ECE3 Final Report

Summer 2020, August 15
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Introduction and Background

The aim of this four week ECE3 project was to program the MSP432 microcontroller from Texas Instruments which would be used to develop an autonomous mobile robot that would follow a black line path. More specifically, the mobile robot must be able to complete two predetermined track courses by precisely going one way and back on the course. An open source integrated development environment (IDE) called Energia was used to create the software framework for the mobile robot which was compatible with the TI launchpad. Specifically in the code, the design selected for development of the project was the combined use of Infrared (IR) sensors and a proportional-derivative controller which is the control loop mechanism that enables the mobile robot to precisely follow the black lines laid out by specific track designs.

The pins that are used for this design of the project includes the motor pins controlling the direction of the wheels pins, awake and ready pins for the PWM (Pulse Width Modulation) and the PWM pins themselves. There are also bumper switch assembly and user programmable LED lights which are additional tools used to help development and debugging process.

To develop the path sensing system, 8 IR sensors have been placed beneath and across the mobile car robot from right to left in which the first IR sensor and reading will correlate to the sensor closest to the right wheel of the car. The IR readings range from 0 to 2500 which correlates to maximum to minimum reflectance or absorption of color or infrared light respectively. The readings are due to the functionality of the sensors converting varying RC times into the value range between 0 to 2500. In other words, the readings of 2500 on the IR sensor would indicate that the IR sensor is on a black segment piece which projects minimum reflectance to the IR sensor. Using the sensor fusion implementation [1], the software for the car would take in the readings of the 8 IR sensors to input into a sensor fusion equation and process the data into a single number known as the fusion output. This number, which is also known as the error, is vital in signifying to the car how accurate or off the car is from the black line path. Ideally, a fusion output number of 0 would indicate that the car is precisely centered on the line while a higher magnitude number of possibly 2300 would mean that the car is experiencing high error and is nearly off the track. The fusion output number also functions as the error variable used in the PD equation. Given the tested variables of Kp and Kd, a PD number is calculated by adding the product of Kp and the error with the product of Kd and the difference in error from the previous error. This PD value is then subtracted to the base speed of the left wheel and added to the right wheel of the car *(PD = K_p * error + K_d * [error - previous_error])*. This overall process concludes the essence of the PD control mechanism which is looped in the software every 50 milliseconds and allows the mobile robot to follow the path.

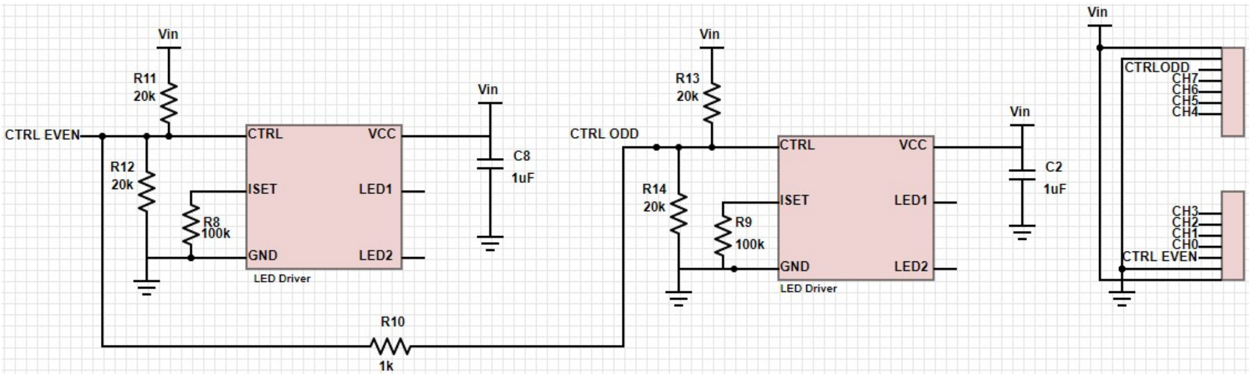


Figure 1. *8-Channel QTRX Sensor Array Circuit Schematic. Created using Scheme-it [2]. Digi-Key Electronics, 2020. Digi-Key. Web. 14 August 2020. www.digikey.com/schemeit/project/*

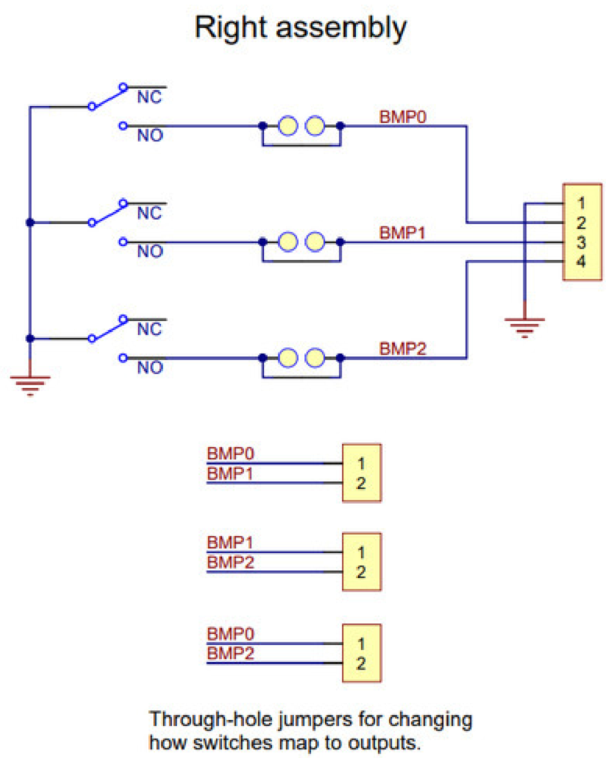


Figure 2. *Right Bumper Switch Schematic [3]. Pololu Corporation 2020. https://www.pololu.com/product/3674*

MSP432 Pin Layout	
Main headers J1-J4:	Energia Pin #
PWML, Left Motor PWM	40
PWMR, Right Motor PWM	39
nSLPL [2]	31
nSLPR [2]	11
DIR_L	29
DIR_R	30
Bump 0 [3]	24
Bump 1 [3]	25
J5:	
Yellow Front Right LED	41
Red Back Right LED	58
Yellow Front Left LED	51
Red Back Left LED	57
Notes:	
[2] This disables a motor driver. 0 to sleep/stop.	
[3] Use Port 4 for edge-triggered interrupts	

Table 1. *MSP423 Pin Layout for pins used in this project.*

Testing Methodology

Test Setup

The testing and experimentation area for this project was done on a 50 x 100 inch hard tile floor which was the entrance of the front doors. Consequently, the only natural lighting came from small glass panes of the front doors. Most of the time, the lighting rarely escaped and directly shined on the tracks. The electrical characteristics of the test setup included the laptop with the energia code, the robot car with the TI launchpad, and numerous printed papers such as the straight line stability check, sensor calibration points, ribbon track, and short straight remote track. For the software, the motor and LED pins have been defined with variables and as "OUTPUT" while the right bumper was also defined using internal pullup resistors signified by "INPUT_PULLUP." Serial prints have also been used during this stage of the project for calculating PD and reading IR values to ensure functionality of the tests conducted. The software functions that are also written before the test was the 180 turn function which is called upon when the weighting of the sensor fusion is 0, in other words when the car detects a black cross piece.

Figure 3. *Workspace and Test Setup environment of the project.*

How the Tests were Conducted

Using the sensor calibration points template, the IR sensors of the car were initially sampled in order to gather data needed for the sensor fusion calibration. With the car and track facing and in front of the experimenter, the car would be tested on the template paper starting with the car on the very left of the track at the position marked -40 which signifies error magnitude of 40 away from the track. 5 sets of readings of the 8 IR sensors would then be recorded to the Serial Monitor and logged onto a Microsoft Excel sheet. Each reading occurs every second only for the initial data recording. The car would continue to the next position that is labeled -36 to repeat the data recording process, and this step continues in increments of 4 error positions until readings from -40 to 40 error has been logged onto the excel sheet.

Now dealing with the raw data, averages of 5 readings are taken for all the sensors at each error position that was experimented with. The minimum values of individual sensors were taken, and each sensor value was subtracted by the corresponding minimum value accordingly. After subtracting the corresponding minimum values, the maximum values of each sensor were used to normalize the overall data values of the sensors to 1000 (by multiplying by 1000 and dividing by the maximum value of the corresponding sensors). The sensor fusion output graph was then created through implementing weighting schemes known as (8-4-2-1)/4 (See Appendix) and (15-14-12-8)/8 on each error position which concluded the sensor fusion calibration process. Utilizing the tested datas such as minimum and maximum values, the process that was done on the excel was then transferred formulaically onto the Energia code in order to obtain values for the variable known as "error" in the PD formula calculations.

To put the PD equation into action for the car, Kp and Kd values would first need to be chosen before extensively testing and experimenting with different numbers to refine the accuracy of the car on the straight line path. Given that the initial speed used was 60 and the maximum error value was 2400, the Kp value to start with was .0125 since a change from 0 to maximum error should generate a PD value or speed change of 50% of the base speed using that Kp value. In this case, 50% of 60 was 30. The Kd value of 0.001 was arbitrarily chosen as a smaller value, and the combination of the Kd and Kp value led to the car did experience some oscillations. PD tuning was then needed to refine the stability of the car from being shaky when following a path. More oscillations would lead to increasing the value of Kd and/or decreasing the Kp value and logging the trials and errors. Perfecting the PD tuning for the base speed of 60 was required at the bare minimum before moving on to higher base speed and repeating the tuning process in order to shave the time trial record of the car.

The final, yet trivial piece of testing included the trial and experiment testing for the 180 turn of the car in which given the base speed used, the right amount of time would be tested such that the car would make a close enough 180 turn needed to head back the other way for a given track.

Data Analysis

Sensor Fusion Calibration

	ORIGINAL DATA (AVERAGE OF 5 READINGS)							
ERROR	S1	S2	S3	S4	S5	S6	S7	S8
-40	2370.2	706.8	697.6	675	721	730.2	697.6	767.4
-36	2500	1254.2	607.6	671	721.2	730.4	698.2	767.6
-32	2500	1787.2	562.8	653	721.6	730.8	698.6	767.6
-28	1555.2	2500	607.4	652.6	721.2	739.6	698.2	767.6
-24	675.6	2500	1161.2	562.6	721	739.6	698.2	767.6
-20	607.4	2389.2	2435.8	562.2	721.2	744.2	698.2	767.6
-16	697.2	1136.2	2500	858.4	674.4	743	697.2	766.2
-12	675.2	767	2500	1531.8	607.6	744	698	767
-8	675	881.8	1252.6	2500	743.4	720.4	707	766.4
-4	674.8	858.6	720.6	2500	1160.2	607.2	706.8	766.6
0	676	860	630.4	1745	1996.8	607.6	698.8	767.8
4	675.2	858.4	720.4	812.2	2500	951.2	629.8	766.4
8	676	860	699	585.2	2485	1875	562.4	768
12	675.2	859.2	721.2	675.2	1299.4	2500	675.2	767.2
16	674.8	859.4	721.2	674.8	674.8	2500	1323	629.8
20	675.4	859.8	721.4	675.4	652.4	2296.4	2436.2	629.8
24	674.4	857.8	720.2	674.4	743	996.8	2500	885.4
28	675	859.4	721	675	721	652.2	2500	1624.6
32	675	859.4	720.6	675	720.6	720.6	1485	2500
36	674.2	859.4	715.4	674.2	720	743.4	733.8	2500
40	675	860.2	716.2	675	720.8	744.2	629.8	2281.6
Minimum	607.4	706.8	562.8	562.2	607.6	607.2	562.4	629.8

Table 2. *Averages of the raw data and minimum values from each IR sensor.*

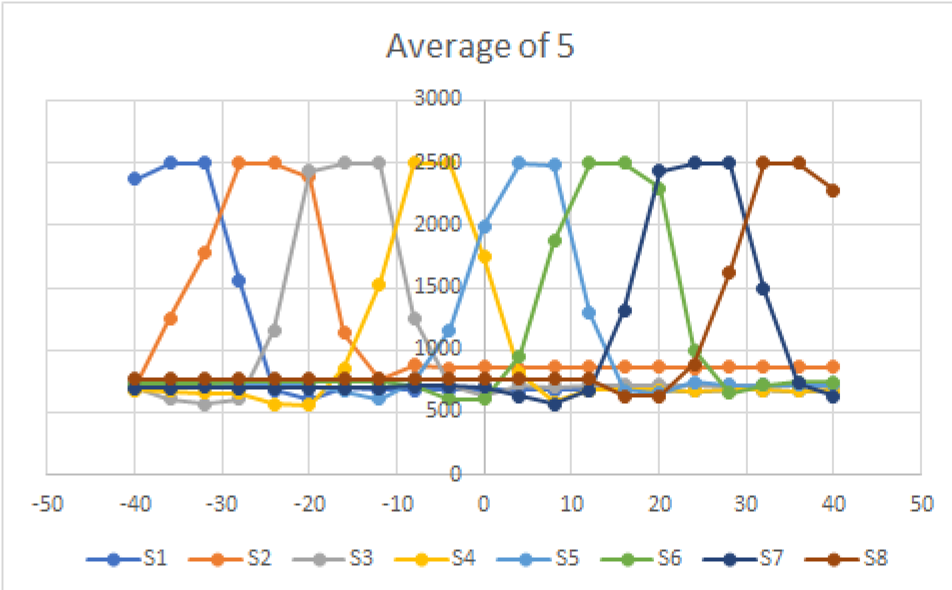


Figure 4. *Graph of the raw data averages.*

DATA WITH MINIMUM VALUE SUBTRACTED								
ERROR	S1	S2	S3	S4	S5	S6	S7	S8
-40	1762.8	0.0	134.8	112.8	113.4	123.0	135.2	137.6
-36	1892.6	547.4	44.8	108.8	113.6	123.2	135.8	137.8
-32	1892.6	1080.4	0.0	90.8	114.0	123.6	136.2	137.8
-28	947.8	1793.2	44.6	90.4	113.6	132.4	135.8	137.8
-24	68.2	1793.2	598.4	0.4	113.4	132.4	135.8	137.8
-20	0.0	1682.4	1873.0	0.0	113.6	137.0	135.8	137.8
-16	89.8	429.4	1937.2	296.2	66.8	135.8	134.8	136.4
-12	67.8	60.2	1937.2	969.6	0.0	136.8	135.6	137.2
-8	67.6	175.0	689.8	1937.8	135.8	113.2	144.6	136.6
-4	67.4	151.8	157.8	1937.8	552.6	0.0	144.4	136.8
0	68.6	153.2	67.6	1182.8	1389.2	0.4	136.4	138.0
4	67.8	151.6	157.6	250.0	1892.4	344.0	67.4	136.6
8	68.6	153.2	136.2	23.0	1877.4	1267.8	0.0	138.2
12	67.8	152.4	158.4	113.0	691.8	1892.8	112.8	137.4
16	67.4	152.6	158.4	112.6	67.2	1892.8	760.6	0.0
20	68.0	153.0	158.6	113.2	44.8	1689.2	1873.8	0.0
24	67.0	151.0	157.4	112.2	135.4	389.6	1937.6	255.6
28	67.6	152.6	158.2	112.8	113.4	45.0	1937.6	994.8
32	67.6	152.6	157.8	112.8	113.0	113.4	922.6	1870.2
36	66.8	152.6	152.6	112.0	112.4	136.2	171.4	1870.2
40	67.6	153.4	153.4	112.8	113.2	137.0	67.4	1651.8
Maximum	1892.6	1793.2	1937.2	1937.8	1892.4	1892.8	1937.6	1870.2

Table 3. *Data with minimum value subtracted and maximum value calculated.*

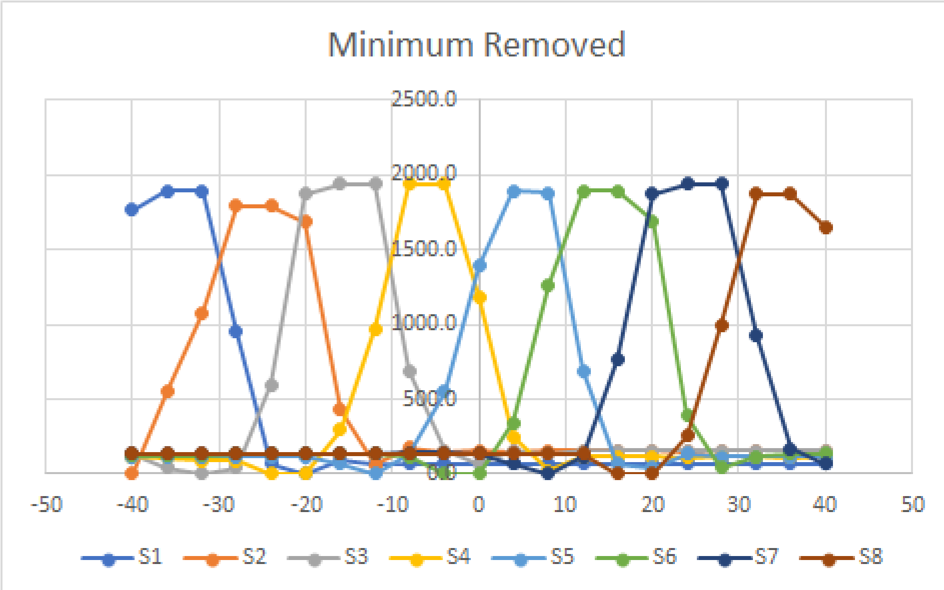


Figure 5. *Graph with the minimum value subtracted from raw data averages.*

DATA NORMALIZED TO 1000								
ERROR	S1	S2	S3	S4	S5	S6	S7	S8
-40	931.4	0.0	69.6	58.2	59.9	65.0	69.8	73.6
-36	1000.0	305.3	23.1	56.1	60.0	65.1	70.1	73.7
-32	1000.0	602.5	0.0	46.9	60.2	65.3	70.3	73.7
-28	500.8	1000.0	23.0	46.7	60.0	69.9	70.1	73.7
-24	36.0	1000.0	308.9	0.2	59.9	69.9	70.1	73.7
-20	0.0	938.2	966.9	0.0	60.0	72.4	70.1	73.7
-16	47.4	239.5	1000.0	152.9	35.3	71.7	69.6	72.9
-12	35.8	33.6	1000.0	500.4	0.0	72.3	70.0	73.4
-8	35.7	97.6	356.1	1000.0	71.8	59.8	74.6	73.0
-4	35.6	84.7	81.5	1000.0	292.0	0.0	74.5	73.1
0	36.2	85.4	34.9	610.4	734.1	0.2	70.4	73.8
4	35.8	84.5	81.4	129.0	1000.0	181.7	34.8	73.0
8	36.2	85.4	70.3	11.9	992.1	669.8	0.0	73.9
12	35.8	85.0	81.8	58.3	365.6	1000.0	58.2	73.5
16	35.6	85.1	81.8	58.1	35.5	1000.0	392.5	0.0
20	35.9	85.3	81.9	58.4	23.7	892.4	967.1	0.0
24	35.4	84.2	81.3	57.9	71.5	205.8	1000.0	136.7
28	35.7	85.1	81.7	58.2	59.9	23.8	1000.0	531.9
32	35.7	85.1	81.5	58.2	59.7	59.9	476.2	1000.0
36	35.3	85.1	78.8	57.8	59.4	72.0	88.5	1000.0
40	35.7	85.5	79.2	58.2	59.8	72.4	34.8	883.2

Table 4. *Data normalized to 1000.*

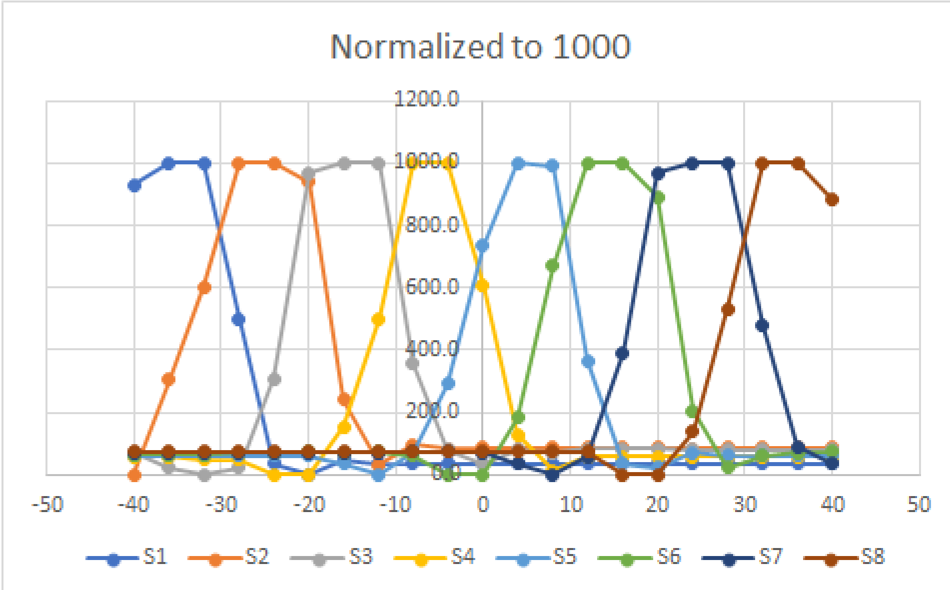


Figure 6. *Graph of the data normalized to 1000.*

WEIGHTING SCHEME		
ERROR	(8-4-2-1)/4	(15-14-12-8)/8
-40	-1647.8	-1491.5
-36	-2065.9	-2081.6
-32	-2348.8	-2556.9
-28	-1757.3	-2344.4
-24	-959.2	-1855.5
-20	-1153.0	-2662.8
-16	-612.4	-1759.5
-12	-477.5	-1757.8
-8	-328.5	-1342.9
-4	-152.8	-777.5
0	73.6	115.8
4	292.6	1004.3
8	534.7	1800.5
12	584.4	1708.3
16	689.7	1826.0
20	1206.5	2656.8
24	1184.0	1993.0
28	1878.8	2446.3
32	2309.2	2461.6
36	1929.8	1806.1
40	1641.2	1491.6

Table 5. *Data of the (8-4-2-1)/4 and (15-14-12-8)/8 Weighting Scheme Calculations.*

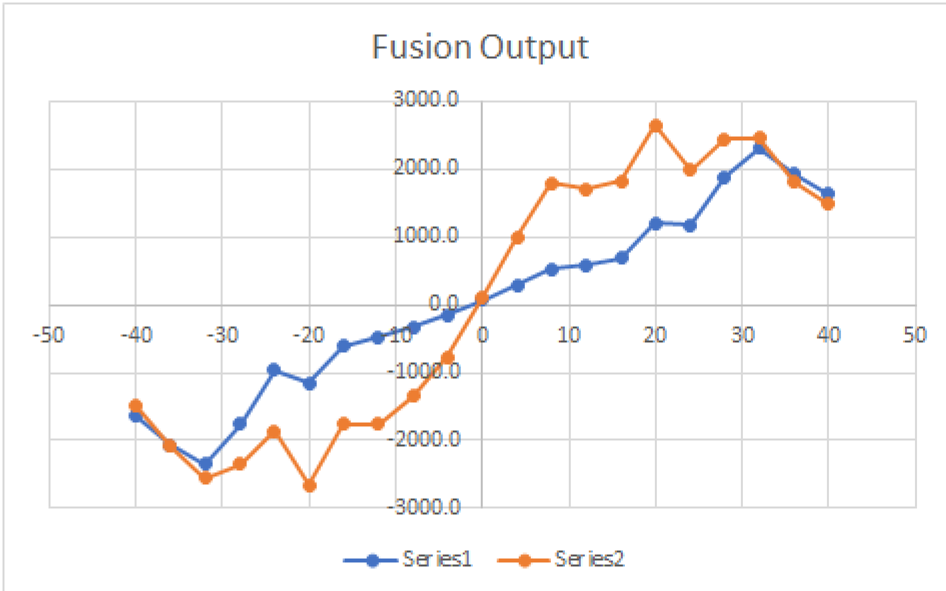
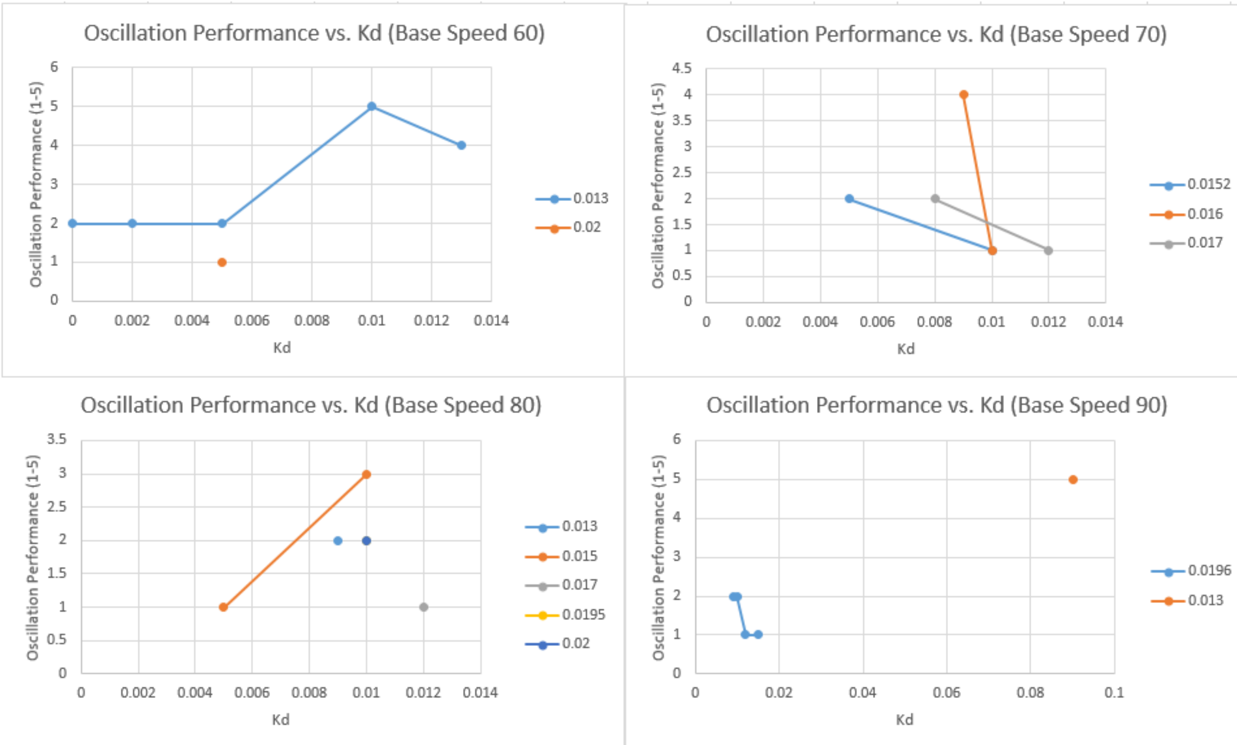


Figure 7. *Data of the Weighting Scheme Calculations plotted on a graph.*

PD Tuning Analysis

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Testing Base Speed 60						
Kp	0.013	0.013	0.013	0.013	0.013	0.02
Kd	0	0.002	0.005	0.01	0.013	0.005
Number of oscillation	5	5	5	3	3	7+
Notes		Kd made no change		more stable	no change	
Testing Base Speed 70						
Kp	0.0152	0.0152	0.016	0.016	0.017	0.017
Kd	0.005	0.01	0.01	0.009	0.008	0.012
Number of oscillation	3	6	7+	3	5	7+
Notes	can't detect X		still oscilalte	good	can't detect X	bad
Testing Base Speed 80						
Kp	0.013	0.015	0.015	0.017	0.0195	0.02
Kd	0.009	0.01	0.005	0.012	0.01	0.01
Number of oscillation	5	3	6	4	5	5
Notes	can't detect X			can't detect X		
Testing Base Speed 90						
Kp	0.0196	0.0196	0.0196	0.0196	0.013	
Kd	0.009	0.01	0.012	0.015	0.09	
Number of oscillation	3	3	5	7+	0	
Notes					BEST	

Table 6. *Data of Kp and Kd values from trial and error method .*



Figures 8-11. *Graphs of Oscillation Performance vs. Kd values for constant Kp values and a given base speed.*

Test Data Interpretation

The raw data obtained from each IR sensor seem to be consistent in it's graphs with each other, but the peaks of the averages for the sensor fusion seem to be flatter than expected compared to the idealized data with sharper peaks. The reasoning for the dullness in the peaks was due to the IR Sensor seeming to strongly read the black strip of the path in 3 consecutive error positions when sampling the data. These results are evident in Figures 4, 5, and 6 as the data was scaled down and normalized to lower magnitude readings. Consequently, implementing the weighting scheme had a more jagged curve as opposed to an ideal smooth curve approximately between 0 and 30 error. As much as the car was moved, the weighting scheme implementation was not able to create a value of zero which makes an offset default value for when the car is dead center on the path. However, the value is small enough such that the car does not seem to oscillate much given that it is already following the line. As the car continues off the track starting from the center, the error value from the weighting scheme would slowly project an increasing value overall until it passes the +/- 30 error threshold in which the error value seems to linearly decrease as opposed to its initial quadratic-like increase. The (8-4-2-1)/4 was the weighting scheme chosen for the PD testing.

The base speeds for which I tested Kp and Kd extensively was the base speed of 60 before proceeding to test for subsequent higher base speed chronologically, using the previous trials as indicators of where to start the testing values. Highlighted data from Table 6 shows the optimal Kd and Kp values that were tested for each given base speed. These datas are consistent throughout all of the positions as they pose the same quality of performance. The overall trend shows the Kp typically being directly proportional to the base speed, but the Kp value for base speed of 90 was the outlier. Furthermore, having the Kp value be the quotient of 50% of the base speed and the maximum error value proved to be a safe estimate mechanism in ball parking which Kp value would most likely get the car through the track albeit unstable at times. From there, a reliable Kd value would be tested for, and the trials concluded the general relationship of Kd being less than Kp for the car to run optimally. However, data appeared to be inconclusive in determining what proportion of Kp should Kd be for the car to run the best. The data crystalizes on the fact of constant Kp and Kd values not being optimal for different base speeds, and the Kp and Kd values must be changed accordingly. For lower base speed, a small Kd value proved to be sufficient, but increasing Kd and lowering Kp for the base speed of 90 seemed to work exceptionally well which was later used on race day.

Results and Discussion

Test Discussion

The tests and data collected were appropriate to the project goals in developing a PD loop function for the car to effectively follow the given paths at any of the detailed starting positions. The sensor fusion calibration and output portion of the testing methodology were essential in making the sensors of the car useful, and the weighting schemes were needed to simplify the definition of error bounds for the car. From there, the PD variables could be further tested and refined given the error.

More work is required in order to reduce other issues and variables that would impact the performance of the car. This includes battery life and the indication of a cross piece by the car. The code for the car must layout the directions for what the car must do in the case of detecting a black cross piece. Regardless of the code, natural lighting will always be an external factor to account for which would impact the time of day to test and calibrate the car or the development of an auto-calibration mechanism into the car. With the given tools and knowledge, extensive testing through trial and error for the PD variables is very vital to ensure increasing accuracy and performance from the car. Evidently, higher base speed would sacrifice the precision and adaptability of the car, so different and higher values of PD variables would need to be tested.

PD has been proven to be very effective in executing this project despite excluding the integral portion for the equation. Kp is the proportional control value which has a direct relationship to the error between the current position and targeted position. Kd is the derivative control value which takes into account the rate of change of the error and also adjusts the speed accordingly. The combination of Kp and Kd allows the car to correctly sense and remain on the path since Kd would offset the constant oscillation which Kp otherwise would have posed in the project.

Race Day Discussion

On Race Day in the summer of 2020, the vehicle performed exceptionally well in terms of precision and functionality. In other words, the vehicle was able to successfully complete the straight and ribbon paths on its first attempt with the given starting positions by the professor. Moreover, the vehicle had experienced no oscillations throughout the duration of its path. In terms of the timing, the vehicle managed to reach the minimum threshold times of under 10 seconds and 20 seconds for the straight and ribbon paths respectively which was expected from the test runs prior to race day. For the straight path, the vehicle obtained a time of approximately 7.4 seconds with the starting position of 2. For the ribbon path, the vehicle received a time of about 14.15 seconds with the starting position of 4. Fortunately, the vehicle did not seem to show any signs of malfunctions or bugs of any sort.

The limitations of the code would be the lack of awareness in terms of battery strength left in the current batteries provided. This is due to the untapped use of having the code read in the current battery life and set the base speed and even Kd and Kp variables depending on the remaining power of the battery. Additionally, a joint limitation of the code and car would be the vulnerability that the IR sensors have towards natural lights such as the sun shining through the small glass window of the door. To minimize this potential hole, the windows had been patched with paper to reduce the external factors impacting the code and car. As for the track, the code has been specifically designed to execute specific paths such as the ribbon and straight paths which included only one intersection and no sharp turns.

The way I would have conducted the project differently would be to tweak the sampling process of the sensor fusion calibration by actually taking a wider range of error due to the imperfections of how the sensor fusion graphs presented. I would have also attempted to implement the integral portion or Control Law parameters into the PID equation in order to refine the accuracy and capabilities of the path finder for the car. With more knowledge, I would look towards adding telecommunication aspects to the program that requires addition to the hardware of the car to wirelessly read the IR sensors to the computer. This would help the PID process and tuning much more in terms of time efficiency and shocking precision for following the line and debugging.

Conclusions and Future Work

Ultimately, the software and hardware design successfully met my goals of completing the track in a timely manner with more efficiency than expected. The hardware design of the car accompanied with the IR sensors and button switches proved to be reliable and intact, and the Energia code was developed enough for the car to experience little to no failure rates by the time race day came around. It did not take long to create the code such that the car can put the IR readings to use and at least complete the track with some sort of initial oscillation, but continuous and tedious testings of the Kp and Kd values resulted in strikingly successful combinations of PD variables that would be used as default for race day.

I have gained a greater understanding of how useful and extensive PID controllers can be which can be applied to the simple IR sensors or large scale autonomous projects that are used in the real world. The underestimated appearance of Kd and Kp values actually proved to be the core facilitators in bringing the PD controlling mechanism of the vehicle to life. However, even a poor choice of Kd and Kp value would still generate conclusive results of how autonomous machines can direct themselves without a conscious host to control them. As for the technicalities of project management, it seems to be an effective approach to break down the project agenda into pieces to tackle each day rather than being consumed by the entirety of the project all at once. With continual testing, I learned that the weakening of the batteries do show in the trials as the functions that intended on making 180 turns only made 170 turns or less which meant more adjustments and variables to constantly consider. Although this project is a simple scale example of a PD controller at work, I attained a greater appreciation for these feedback mechanisms which are the very framework that led to development in some of the industrial systems and projects people know today.

With more time, I would have redone the sensor fusion calibration and sampling better in order to improve the sensor fusion output graph which would produce more distinct peaks. This would have a greater impact on the precision of the sensor fusion and path following mechanism, and changing the values of Kp and Kd are likely to have more noticeable impacts. Another approach would also be the self-calibration implementation which would also make the hardware of the project be more adaptable to the environment given the varying natural light that would impact IR sensor readings. I would have more confidently looked towards implementing an auto calibration mechanism to the car which would also use more of the bumpers, buttons, and user switches that had been unused, yet available to me throughout my project. If time allows, plenty of more trial and error tests would be conducted for the Kp and Kd values, but with much greater base speed in order to see where the true speed limits of PID are at, assuming there are limits in the given range of 0 to 255 for the motor.

References

[1] Briggs, Dennis M. "Sensor Fusion Explanation." Dennis M. Briggs, 14 July 2020.

[2] Digi-Key. "Scheme-It." *Scheme-It | Free Online Schematic and Diagramming Tool | DigiKey Electronics*, Digi-Key Electronics, 14 Aug. 2020, www.digikey.com/schemeit/project/.

[3] Pololu. "Pololu - Right Bumper Switch Assembly for Romi/TI-RSLK MAX (Through-Hole Pins Soldered)." *Pololu Robotics & Electronics*, Pololu Corporation, 2020, www.pololu.com/product/3674.

Appendix

(8-4-2-1)/4

The weighting scheme used for the sensor fusion process. Given that S1 through S8 resembles the readings of sensor 1 to sensor 8 for one error respectively, the format of (8-4-2-1)/4 correlates to the mathematical formula of (-8*S1 - 4*S2 - 2*S3 - 1*S4 + 1*S5 + 2*S6 + 4*S7 + 8*S8) / 4. The same approach goes for (15-14-12-8)/8 weighting scheme with only the corresponding numbers of the formula varying.