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Infusing Mechatronics and Robotics Concepts in Engineering Curriculum

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Abstract: Mechatronics and Robotics have continued to grow in importance in recent years which has led many colleges and universities to start offering courses on these topics. A brand new technical elective course, "Introduction to Mechatronics", was offered for the first time in spring 2012 at the author's institution. While the course provides for ten weeks of instruction in Mechatronics, as an elective it does not reach a sufficient number of students. The author received a competitive grant internal to the institution for a project to infuse mechatronics and robotics concepts and applications throughout the engineering curriculum. The project was completed during academic year 2011-12.

Several hands-on modules were developed for three courses in the engineering curriculum, spanning the entire freshman to senior experience. The modules were developed with "active learning" principles in mind, to ensure students' full participation in the learning process in the classroom. The author chose the affordable and now widely adopted LEGO Mindstorms platform to illustrate basic mechatronics concepts and applications.

The targeted courses were the freshman "Introduction to Engineering and Design" course, junior "Kinematics" course, and senior "Dynamic Systems and Control" course. The modules were deployed in the three courses throughout the academic year, and were assessed using a variety of assessment tools including rubrics and student surveys. In end-of-course surveys students expressed satisfaction with the hands-on modules and suggested ways to improve the experience. The paper will present the modules developed for the three courses, including learning objectives, hands-on activities, performance results, and survey data. Conclusions and future plans will be addressed.

I. Introduction

As Mechatronics and Robotics have become more and more prevalent in numerous industries the number of courses[1, 2] on these topics in engineering programs has been growing steadily. The author took advantage of an internal funding opportunity at Baker College to propose a project consisting of introducing Mechatronics and Robotics concepts in the curriculum of several engineering and technology programs. The Jewell Educational Grants for Teaching and Learning Innovation provide winning proposals with up to $20,000 in funding for projects that must be completed in one academic year. The proposals are due by April 15 of each year, with the selected projects running September 1 through August 31 of the following year. A Final Report detailing the materials developed as well as the assessment results from projects' implementation is due by October 31.

One of the goals of the project was to reach students from multiple programs in the Division of Engineering and Technology at Baker College. The Division offers 4-year engineering programs, as well as 2-year Associate level technology programs. The author chose a freshman level course, "Introduction to Engineering and Design", which enrolls students from both 4-year and

2-year programs, and two Mechanical Engineering courses, “Kinematics” and “Dynamic Systems and Control”, to be part of the project. These courses were chosen to span multiple years in the engineering curriculum.

The objectives of the project were to:

- Introduce engineering and technology students to Mechatronics and Robotics concepts and applications
- Increase students’ conceptual understanding and learning of advanced topics such as feedback control systems and others
- Ensure students are able to apply theoretical knowledge to solving real-world open-ended problems
- Provide students opportunities for practical experience and training

The platform adopted for the project was the widely popular LEGO Mindstorms due to its affordable cost and versatility. Each LEGO Mindstorms kit includes three servo motors with integrated rotation sensors, a variety of gears, two touch sensors, and one each of sound, light, and ultrasonic sensors. The controller, motor, and sensors are shown in Figure 1. Additional sensors not included in the kit are available such as angle, gyro, and acceleration sensors. The latter sensors have not been used in the modules described in this paper, but are under investigation for future modules.

Fig. 1 Controller, servo motor, and sensors in LEGO Mindstorms kit.

The controller can be programmed in NXT[3], a simplified version of the graphical programming software Labview, and also in RobotC[4], a version of the C programming language. More complex applications using the LEGO Mindstorms kit, programmable using Matlab and Simulink[5], are possible. The modules described in this paper are based on the use of NXT2.0.

The project plan was to develop three modules for each course, to be used as hands-on laboratories supplementing the regular instructional activities of the course. Due to time constraints only seven of the nine targeted modules were developed during the academic year of the project. Plans to continue developing and implementing modules for the three courses based on the existing platform are under way.

II. Materials Developed

The modules developed as part of the project are presented in Table 1. The material in each module is organized in the following sections:

1. Learning Objectives - section describes the four or five learning objectives of the module. The objectives of each of the seven modules are shown in Table 1.
2. Equipment - section details all equipment needed for the module as well as the software programs that will be used.
3. Knowledge Base - this section summarizes the concepts and laws the module focuses on in one page for quick reference.
4. Activities - section describes in-class guided activities that will be done by students working in groups of two or three.
5. Assignment - section assigns an open-ended activity to be performed by students to further their understanding of the topics and enhance their problem-solving abilities. This activity is ideally done during class time, but it can be completed by students outside of class time if needed.
6. Results and Conclusions - the final section is where students will reflect on their learning by answering questions and writing a short Conclusions paragraph.

Table 1. Modules Developed and Deployed in Academic Year 2011-12

Course	**Module**	**Learning Objectives**
"Introduction to Engineering and Design"	1. Translational Kinetic Energy	a) Design an experiment to determine the Translational Kinetic Energy of an object moving in a straight line. b) Determine the speed of a moving object by two different methods. c) Apply the SI and English Engineering systems of units to practical problems. d) Use tables and graphs to summarize and analyze experimental data. e) Become familiar with the NXT Programming Software and LEGO Mindstorms robots.
	2. Closed-Loop Control Systems	a) Understand effect of open loop vs. closed loop control on variable to be controlled. b) Investigate open loop and closed loop control of position with the Taskbot. c) Investigate the effect of the Proportional Gain on the position of the Taskbot. d) Create graphs in Excel and use them to analyze and interpret experimental data.
	3. Rotational Speeds, Gear Sets, Speed and Torque Ratios	a) Understand rotational speed expressed in units of rpm and radians/s, linear speed in units of m/s, and the connection between the two speeds. b) Understand Gear Ratios and Velocity Ratios of gear sets. c) Understand Torque Ratios of gear sets. d) Design gear sets to achieve desired speeds with the Taskbot.
"Kinematics"	1. Kinematics Fundamentals	a) Understand Kinematics terms such as links, joints, mechanisms, structures, mobility. b) Understand types of motion - rotation, translation, and complex motion. c) Identify different types of links and joints based on various classification criteria.

		d) Illustrate the Grashof condition for four-bar linkages using LEGO based linkages. e) Illustrate each possible type of planar four-bar mechanism according to Barker's classification using LEGO based linkages. f) Illustrate the Grashof-type rotatability criteria for higher-order linkages using LEGO based linkages.
	2. Quick-Return and Straight-Line Mechanisms	a) Understand limiting conditions of a mechanism - toggle positions, stationary positions, transmission angle. b) Design and demonstrate a four-bar quick return mechanism. c) Design and demonstrate a straight-line four-bar linkage.
"Dynamic Systems and Control"	1. Closed-Loop vs. Open-Loop Control Systems	a) Understand the effect of open-loop vs. closed-loop control on the variable to be controlled. b) Identify the components of the open-loop and closed-loop control systems as they apply to the Taskbot. c) Investigate the open-loop and closed-loop control of the Taskbot 'Heading' variable. d) Investigate the open-loop and closed-loop control of the Taskbot 'Heading' variable under external disturbance.
	2. Sensors	a) Understand the role of sensors in a closed-loop control system. b) Understand general characteristics of sensors and their importance when choosing a sensor. c) Identify and understand the functionality of various sensors from the LEGO Mindstorms Educational Kit. d) Be able to choose appropriate sensors for specific applications. e) Be able to write programs for the Taskbot equipped with sensors to achieve a desired behavior.

The first module in each of the three courses also had to introduce students to the LEGO Mindstorms platform, including the available sensors and actuators as well as the programming environment. Simple programs written by the author in NXT2.0 were provided to students for use in the Activities section of each module. Students had to adapt these programs or write new ones in order to complete the Assignment sections.

The modules in the "Introduction to Engineering and Design" and the "Dynamic Systems and Control" courses required the most programming effort. The two modules in the "Kinematics" course focused on introductory concepts such as kinematics terms, types of mechanisms, and the Grashof condition. Future modules for "Kinematics" will address position, velocity, and acceleration of linkages and motion design.

The complete Module 1 from the "Dynamic Systems and Control" course is included in Appendix A. The module is organized in sections as described above. It also includes screen shots from one of the NXT programs to help students as they learn the basics of this programming language.

To assess the effectiveness of the modules in accomplishing the learning objectives of each module and of the project itself, assessment tools were developed including assessment rubrics for each module, and a student survey for each of the three courses. The assessment rubric for the modules in the "Introduction to Engineering and Design" course is included in Appendix B. Results of the student surveys are presented in the following section.

III. Results and Discussion

"Introduction to Engineering and Design" course

This is a freshman course taken by students in engineering programs, as well as associate level technology programs. Twelve students in the Mechanical Engineering, Industrial Engineering, and Mechanical Technology programs completed the course in fall 2011, when the three modules described in the section above were deployed for the first time. The modules were inserted throughout the course to follow lectures on the corresponding topics. The course uses "Exploring Engineering", 2nd edition, by Kosky et al. as a textbook. The course traditionally requires an end-of-course design project, on a topic picked by the instructor. In fall 2011 it was natural to base the design project on the LEGO Mindstorms platform. One of the completed projects is illustrated in Figure 2.

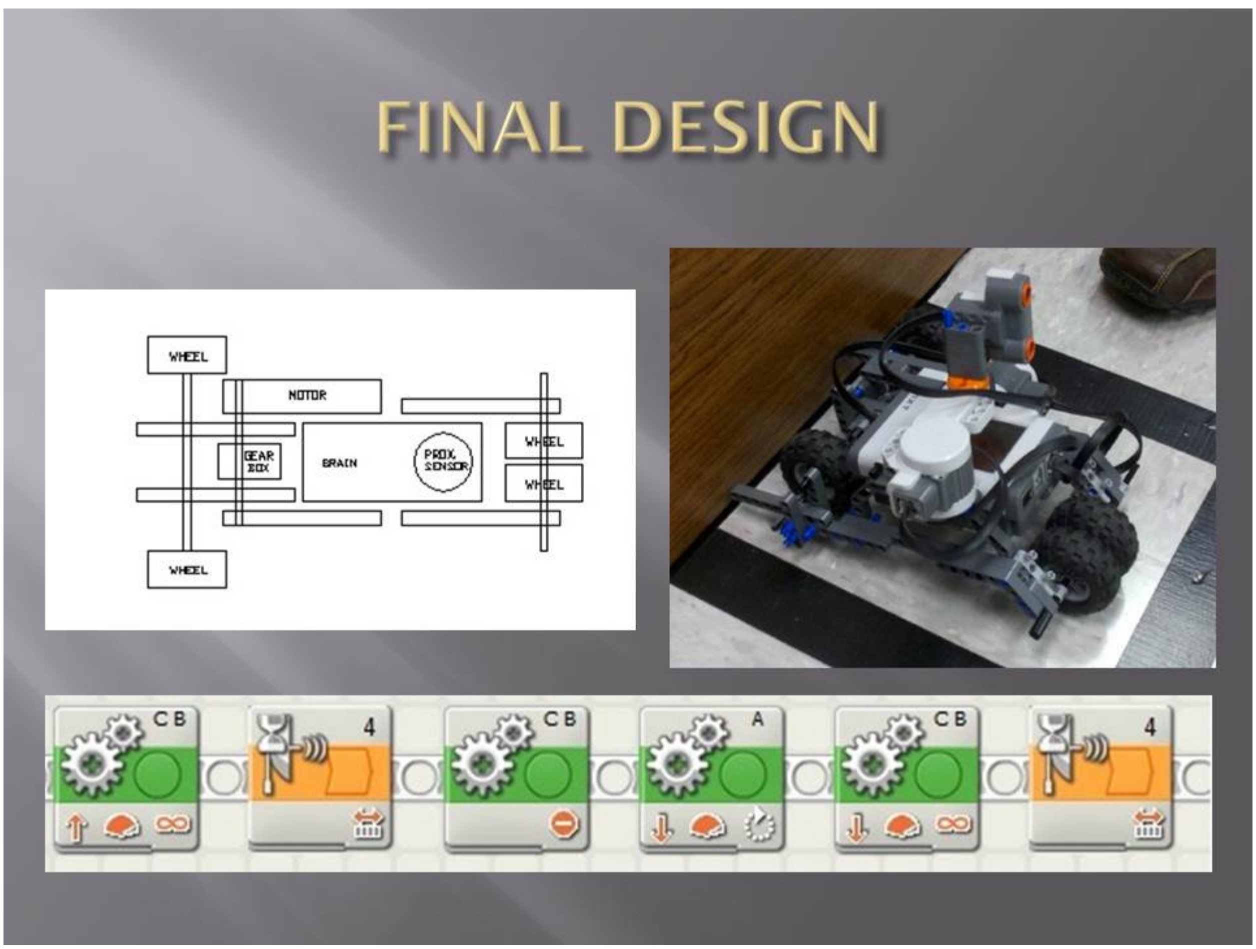

Fig.2 LEGO Mindstorms vehicle for end-of-class project in "Introduction to Engineering and Design".

The modules were well received by students who found the LEGO platform very interesting. As the modules were deployed for the first time in a classroom environment a couple of issues arose. The time allotted for completion of the modules, which was estimated by the author to be about 60 minutes, turned out to be more than two hours, and students had to make appointments to finish the Assignments outside of class. Students also found the learning curve to become familiar with the LEGO Mindstorms platform a bit steep, and suggested extending the time allotted for learning it.

Table 2 presents the results of the student survey from the “Introduction to Engineering and Design” course. The response scale ranged from 1 - Strongly Disagree to 5 - Strongly Agree. Questions 11 - 14 received an average score between 4 and 5, with the exception of question 10 related to the time allotted to each module.

Table 2. Student Survey Results Summary for “Introduction to Engineering and Design”.

	Question	Average Score, Out of 5
1.	The experimental Modules in the “Intro to Engineering and Design” course were a good learning experience.	4.56
2.	Module 1: “Translational Kinetic Energy” helped me understand the concept of TKE.	4.67
3.	Module 1 increased my confidence in solving TKE related problems.	4.44
4.	Module 2: “Closed-Loop Control Systems” helped me understand the concept of control systems and controlled variables.	4.44
5.	Module 2 helped me understand the difference between open-loop and closed-loop control systems.	4.67
6.	Module 3: “Rotational Speed, Gear Sets, Speed and Torque Ratio” helped me understand how gears work.	4.56
7.	Module 3 increased my confidence in solving gear ratio, speed and torque ratio problems.	4.22
8.	Module 3 increased my confidence in designing a gear set to achieve a desired speed or torque.	4.22
9.	The experimental Modules increased my knowledge of robotics and programming.	4.56
10.	The time dedicated to the experimental Modules was about right.	3.56
11.	Overall the experimental Modules added value to the “Intro to Engineering and Design” course.	4.44
12.	The Robotics Design Project was useful to introduce me to the topic of engineering design.	4.67
13.	The experimental Modules and the Design Project helped my ability to work as part of a team.	4.33
14.	I would recommend including LEGO based hands-on Modules related to course topics in other courses in my program.	4.67

The additional questions shown below, questions 15 - 18, asked students to describe their experience with the Modules in a sentence format.

15. Out of Modules 1, 2, and 3, the one I enjoyed the most was:
The answers were: 1 - Module 1, 3 - Module 2, and 5 - Module 3. Most students enjoyed the last module most, probably also because by this time they became quite familiar with the platform.

16. If you thought the time dedicated to the experimental Modules was too short or too long, please comment on this here:
A majority of students said time was too short. This was also reflected in the 3.56/5 score on question 10 above, the only score below 4 out of the first 14 questions.

17. Please make any suggestions for improvements in the "Introduction to Engineering and Design" course - activities/experiments to be added, topics for Design Project, etc.
One student suggested having better explanation of the NXT programming language.

18. Any other comments?
One student commented "The LEGO's for designing and programming was a big hit with me. Trial + Error and solutions."

"Kinematics" course

The course is taken during junior year by students in the Mechanical Engineering program. It introduces students to the kinematics of mechanisms including position, velocity, and acceleration analysis, and motion design. The textbook used is "Design of Machinery", 5th edition, by Norton. The course has traditionally been taught in a mostly-lecture format, supplemented by computer simulations available with the textbook. Having a hands-on experience with mechanisms and how they move is even more helpful for students than simulations, which motivated the author to develop the LEGO based modules.

Two modules were developed to enhance student understanding of mechanisms at an introductory level. The modules instruct students to build a variety of linkages which they animate using the servo motors included in the sets. The ability to quickly adjust links' lengths with the LEGO pieces is a valuable feature of the kits. The first module focuses on four-bar linkages and the Grashof condition. The Assignment in this module asks students to create a deltoid four-bar mechanism and describe its motion. Figure 3 shows a four-bar linkage with a motor attached. The second module asks students to build quick-return and straight-line mechanisms, and compare their actual motions with the expected ones. Trajectory generation will be addressed in a future module; this will require use of additional sensors such as the angle and acceleration sensors to collect data on position, velocity and acceleration of the mechanism.

The course was taken in spring quarter 2012 by seven Mechanical Engineering students. After completing the two modules students provided similar feedback to the one received in the

"Introduction to Engineering and Design" course. Students characterized the LEGO Mindstorms kits and the activities as very interesting; however they found the modules took a very long time to complete, exceeding the time allotted in class. The author plans to revise the modules content to keep only the activities with highest impact in student understanding.

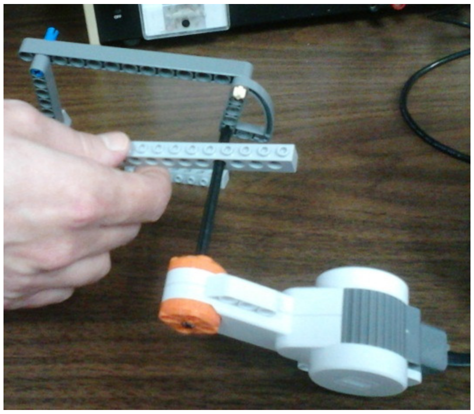

Fig. 3. LEGO four-bar linkage with attached motor.

"Dynamic Systems and Control" course

This is a senior level course for Mechanical Engineering which introduces students to modeling and design of closed-loop control systems. The textbook used is "Modern Control Systems", 12th edition, by Dorf and Bishop. Many Mechanical Engineering students find fundamental concepts such as closed-loop control systems and transfer functions as very abstract and difficult to grasp. The extensive mathematical derivations required are somewhat alleviated by the use of Matlab and Simulink throughout the course. As the course does not have a laboratory component there is a gap between theoretical concepts and practical applications in the class. The LEGO based modules were developed to bridge this gap at least partially. The first module focuses on fundamental differences between open-loop and closed-loop control systems in steady-state error and ability to reject external disturbances. The second module focuses on sensors and their role in closed-loop control systems. Future modules for this course will also take advantage of additional sensors to implement different closed-loop control systems.

Table 3 shows a summary of the student survey results for this course. The course was taken by eight Mechanical Engineering students during winter quarter 2012.

Table 3. Student Survey Results Summary for "Dynamic Systems and Control".

	Question	Average Score, Out of 5
1.	The experimental LEGO Modules in the "Dynamic Systems and Control" course were a good learning experience.	4.37
2.	Module 1: "Closed-Loop vs. Open-Loop Control Systems" helped me	4.37

	understand the concept of open-loop control systems.	
3.	Module 1 helped me understand the concept of closed-loop control systems.	4.50
4.	Module 1 helped me understand the difference between closed-loop and open-loop control systems.	4.62
5.	Module 1 increased my confidence in applying the closed-loop and open-loop control systems knowledge to a real life problem.	4.37
6.	Module 1 increased my knowledge of robotics and programming.	4.12
7.	The time dedicated to Module 1 was about right.	3.62
8.	Overall the experimental Module added value to the "Dynamic Systems and Control" course.	4.37
9.	The "Dynamic Systems and Control" Design Project was a good way to apply the course topics to a concrete problem.	4.37
10.	I would recommend including LEGO based hands-on Modules related to course topics in other courses in my program.	4.5

The additional questions shown below, questions 11 and 13, asked students to describe their experience with the Modules in a sentence format.

11. If you thought the time dedicated to the experimental Modules was too short or too long, please comment on this here:
Once again, a majority of students said time was too short. This was also reflected in the 3.62/5 score on question 7 above, the only score below 4 out of the 10 questions.

13. Any other comments?
"I think the LEGO module was really worthwhile and would have appreciated doing more."
"This class is extremely confusing. While it looks like I understand, I really don't."
"Hands-on learning is always better than just looking at a book."
"Lab was very fun. I want my own LEGO Mindstorms kit!"

One of the comments above reflects how difficult this senior level class is, conceptually, mathematically and overall. Even this student however rated the experimental Module 1 very positively.

IV. Conclusions

The paper presented the author's experience of developing and deploying experimental modules based on LEGO Mindstorms kits to three engineering courses from freshman to senior level. This was the first time the author used this platform for college level engineering courses. The author was supported in this project by an internal institution grant. The project turned out to be fairly ambitious for full completion within one academic year, as the author did not get any teaching load reduction and developed the modules outside the regular work schedule.

Consequently not all projected modules could be developed, and not all data could be collected in time from the three courses.

The modules were well received by students in all three courses, who found the LEGO Mindstorms platform interesting and worthwhile. The existing modules will need to be revised to make them more concise and less time consuming. At the same time new modules are planned for the "Kinematics" and the "Dynamic Systems and Control" courses which will incorporate additional sensors. Overall the introduction of the LEGO based experimental modules was beneficial to student learning in the three courses and students recommended expanding the project to different courses in their programs.

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Appendix A. Module 1 from "Dynamic Systems and Control" course.

"Module 1: Closed-Loop vs. Open-Loop Control Systems

1. Objectives

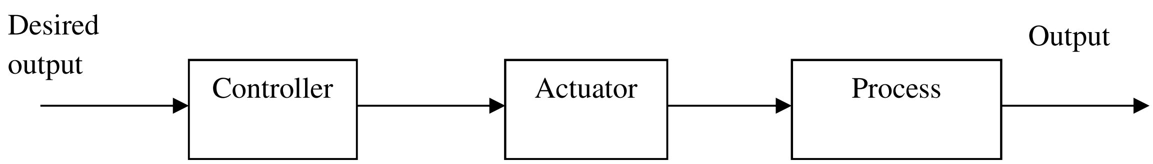
a) Understand the effect of open-loop vs. closed-loop control on the variable to be controlled.
b) Identify the components of the open-loop and closed-loop control systems as they apply to the Taskbot.
c) Investigate the open-loop and closed-loop control of the Taskbot 'Heading' variable.
d) Investigate the open-loop and closed-loop control of the Taskbot 'Heading' variable under external disturbance.

2. Equipment

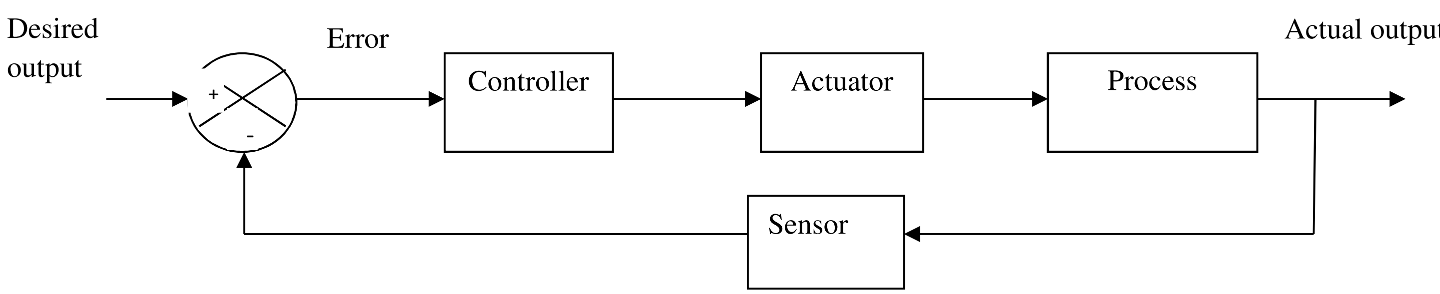
Taskbot LEGO robot.
NXT programming software, programs "angle-open" and "angle-closed", Excel software.

3. Knowledge Base

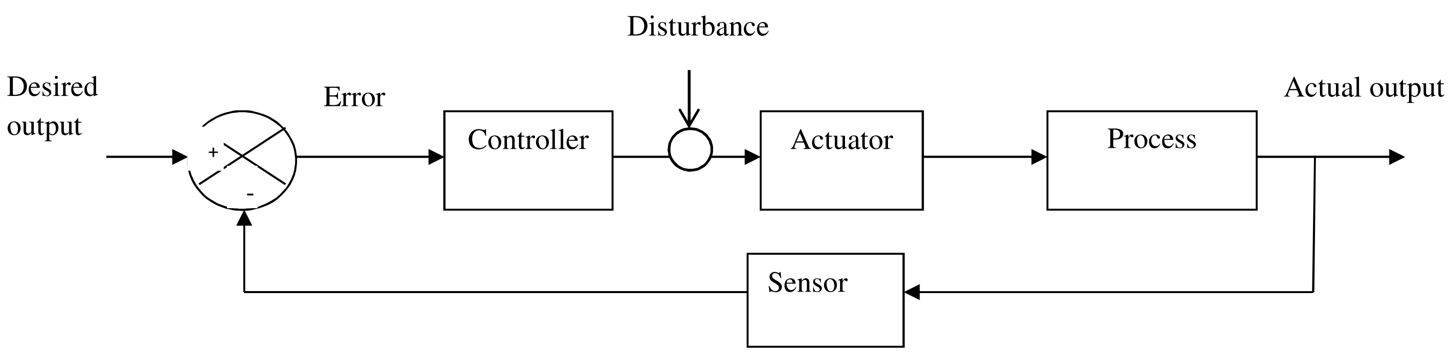
- Open-loop control of variable - Block diagram



- Closed-loop control of variable - Block diagram



- Closed-loop control of variable under external disturbance - Block diagram



4. Activities

a) Investigate open-loop control of the Taskbot 'Heading'

The Taskbot is a robot built from the LEGO Mindstorms Educational kit. The kit contains three DC motors and a variety of sensors including ultrasonic to detect distance from an obstacle, sound sensor to detect sound, light sensor to detect the amount of light reflected from a surface, and touch sensor to detect bumping into an obstacle. In addition to these sensors, the DC motors have built-in optical encoders capable of measuring the angle of turn of each motor. The Taskbot uses two motors attached to two wheels to make the robot move. The motors can be programmed to turn at full power or at a fraction of the full power using a variable ranging 0-100 (100 is full power). The power of the left and right motors is also used to program the direction in which the robot travels. When the power to the two motors is the same the robot is expected to travel in a straight line. When one motor turns faster than the other one, the robot will make a turn.

In this lab you will use the built-in optical encoders to detect the angle of turn of each motor and derive a conclusion about the Taskbot 'Heading'. We can define this variable as:

Heading = Angle C – Angle B (1)

where Angle B and Angle C are the angles of turn, in degrees, of the left and right motors (denoted B and C).

The goal is to have the Taskbot travel in a straight line, which is described by Heading = 0.

You will measure the actual Heading of the robot for open-loop control of the Taskbot first, and then for closed-loop control. The open-loop control is achieved by running the program "angle-open", and the close-loop control is achieved by running the program "angle-closed". Run program "angle-open" to measure the angles of turn of the two motors while the Taskbot travels forward for 10 seconds. The angles are shown on the Taskbot display. After reading the values, stop the program from running using the gray lower button on the Taskbot. If you do not stop the running program, next time you will try to download a new program in the NXT you will get the following message: "Error - the file is currently in use on the NXT device!"

Collect data for the motor powers in Table 1 below. Each measurement should be repeated three times in order to average out possible errors. The unequal settings of the powers for the motors in the last three lines are one way to introduce a disturbance in the system.

Table 1. Desired vs. Actual Taskbot Heading with open-loop control

Desired Heading (degrees)	% Power B	% Power C	Angle B (degrees)	Angle C (degrees)	Actual Heading (degrees)
0	75	75			
0	75	75			
0	75	75			
0	75	50			
0	75	50			
0	75	50			

b) Investigate closed-loop control of the Taskbot 'Heading'

For the second part of the experiment use is made of the built-in encoder sensors to continuously read the angles of turn of the motors and adjust the power of one motor to correct for any angle differences. The program reads Angle B and Angle C, computes the difference and multiplies the difference by a constant, Kp, to derive a correction to the power of motor B.

Power B = 75 + (Angle C – Angle B) *Kp (2)

This type of closed-loop control is called Proportional Control. The value of the constant Kp affects the accuracy of the Actual Output. A large value of Kp is preferred, however if Kp is too large the system starts to oscillate. The constant is entered in the program as shown in Figure 1 on the next page.

The closed-loop control runs in a continuous loop, with a rate of about 20ms (0.02s) set by the processor of the LEGO Mindstorms. The loop timing can be adjusted using a Wait block as shown in Figure 2 on page 5. Run program "angle-closed" to measure the angles of turn of the two motors while the Taskbot travels forward for 10 seconds. The angles are shown on the Taskbot display. After reading the values, stop the program from running using the gray lower button on the Taskbot. If you do not stop the running program, next time you will try to download a new program in the NXT you will get the following message: "Error - the file is currently in use on the NXT device!"

Collect data for the motor powers in Table 2 below. Each measurement should be repeated three times in order to average out possible errors. The unequal settings of the powers for the motors in the last three lines are one way to introduce a disturbance in the system.

Table 2. Desired vs. Actual Taskbot Heading with closed-loop control

Desired Heading (degrees)	% Power B	% Power C	Time Rate (s)	Kp	Angle B (degrees)	Angle C (degrees)	Actual Heading (degrees)
0	75	75	0	1			
0	75	75	0	1			
0	75	75	0	1			
0	75	50	0	1			
0	75	50	0	1			
0	75	50	0	1			
0	75	75	0.05	1			
0	75	75	0.05	1			
0	75	75	0.05	1			
0	75	75	0.05	5			
0	75	75	0.05	5			
0	75	75	0.05	5			

Figure 1. The “angle-closed” program – multiplication constant Kp.

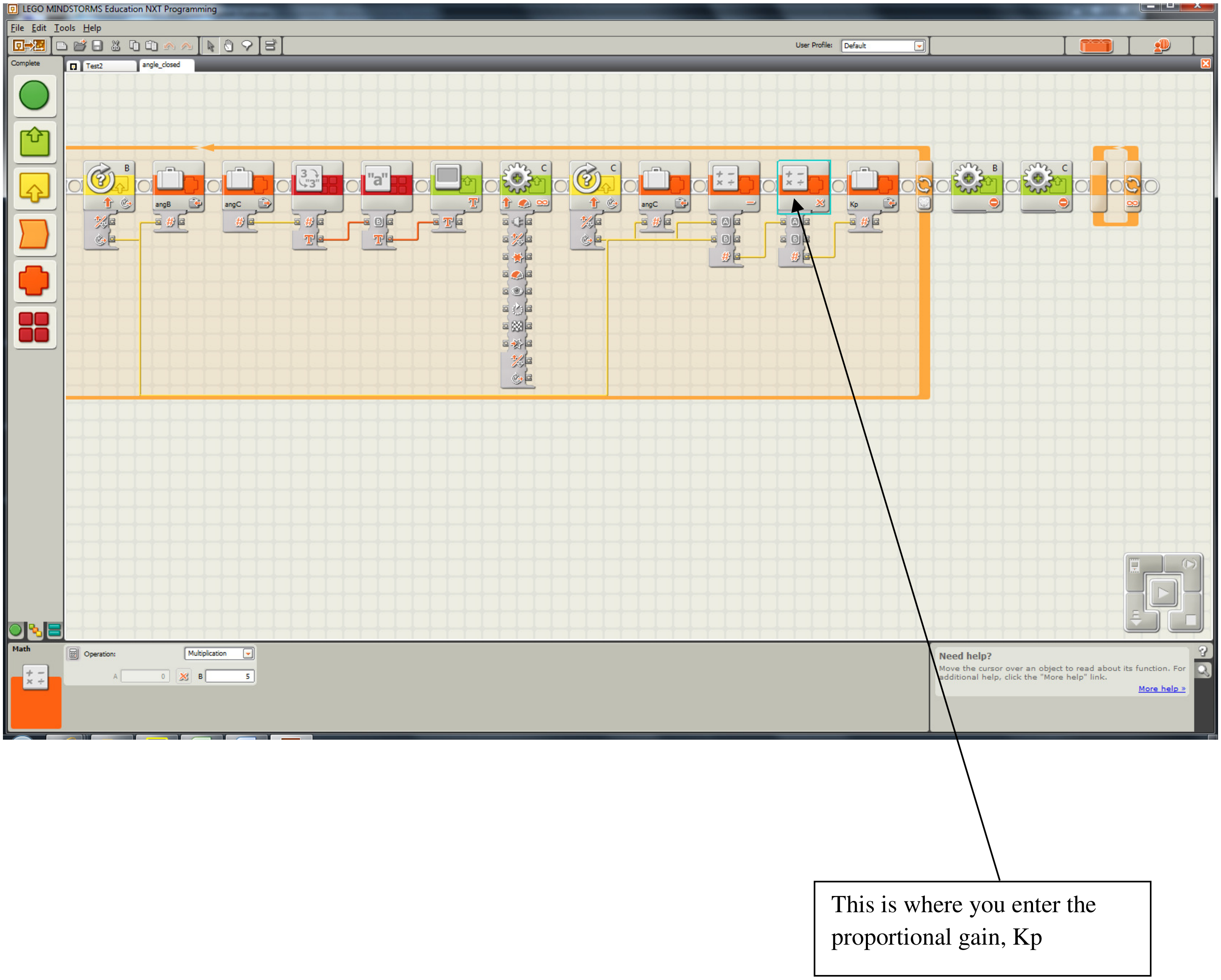
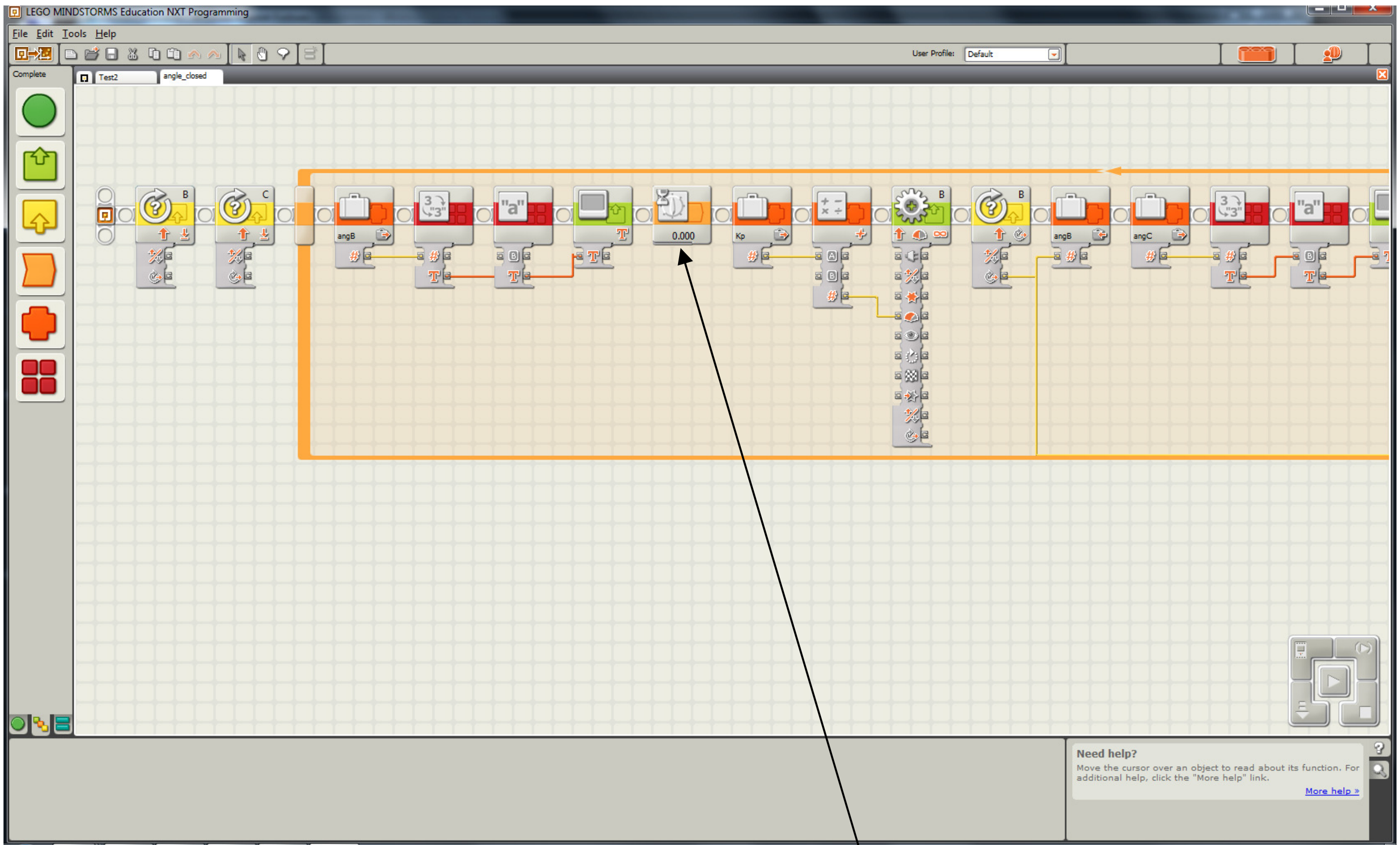


Figure 2. The “angle-closed” program – Wait block to change the Time Rate of the continuous loop.



This is where you enter the Time Rate (in seconds).

Answer the following questions:

Q1 - Identify the Controller, Actuator, Process, Sensor and Error for the Taskbot control system.
Controller =
Actuator =
Process =
Sensor =
Error =

Q2 - Compare the Actual Heading for open-loop control, with and without disturbance, to the Actual Heading for closed-loop control, with and without disturbance.

Q3 - Which of the two control systems (open-loop and closed-loop) performs better, with and without disturbance?

5. Assignment
Use the learning from 4b) to program the Taskbot to travel in a straight line for a distance equal to exactly 3 meters, in a minimum time. The maximum allowed horizontal deviation from the straight line trajectory is 3 cm.

Describe your method below, including changes to the motor powers, the gain Kp, the Time Rate of the loop, or any other parameter.

Distance traveled = ______________, Error from allowed horizontal deviation = __________

Time = ______________

6. Results and Conclusions
Turn in Module 1 with:
- all tables completed, and all questions in 4a), 4b) (Q1-Q3) answered.
- the method used and the results obtained in part 5."

Appendix B. Assessment Rubric for "Introduction to Engineering and Design" Modules

Module	Criterion	Performance Level			
		Accomplished	Satisfactory	Developing	Unsatisfactory
#1	Ability to perform assigned task	Completed/ obtained value for TKE	Almost completed/ obtained velocity value, no TKE value	Attempted/ ran experiment, did not calculate velocity or TKE	Did not attempt
	TKE Accuracy	Within 5%	Within 10%	Within 20%	> 20%
	Ability to answer end-of-module questions	80% answered correctly	70% answered correctly	60% answered correctly	< 60% answered correctly
#2	Ability to perform assigned task	Completed/ obtained value for # degrees	Almost completed/ programming done, did not obtain value for # degrees	Attempted/ set-up experiment, started programming	Did not attempt
	Degrees accuracy	Within 5%	Within 10%	Within 20%	> 20%
	Ability to answer end-of-module questions	Complete, accurate answers	Complete, mostly accurate answers	Attempted to answer	Incomplete
# 3	Ability to perform assigned task	Completed/ new gear train introduced, gave detailed description	Almost completed/ new gear train introduced, did not give detailed description	Attempted/ new gear train unfinished, no detailed description	Did not attempt
	Top speed	Achieved	Sound approach, incomplete testing	Started work	Did not attempt
	Ability to answer end-of-module questions	80% answered correctly	70% answered correctly	60% answered correctly	< 60% answered correctly