results						
No.	Strongly Agree	Agree	Neither	Disagree	Strongly Disagree	Weighed Average
Q1.	6	4	2	0	0	1.33
Q2.	4	7	1	0	0	1.40
Q3.	7	3	2	0	0	1.27
Q4.	9	2	0	1	0	1.13
Q5.	6	1	4	1	0	1.60
Q6.	7	3	2	0	0	1.27
Q7.	3	5	4	0	0	1.67

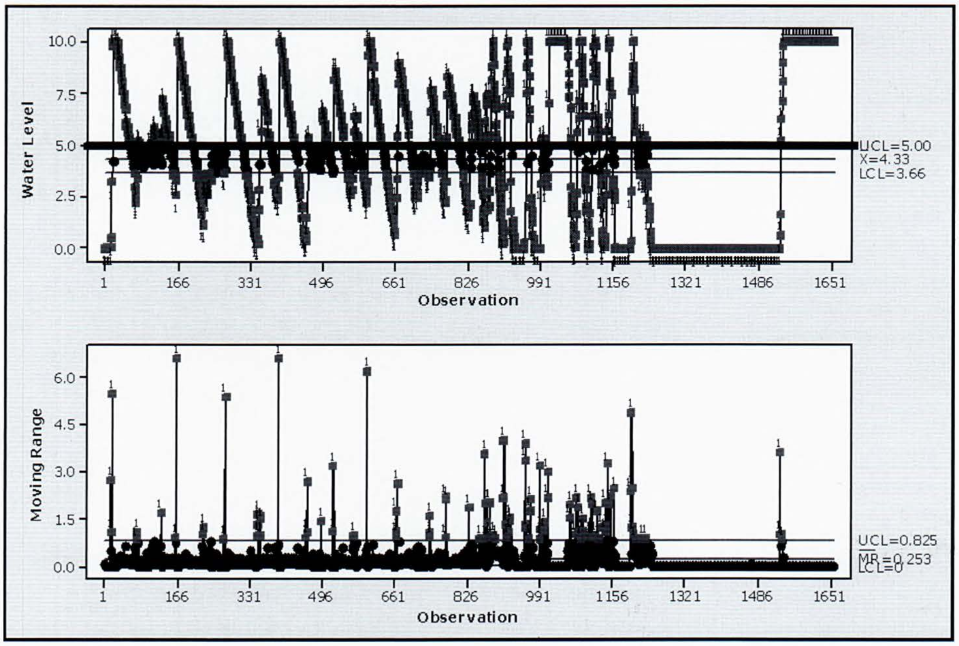

Figure 6. *Performance of Tank A in the second game.*

and treatment group showed no statistical difference F(3,44) = 0.55; p = 0.625. This means that playing the game once did not directly lead to improving the performance of the students.

Qualitative analysis

One important aspect of the remote laboratory game is the ability for post-game analysis to determine the gaps in student understanding. An illustrative analysis of the second game is presented next. The second game was played between Team-A and Team-B, both teams composed of two students. Team-A was defending Tank A while attacking Tank B and Team-B was defending Tank B and attacking Tank A.

Figure 6 shows the behavior of Tank A over the three-hour period of play. The top graph in Figure 6 shows the actual level of a tank as a function of time. The bottom graph in Figure 6 shows the moving range of the water level for the last two time intervals. The moving range shows the level of fluctuation over time; spikes in this graph represent drastic changes in the water level over short periods of time indicting turbulence or level instability. The first half of the game is characterized by the level going out of control and then coming back into control for brief periods of time before it is out of control again. Team-A was not very conscious of how they used up the limited amount of changes to K_p and K_i and hence ran out of changes about 70% into the game. This means that afterward Team-B had a free reign over changing the parameters as they liked. This is reflected in the uncontrolled variation seen after about two-thirds of the game. It is interesting to note that towards the end, Team-B had brought down the level of tank to zero, which means that the tank was accumulating maximum error. They chose to play with the tank, however, and made it saturate by pushing it to the other direction. This posed no advantage in terms of the game. A post-interview with the students indicated that they were just "playing around" with the opponent's system to see what would happen. The invaders' median K_p was 3 (with 95% confidence intervals of [2,5] using Wilcoxon signed rank test) while the defenders' median K_p was 5 (with a 95% interval of [4,6]). Though not statistically different, this means that invaders were trying lower-range K_p values to over-dampen the system and hence build up error while the defenders were trying the opposite strategy. An optimal strategy, however, would be to simply use a K_p of 1.0—indicating that the invaders perhaps did not fully comprehend what K_p does. Similarly, the invaders' estimated median for K_I was 0.75 (with 95% confidence interval of [0.5, 0.95]) while the estimated median for K_I for the defenders was 0.5 (with 95% confidence intervals of [0.45, 0.75]). Clearly, the invading team was trying to destabilize the system by using high values of K_I. Why the defending team was also using reasonably high values, however, tends to suggest a misunderstanding of how K_I works.

Figure 7 shows the behavior of Tank B. As the Figure shows, Team-B was eventually able to find the values of parameters to get the water level within control. Team-B was partially helped by the fact that the Team-A ran out of turns. The invaders' estimated median for K_p was 5.5 (with a 95% confidence interval of [5, 9.5]). The defenders' estimated median for K_p, on the other hand, was 7 (with a 95% confidence interval of [5, 7]). The invader's estimated mean for K_I was 0.4 (with a 95% confidence interval of [0.2, 0.5]). The defender's estimated mean for K_I was 0.25 (with a 95% confidence interval of [0.15, 0.4]). In other words, the defending team kept trying the middle values for K_p while the invading team tried a range of higher values. Similarly, the defenders used a reasonably low K_I while the invaders also kept the K_I below 0.4. Again, this confirms Team-A's fundamental misunderstanding of how K_I impacts the system response.

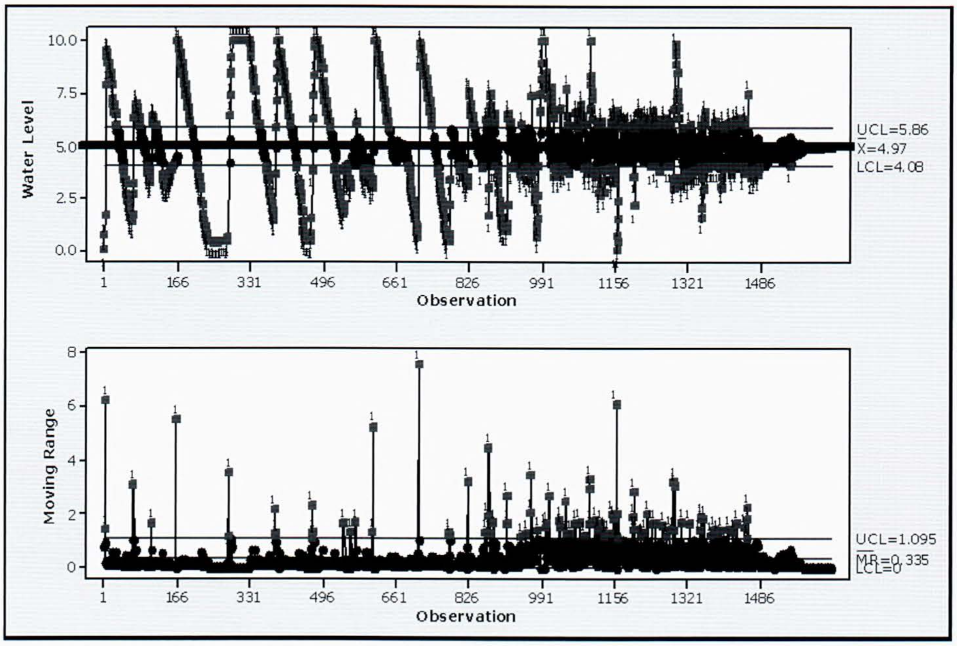

Figure 7. *Performance of Tank B in the second game.*

DISCUSSION

While playing the remote game did not show a statistical increase in the performance of students, this is perhaps expected since the students only had one chance to play the game. The performance could perhaps be improved if they were allowed to play the game many times. The post-game survey results, however, clearly indicated that they enjoyed the game and that they would recommend it to their friends. This was confirmed by the excitement shown by students while playing the game as well. It is interesting to note that half the students used the mobile phone to receive the SMS messages but chose to use the laptop to play the game. The other half were comfortable using a mobile device. The students also indicated that three hours was too long and thought that the time for the game should be reduced to one hour only.

A number of improvements can be made in the game. For example, since the game creator can view the performance of each team, he or she can easily use Facebook to communicate with the students to either mentor or ask them why they are using a particular strategy. Live video showing the tanks and turbulence of the water would also add to the gaming experience. Since Facebook mobile currently does not support video, however, this feature can be included only if the game is played on a laptop.

One final observation is that despite dealing with off-the-shelf hardware, currently available technology makes it very easy to put together a remote laboratory. The challenge lies in one's ability to utilize this technology in a pedagogically sound and interesting manner.

CONCLUSION

This paper has shown how remote laboratories can be used for game-based learning. A game specifically designed to teach a particular control topic was developed using a sound pedagogical foundation. In addition, the game design was evaluated against various criteria for what constitutes a good game. Finally, a pilot study was conducted to further validate the game design. The pilot study indicates that the game was well received by the students who enjoyed the game. Pre- and post-tests comparing this group to a control group, however, did not show any significant statistical differences.

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