Synchronized Robot: A PID Control Project with the LEGO Mindstorm NXT

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Abstract:

Typical courses in introduction to controls are usually heavy in theory and light in practical application. In order to emphasize practical application in this type of course, such as the implementation of a PID controller, there are problems with most of the commonly used options. The first option is to provide the students with an approximate model of a system and have them use simulation to implement a PID controller. The simulation approach is limited because there is not an “actual system” to control and the model is likely oversimplified. A second option requires the instructor to create a control system that all students use. This approach is expensive, time consuming, and not all students have access to the system at the same time. A third possibility requires students to build their own system and then control it. The problem with this approach is that so much time is dedicated to mechanical and electrical design, while important control theory concepts are left out or deemphasized. A solution to these problems is providing the students with a LEGO Mindstorm NXT kit, which allows them to quickly design their system so they can focus on the application of control theory. These kits are inexpensive and can be used for other functions such as freshman orientation courses and outreach events when not being used for controls.

In the Introduction to Control Systems Engineering course (ECE 4413) at the University of Oklahoma (OU), students were given a LEGO Mindstorm NXT kit and some brief training in the LabVIEW programming environment in order to complete a class project. The students implemented PID control algorithms to produce synchronized robots that tracked each other’s movement. Implementing PID control in LabVIEW without any built-in PID functions allows students to discover how the control algorithm works in a visual way. With this method, the likelihood of retaining the knowledge would appear to be much greater than modifying a built-in function while doing simulations. This paper will show how this project increased the students’ understanding of PID control. Pre-project and post-project quizzes are used to provide statistical evidence of improvement. Students’ perceived value of the project is also explored. Additionally, details of the project are provided so that other universities looking to emphasize practical application in their introductory controls course can replicate it.

I. Introduction

The most practical topic in most controls courses is the implementation of a PID controller. For instructors of control engineering classes that want to emphasize practical application, there are many options for implementing PID control techniques into projects. The simplest way is to create a project where PID control is explored through simulation. With simulations, learning is somewhat limited because students are usually provided an oversimplified model and only asked to make slight modifications to provided or existing code. Additionally, simulation doesn’t work well for a system that has a model that is unknown or difficult to attain, which is usually what the students will face in industry.
Another option is for the instructor to create a complicated hands-on project and all of the students control the same system at different times. There are many reasons why it is difficult to create a control system that is dedicated for student projects. First, it is time consuming and expensive to create and maintain them. Secondly, once a control system is created, the instructor might have difficulty in managing the time for all students to work on it. The cost would be highly increased if the instructor decides to create numerous identical control systems. The third issue is that current students can get project information from previous students instead of learning it for themselves since the system will likely not change from semester to semester.

Another possibility is the students build the system from scratch and then control it. The problem with this approach is that so much time is dedicated to mechanical and electrical design, while important control theory concepts are left out or deemphasized. The idea presented in this paper is to use the final option of having the students build their own system, but provide them a kit so they can focus more on implementing the PID controller.

II. ECE 4413 Course Information

ECE 4413 is a senior level elective course that is titled: Introduction to Control Systems Engineering. This introductory course is a typical first course in controls that covers topics such as: modeling linear systems using the Laplace and State-Space methods, time response characteristics, stability, feedback, system performance, frequency response, block diagram simplification, and controller design with emphasis on the PID algorithm. The pre-requisite for ECE 4413 is a junior-level course titled “ECE 3793: Signals and Systems”. In all of the textbooks the authors reviewed and the control system courses they have been involved with in the past, PID control is a topic that is always covered toward the end of the semester. The first problem with this late coverage is that it usually makes it difficult to have a PID control project. Secondly, since PID control is the most practical aspect of this theoretical course, students can easily find themselves losing interest because they don’t see how the information they are learning applies to the real world until the PID control section is covered. In order to prevent these negative outcomes, the material in ECE 4413 in the Fall 2013 semester was taught in a way that allowed PID control to be covered in the middle of the semester instead of the end. Topics (such as state space modeling, sensitivity, disturbances, and advanced block diagram reduction techniques) that are not required to be covered in order to understand PID control were moved to the end of the semester, while feedback control systems and root locus design techniques were covered earlier. In order for models to be created for electrical and mechanical systems at the beginning of the semester, the students were taught techniques that do not involve block diagram reduction, such as differential equations and matrix techniques utilizing the Laplace transform.

Another objective in this course is to provide the students an opportunity to use Matlab and LabVIEW software in a more applied way than previous courses. Matlab is used throughout the semester to provide the tools needed to solve the homework assignments and a method to check their work when asked to solve problems without a computer. LabVIEW was used primarily in team projects that will be discussed in more detail later in this paper. When forming a team it is important to keep the project groups small so that every student has the opportunity to work on the LabVIEW software. However, having multiple members provides valuable experience in working on team projects. One solution to this dilemma is setting up teams like a FIRST
Robotics competition (FRC) where there are “individual teams” and multiple individual teams make up an alliance. In ECE 4413 each individual team was comprised of two students and two individual teams worked together on an alliance. Each team would create a robot that would work with its alliance team’s robot. The Synchronized Robot project described in this paper works perfectly for this team structure.

III. LEGO Mindstorm NXT Platform Description

For the idea discussed in this paper to be implemented by others, the kit that students are given to complete their robotics project will first be described. All parts are put in a small lightweight toolbox that the students can easily carry around with them. The LEGO Mindstorm NXT kit (Part # 8547) includes 1 32-bit microprocessor LEGO NXT brick, a battery with charger, a USB cable to connect the NXT to the computer, 3 interactive servo motors with internal encoders, 2 light sensors, 2 touch sensors, 1 sound sensor, and 1 ultrasonic sensor. Many additional sensors are also available from LEGO. The LEGO Mindstorm NXT kit also includes an adequate supply of LEGO pieces. The light sensors can be used in reflective mode with an internal LED source or in ambient mode, where a flashlight or other form of external lighting can be used to control the robot. The students are then required to install LabVIEW and the LEGO Mindstorm NXT Module on their laptops, both of which can be downloaded from NI.com. The LEGO Mindstorm NXT has proven to be a versatile platform as they have been used at our university in numerous ways and for varying student levels. The same platform has also been used for hands-on activities for high school outreach events and freshman orientation projects. Using the LEGO Mindstorm NXT platform with LabVIEW has allowed it to be used for engineering courses, Robotics Club events, and even LabVIEW training seminars for graduate students.

IV. Phase 1 Robot Project – LabVIEW State Machine Architecture

One difficulty in implementing this project is that many of the students in the course are not proficient in LabVIEW. In fact, roughly one-third of the class had no LabVIEW experience at all. With experience doing a similar project to the Phase 1 Robot Project in a different course, it was determined that some LabVIEW training would be needed. Therefore, LabVIEW tutorials were provided for the students in order for them to reach a modest level of proficiency. The LabVIEW training started at the beginning of the course and was done in parallel with control theory topics that were presented in lecture. Once the students completed this training and finished a LabVIEW state-machine homework assignment, the LEGO Mindstorm NXT kits were handed out. One lecture was dedicated to getting the teams and alliances set, handing out the Mindstorm kits, and showing the students how to program their LEGO Mindstorm using the LabVIEW NXT module. Next, they were given their first challenge: Make the two alliance robots travel back and forth in a synchronized fashion using a state-machine architecture. The project will be repeated in Phase 2 using PID control. Requiring the students to first do the synchronization with state-machines allows them to get comfortable programming in LabVIEW and see how much better results they can achieve when using PID control techniques later in Phase 2. Furthermore, the Phase 1 Project was only worth ~ 6% of their final grade, but Phase 2 was worth 20% of their final grade.
A. Setting up the robots for the competition

The following figure shows how each of the alliance’s robots were set up in the competition.

![Robot Setup Diagram](image)

**Figure 1: Synchronized Robot Competition Overview (Used for both Phase 1 and Phase 2)**

The alliances work together to create an L-Shaped wall that can be used in combination with the follower robot’s ultrasonic sensor to determine the distance between the robots. The goal is for the follower robot to maintain a fixed distance between it and the leader robot. The desired distance needs to be measured so that the follower’s light sensor is over the strip of silver tape. The amount of time the light sensor is over the silver tape is calculated by the follower scoring LabVIEW program (VI), which is shown Figure 2 below. The students build their state machine program inside this VI template.

![LabVIEW Score Program](image)

**Figure 2: Phase 1 Follower Robot Template and Scoring VI**
The leader robot is also programmed inside a template, as shown in the Figure 3. This template also includes the scoring measurement of the total radians of movement of the leader robot. The final score is calculated by multiplying the radians of movement by the percentage of the time the follower was over the silver tape. This final scoring metric determines the amount of movement where the robots were “synchronized” (within the desired range of distance of each other).

![Figure 3: Phase 1 Leader Robot Template and Scoring VI](image)

**B. Competition Rules**

The robots have 30 seconds to build up their score by traveling back and forth across a round black panel that has an approximate diameter of 4’ with 2” white ring around the outside edge. The panel is raised so that if either robot crosses the white outer ring they will fall off and not be able to increase their score further. Each alliance of two teams performs two runs. Each team of an alliance acts as a leader in the first run then switches its role to a follower in the second run. These two scores are averaged and bonus points awarded to the alliance that has the highest average score.

**V. Phase 2 Robot Project – LabVIEW PID Control**

The Phase 2 Project was much more complicated than the Phase 1 Project since a PID control algorithm was required to be programmed into LabVIEW and there were two separate challenges in the project (see Part 1 and Part 2 below). Depending on the complexity of the LabVIEW programs they created, the sampling rate and accuracy of digitization might be varied from group to group. Therefore, we do not focus on specifying the detailed characteristics of digital control implementation in this paper.

The following two parts of the project were combined into one final score.
Part 1 – For this part, the students did the exact same thing as the Phase 1 Project except they were required to use PID control in the follower instead of a state-machine. New LabVIEW template files were created in a similar fashion to those shown in Figure 2 and Figure 3. The main difference is that there are two sequential while loops for parts 1 and 2. An example of one of the team’s LabVIEW code for the follower robot for part 1 is shown in Figure 4.

![Diagram of LabVIEW code](image)

**Figure 4: Example of Student Phase 2 Follower Robot Part 1 LabVIEW Code**

Part 2 – After the 30 seconds expires from Part 1, a new while loop will execute in the template. The follower is required to go to the edge and travel all the way around the panel by tracing the white ring without falling off. During this time, at least a part of the robot must stay within one inch of the white ring. After the follower robot finishes one trip around the panel, the orange button on the NXT brick is pressed and the scores are read. The leader robot tries to stay in the panel, but not run into the follower. This requires additional synchronization between the robots. If the robots got out of sync they could run into each other and the follower would not be able to successfully complete the revolution around the panel, which would result in a major score deduction (scale factor of 0.1). Some teams used a state-machine architecture for Part 2 and some used PID control. Figure 5 shows the follower LabVIEW code for one of the teams that used PID control for Part 2.

The scoring for the Phase 2 Project is described below. The alliances that had the best Part 1 score and the individual teams that had the best Final Score were awarded bonus points.

- The Part 1 scoring is the similar to Phase 1 Project: \((\text{Silvertime}/30) \times \text{Total Movement}\).
- The Part 2 scoring is the time it takes the follower robot to find the white ring and finish one trip around the panel. This time is used to adjust the Part 1 score based on the team ranking.
- FINAL SCORE = Part1_Score * Scale_Factor
- If Part 2 is not successfully completed then the scale factor is 0.1.
- If Part 2 is successfully completed then the scale factor is determined by the team ranking as compared to other students in the class.

<table>
<thead>
<tr>
<th>Team Part 2 Ranking</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>9th</th>
<th>10th</th>
<th>11th</th>
<th>12th</th>
<th>13th</th>
<th>14th</th>
<th>15th</th>
<th>16th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Factor</td>
<td>20</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 5**: Example of Student Phase 2 Follower Robot Part 2 LabVIEW Code

VI. Procedure for Project Preparation and Performance Assessment

In this section, the comprehensive procedure used in the class project is described. With this procedure (Figure 6), the instructor was able to (1) prepare necessary background and skills for students prior to the project and (2) evaluate the competency and confidence of students upon project completion.
A. Background and Skill Preparation for the Project

In order to successfully implement the PID control algorithm using LabVIEW on the LEGO Mindstorm NXT and use the robots for the class competition, students were required to gain some backgrounds/skills through the following tasks (Figure 7).

- Task 1: Complete the project using state machine in LabVIEW (Phase 1 Project). Upon completion, students were expected to increase their competency in LabVIEW, learn how to setup the project as shown in Figure 1, and how the scoring schemes were executed in the LabVIEW template program.
- Task 2: Simulate the PID control algorithm. Students were required to complete the take-home midterm problem where they had to simulate PID control algorithm in Matlab. Upon completion, students were expected to understand the principles of the PID control algorithm as well as practical tuning methods for the proportion gain $K_p$, integration gain $K_i$, and derivative gain $K_d$ such as Ziegler-Nichols.
- Task 3: Implement PID control in LabVIEW. Students were instructed to implement a PID control algorithm in LabVIEW. By doing a homework assignment in LabVIEW, students practiced to obtain major components of the PID control algorithm such as error between the output feedback and the reference, temporal difference for the derivative part, or accumulation of error for the integral part of the controller. The students also experimented with anti-windup and gain scheduling schemes.

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**Figure 6: Step-by-Step Procedure of the Project**

1. **Instructor prepares backgrounds and skills for students**
2. **Students take Bonus Quiz 1 on the PID control algorithm with LabVIEW**
3. **Students implement PID control on the NXT for the project**
4. **Students take Bonus Quiz 2 on the PID control algorithm with LabVIEW and ~6 weeks later take the final exam**
B. **Bonus Quizzes**

In order to evaluate the improvement of students’ scores as well as their confidence in implementation of the PID control algorithm in a practical device such as the NXT robot, bonus quizzes with similar formats were given before and after the Phase 2 Project.

- Students were given 4 block diagrams which implemented the PID control algorithm in LabVIEW. Only one block diagram implemented the PID control correctly (see Figure 8 and Figure 9).
- In order to test for correct PID control structure, students were asked to select the block diagram that implemented the PID control algorithm correctly.
- In order to test for correct PID control parameters, students were asked to find the control gains Kp, Ki, and Kd from the block diagram they selected.
- Student selected how they wanted to be graded in the bonus quizzes by answering the final question: “Do you want to go for **10 points** with the potential of drop down to **1 point** if any of your answers are wrong? *(Selecting No indicates you are opting for **5 points**) Circle → **Yes** or **No”***
- Students’ grades were determined using the following rules
  - **10 points** – Answer **Yes** on the final question and write down correct control gain Kp, Ki, Kd for the correct block diagram of the PID control algorithm
  - **5 points** – Answer **No** on the final question
  - **1 point** – Answer **Yes** on the final question and either select incorrect block diagram or enter incorrect control gains.
- It is important to note that students were not allowed to see neither the solutions nor the results of the first bonus quiz. In addition, after the project completion, the second bonus quiz was given with a similar format, but the LabVIEW block diagrams were wired
differently. Both of the quizzes were given without advance notice, therefore students were not able to study for the quizzes and just answered with knowledge and skill that they possessed at that time.

![Correct PID Block Diagram](image)

**Figure 8: Correct PID Block Diagram**
C. Final Exam LabVIEW Question

On the final exam, in addition to the standard questions, students were given a LabVIEW block diagram that implemented the PID control algorithm incorrectly. They were asked to correct the diagram (test for PID control structure) and find the control gains (test for PID control parameters). The final exam was approximately 6 weeks after the Bonus Quiz 2 so it showed whether the students retained the knowledge. It is important to note that the bonus quizzes were not returned to the students until after the final exam so the students had to rely on the knowledge they gained from the Phase 2 Project instead of studying the answers to the questions.

VII. Results

A. Selection Criteria

Out of total 30 students in the class, there were 21 students who met all of the following selection criteria and gave written consent to participate in this study.

1. Had not implemented PID control algorithm in the LEGO Mindstorm NXT before the Bonus Quiz 1: 3 out of 30 students did not meet this selection criterion.
2. Showed up in class and answered both bonus pre-project and post-project quizzes: 5 out of 30 students did not meet this selection criterion.
3. Showed up for the final exam: 1 out of 30 students did not meet this selection criterion.

B. Evaluation Methods

The first evaluation metric were the grades from two bonus quizzes and one LabVIEW question on the final exam.

1. Students’ grades and their selection on the final question of the bonus quizzes are collected and organized in
2. Table II.
3. Students who answered both PID structure questions and PID parameter questions correctly were considered to achieve “100% correct” in
4. Table II.

In addition to the bonus quizzes and final exam question, the students’ self-perceived value of
the synchronized robot project was assessed in a survey shown in Table I. The survey is on a 5 point Likert scale where 5 is the most favorable response and 1 is the least favorable response. For question Q1, Q2, Q4, and Q6, students responses were associated to three categories: negative (responses 1 and 2), neutral (response 3), and positive (responses 4 and 5). These categories are used for some of the data analysis described later.

Table I - Survey Questions and Responses

<table>
<thead>
<tr>
<th>Question</th>
<th>Average Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q1) The NXT Synchronized Robot Project helped me understand PID control more than the homework assignment where I did Matlab simulations using PID control.</td>
<td>4.0</td>
</tr>
<tr>
<td>(Q2) If asked to implement a PID control algorithm in the future I am confident I could do it.</td>
<td>3.9</td>
</tr>
<tr>
<td>(Q3) The NXT Synchronized Robot Project was very difficult.</td>
<td>2.7</td>
</tr>
<tr>
<td>(Q4) Working with my group and alliance greatly improved my ability to work on a team.</td>
<td>3.6</td>
</tr>
<tr>
<td>(Q5) I would rate my competency in LabVIEW prior to this class the following number.</td>
<td>2.5</td>
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<tr>
<td>(Q6) This project greatly improved my competency in LabVIEW.</td>
<td>3.3</td>
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</table>

C. Data Analysis

Data presented herein are from the 21 students who met the selection criteria as described previously. Shaded numbers in Table II correspond to Final Question “Yes” responses.

Table II – Results from Bonus Quizzes and Final Exam

<table>
<thead>
<tr>
<th>Student</th>
<th>Score</th>
<th>100% correct</th>
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<tbody>
<tr>
<td></td>
<td>BQ1</td>
<td>BQ2</td>
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<tr>
<td>S1</td>
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<td>S21</td>
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</table>

Note: BQ1, BQ2 = Bonus Quiz 1, 2; FE = Final Exam
100% correct = (correct PID structure + correct PID parameter)
Statistical Analysis: In order to answer the question of whether or not the project helped students improve their score between the Bonus Quiz 1 (pre-project) and the Bonus Quiz 2 (post-project), statistical analysis was carried out to test the hypothesis that “students’ scores before the project are less than their scores after the project”. One-tailed, paired t-test ($\alpha = 0.05$) between the scores of pre-project and post-project quizzes supported the hypothesis with the probability of accepting the null hypothesis was only 0.026716 (less than $\alpha$). This concludes that the project helped students improve their scores in the bonus quizzes.

In addition, the percentage of students who answered both questions on PID control structure and PID control parameters correctly (referred as 100% correct in Table II) also increased from ~9.5% (2 out of 21) before the project to ~42.9% (9 out of 21) after the project and ~57.1% (12 out of 21) in the similar LabVIEW question in the final exam.

Results in Table II also answered the question about the students’ confidence in accepting the challenge by selecting Yes on the final question of the bonus quizzes. Percentage of students who chose to accept the challenge increased from ~19% (4 out of 21) before the project to ~57.1% (12 out of 21) after the project. Among the students who accepted the challenge, the percentage of getting 100% correct increased from 50% (2 out of 4) before the project to 75% (9 out of 12) after the project. Students’ responses to survey questions are shown in Table I and Figure 10. Numbers of responses to questions Q4 and Q6 did not add up to 21 since one student did not specify his answers.

![Student Survey Answers](image)

**Figure 10: Students Responses to Survey Questions**

It is very promising to observe that by completing a “not-very-difficult project” (in Q3, only ~23.8% of students, or 5 out of 21, agreed that the project was very difficult) such as the Synchronized Robot Project, students reported improvement in many aspects.

- In Q1, ~66.7% of students (14 out of 21) said that the project helped them understand PID control more than the homework assignment where they simulated PID control algorithm using Matlab. Only ~4.8% of students (1 out of 21) disagreed.
- In Q2, ~66.7% of students (14 out of 21) felt confident to implement the PID control algorithm in the future. None of the students disagreed.
- In Q4, ~52.4% of students (11 out of 21) said that working with their group and alliance greatly improved their ability to work on a team. Only ~4.8% of students (1 out of 21) disagreed.
- According to responses to Q5, prior to the class, only ~33.3% of students (7 out of 21) had a high level of competency in LabVIEW compared to ~47.6% of students (10 out of 21) had a low level of competency. After the project, ~52.4% of students (11 out of 21) said that their competency in LabVIEW had been greatly improved by doing the NXT Synchronized Robot Project (response to Q6). It is noted that all of ~23.8% of students (5 out of 21) who disagreed with Q6 already had high level of competency in LabVIEW prior to this class.

VIII. Conclusion

This paper shows that using the LEGO Mindstorm NXT offers advantages over using other alternatives for a PID control project. By providing the students with an interesting and challenging robot competition the students were able to learn PID control concepts. The pre-project and post-project quizzes and responses to the final exam question show that the project increased the students’ knowledge in how to correctly implement a PID control algorithm. The students also self-reported in the survey that the project was beneficial to them in the following ways: 1) Helped them understand PID Control, 2) Gave them confidence they could implement PID control in the future, 3) Improved their ability to work on a team, and 4) Improved their competency in LabVIEW. Additional evidence that the project was effective came from the course evaluations that 18 students completed. To the statement “In general, the instructor taught this course effectively” an average response of 4.78 out of 5 was reported, which was 15% higher than the average response to this question from all College of Engineering course evaluations at OU. To the statement “The way in which the course was taught helped me develop analysis and design abilities” an average response of 4.61 out of 5 was reported, which was 18% higher than the average response to this question from all College of Engineering course evaluations at OU. One student commented: “Integration of LabVIEW programming into the course gave another angle on the way control systems can be implemented”. The qualitative and quantitative results from this project suggest that it is worthy of consideration for others looking to emphasize practical application in their introductory controls course.

IX. References