Portland State University

Embedded Systems on FPGAs

ECE544

Closed-Loop Control With PWM

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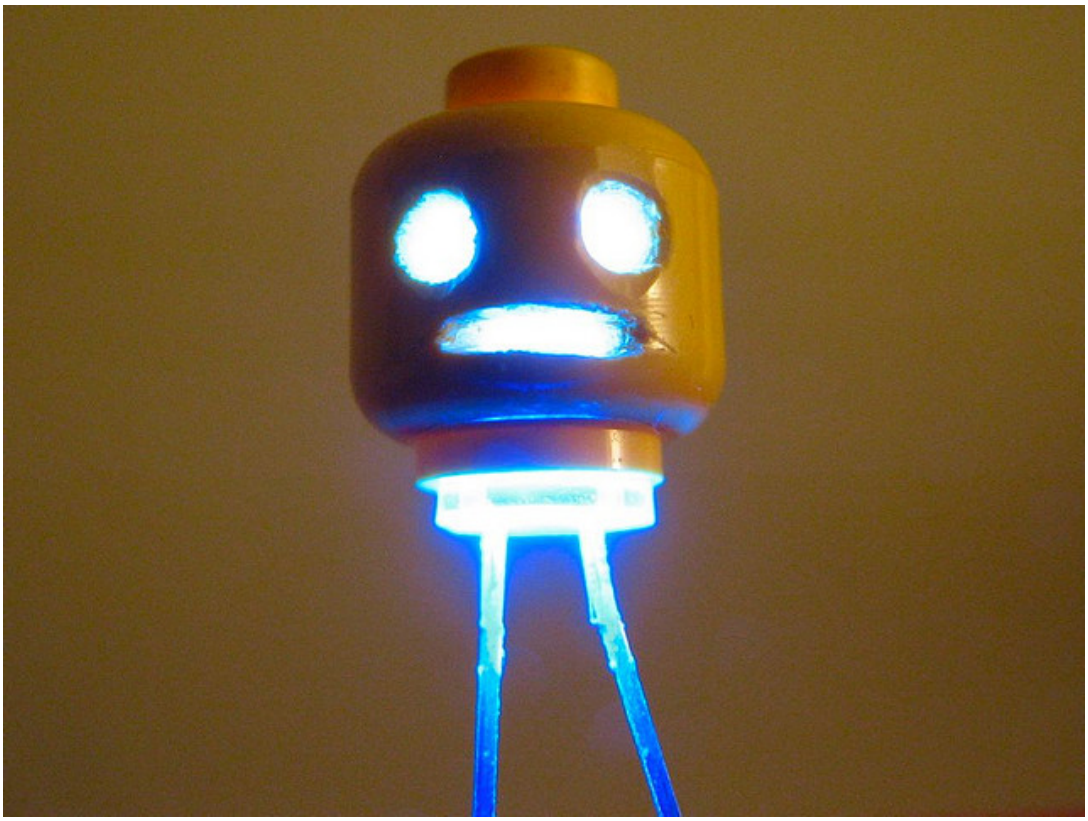

1 Introduction

This project demonstrates how closed-loop control can be used in modern applications. Our embedded system monitored the brightness of an LED with a light sensor and calculated the corresponding PWM output to stabilize the brightness at the desired setpoint.

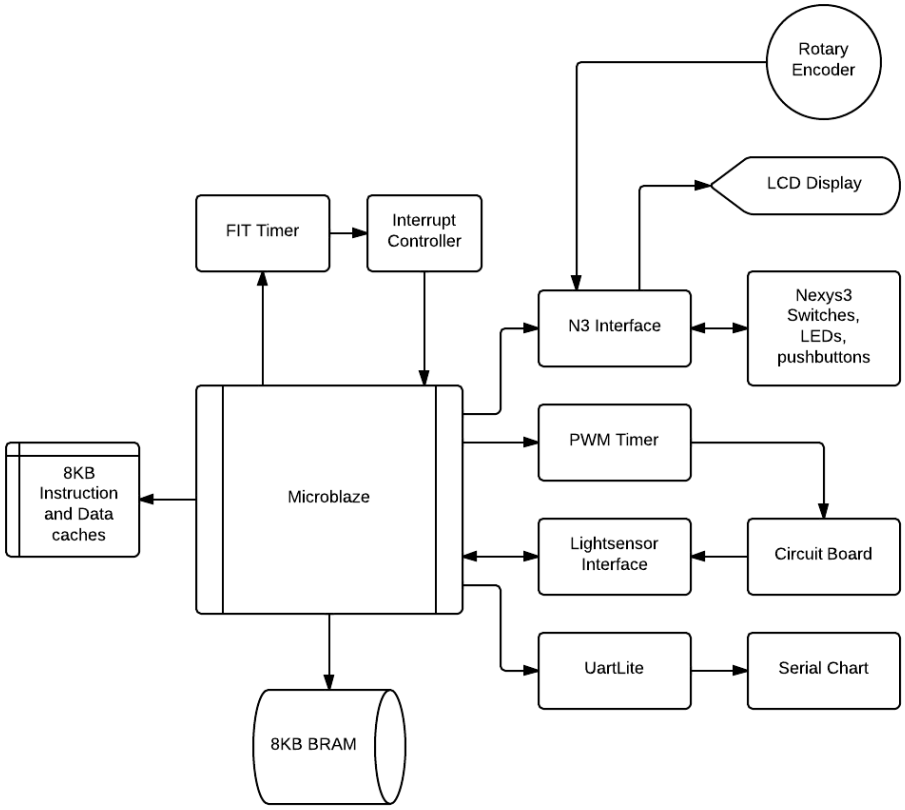

Figure 1: Block Diagram of Control System

2 System Design

As seen in figure 1, our embedded system includes numerous peripherals and components. Our **lightsensor** peripheral interacts with the circuit we built on a breadboard. This connects the **PWM timer** to the LED (through pin 7), and receives the detected brightness from the light sensor through another pin (pin 9). The **Uartlite** peripheral sends the computed data to the external hardware serially through a USB port. This data can then be seen using different programs, such as *Putty* or *Serial Charter*. The graphs showing our results (reference) were created using *Serial Charter*. The **N3EIF** interface controls the communication to the LCD display and the rotary encoder. In order to allow this functionality, 8KB of **BRAM** was added, and instruction and data caches were included as well. While GPIO pins were technically included in our system, they existed simply for debugging purposes and therefore were not added to the diagram.

3 Implementation

3.1 Control Methodology

Being able to control a dynamic system is an integral part of many everyday systems. Accomplishing this requires a feedback loop with an external measurement of the output being fed back into the system. These systems can be controlled in a number of ways. Two popular methods are **Bang Bang** and **PID**.

3.1.1 Bang Bang

Bang bang is quite straightforward: if the output is lower than desired, the controller puts the control signal at its highest amount. Likewise, if the output is higher than desired, the signal is set to the lowest level. While sometimes effective, this is a crude and cheap method for controlling systems, and is usually only used in devices where accuracy is not extremely important. The algorithm used in our program is seen below.

Listing 1: Bang Bang Algorithm

```
for (smpl_idx = 1; smpl_idx < NUM_FRQ_SAMPLES; smpl_idx++)
    {
        sample[smpl_idx] = LIGHTSENSOR_Capture(LIGHTSENSOR_BASEADDR, slope, offset
            , is_scaled, freq_min_cnt);
        volt_out = (-3.3 / 4095.0) * (sample[smpl_idx]) + 3.3;
        if (volt_out < setpoint)
        {
            Status = PWM_SetParams(&PWMTimerInst, pwm_freq, MAX_DUTY);
            delay_msecs(1);
            if (Status == XST_SUCCESS)
            {
                PWM_Start(&PWMTimerInst);
            }
        }
        else
        {
            Status = PWM_SetParams(&PWMTimerInst, pwm_freq, MIN_DUTY);
            delay_msecs(1);
            if (Status == XST_SUCCESS)
            {
                PWM_Start(&PWMTimerInst);
            }
        }
        delay_msecs(100);
    }
```

3.1.2 PID

The more prevalent method, PID, involves making multiple calculations to predict the accurately control the behavior of the output. The proportional (P) method involves using the previous error margin to calculate the next appropriate one. The integral (I) method calculates how the system behaves over time, and the derivative (D) calculates how fast the output is changing at that point in time. Our implementation is seen in listing 2.
Using a specific arrangement of these parameters will yield a large increase in accuracy, so tuning the application is desirable. When tuning, we first attempted to follow the *Ziegler-Nichols*

method. After understanding how each method changes the output, we modified the parameters as we saw fit to acquire the most accurate configuration for our control system.

Listing 2: PID Algorithm

```
1    for (smpl_idx = 1; smpl_idx < NUM_FRQ_SAMPLES; smpl_idx++)
2    {
3        delay_msecs(100);
4
5        // get count from light sensor and convert to voltage
6        sample[smpl_idx] = LIGHTSENSOR_Capture(LIGHTSENSOR_BASEADDR, slope, offset,
             is_scaled, freq_min_cnt);
7        volt_out = (-3.3 / 4095.0) * (sample[smpl_idx]) + 3.3;
8
9        // calculate derivative;
10       error = setpoint - volt_out;
11       deriv = error - prev_error;
12
13       // calculate integral
14       if (error < setpoint/10) integral += error;
15       else integral = 0;
16
17       // Control offset is gotten from characterization
18       volt_out = offset + (error * prop_gain) + (deriv * deriv_gain) + (integral
             * integral_gain);
19       duty_out = (volt_out)* (MAX_DUTY+1)/VOLT_MAX;
20
21       // establish bounds
22       if (duty_out < 1) duty_out = 1;
23       if (duty_out > 99)duty_out = 99;
24
25       // activate PWM
26       Status = PWM_SetParams(&PWMTimerInst, pwm_freq, duty_out);
27       if (Status == XST_SUCCESS)  PWM_Start(&PWMTimerInst);
28   }
```

3.2 Peripheral Interface

The **TSL237** light-to-frequency converter outputs a period that directly corresponds to the intensity of the light emitted from the LED. The PWM detection module receives this information and converts it to a "count", which is then scaled to fit within the parameters (between 0 and 4095) needed for our control calculations. These functions are handled in the light sensor driver. The driver initially converted the scaled counts to a voltage, but we later decided to move that functionality to the program application. The peripheral has the user-visible registers described in table 1.

Register	Number	Format	Description
Control	slv_reg0	RESERVED[30:0], EN	Enable of the peripheral
Status	slv_reg1	RESERVED[30:0], EN	Current settings of the peripheral
HighTime	slv_reg2	HighTime[31:0]	Detected high time count
Period	slv_reg3	Period[31:0]	Detected period count
SpareReg1	slv_reg4	RESERVED[31:0]	No specific purpose
SpareReg2	slv_reg5	RESERVED[31:0]	No specific purpose

Table 1: Lightsensor peripheral registers

3.3 Peripheral Driver

The `lightsensor` driver enables the software application to communicate with the external peripheral. It has six functions:

- **LIGHTSENSOR_Init()** Initializes the `lightsensor` peripheral driver. It waits until the light sensor self test is done then it sets the control enable bit to 0.
- **LIGHTSENSOR_Start()** Starts the PWM detection in the peripheral. This function sets the Control Enable bit to 1.
- **LIGHTSENSOR_Stop()** Stops the PWM detection in the peripheral. This function sets the Control Enable bit to 0.
- **LIGHTSENSOR_Capture()** This function returns the period count by reading the PERIOD register. If the characterize function has been called already, the `is_scaled` boolean would be set to true and the capture function returns the scaled period count based on the formula

$$count = (Xuint32)(slope * (period - min) + 1); \tag{1}$$

- **LIGHTSENSOR_SetScaling()** Not implemented since we decided to do the scaling directly in the application program. Here is what the scaling looks like in the code:

$$diff = freq\_max\_cnt - freq\_min\_cnt; \tag{2}$$

$$slope = 4095.0/diff; \tag{3}$$

- **LIGHTSENSOR_Count2Volts()** Also not used because we do the conversion in the program directly. Here is what the conversion looks like in the code:

$$volt\_out = (-3.3/4095.0) * (sample[smpl\_idx]) + 3.3; \tag{4}$$

3.4 Frequency detection

The measurements output by the light sensor were received by a hardware module that interpreted the data. This Verilog program closely resembles the PWM detection module done in project 1. It increments the count on each clock edge, depending on whether the input is high or low. Once a full period is detected, the high count and period are sent to registers which are able to be read by the light sensor driver.

3.5 User Controls

The program starts by characterizing the system. This allows the initial scaling to be performed, which varies by the amount of light detected by the light sensor. After this is done, the default control parameter values are displayed and the user is given a chance to change them. The type of test and starting input voltage can also be selected. Once these have been configured, the user starts the test with the rotary button. When it has finished, long pressing on the rotary button sends the data to the computer connected serially via the UART port. If the user wants to change the test, they can modify the switch values and update the LCD by pressing on the rotary button. While the user interface remained close to the recommended specifications, it also included a few features that made it amazingly incredible. The control assignments are seen in table 2.

Name	**Value**	**Function**
Switch[1:0]	00	Bang Bang
Switch[1:0]	01	PID
Switch[1:0]	10	Unused
Switch[1:0]	11	Characterization
Switch[2]	0	Vin Low
Switch[2]	1	Vin High
Pushbutton	North	Move Cursor
Pushbutton	East	Increase Value
Pushbutton	West	Decrease Value
LCD Display	Row 1	PID Values
LCD Display	Row 2	Setpoint and Offset
Rotary Encoder	Clockwise	Increase Setpoint
Rotary Encoder	Counter-Clockwise	Decrease Setpoint
Rotary Encoder	Press Button	Next section
Rotary Encoder	Long Press Button	Initiate test

Table 2: Nexys3 Controls

4 Results

4.1 Characterization

Our characterization is fairly linear. It drops off at the end because the stepping from high to low ends at the 99th sample.

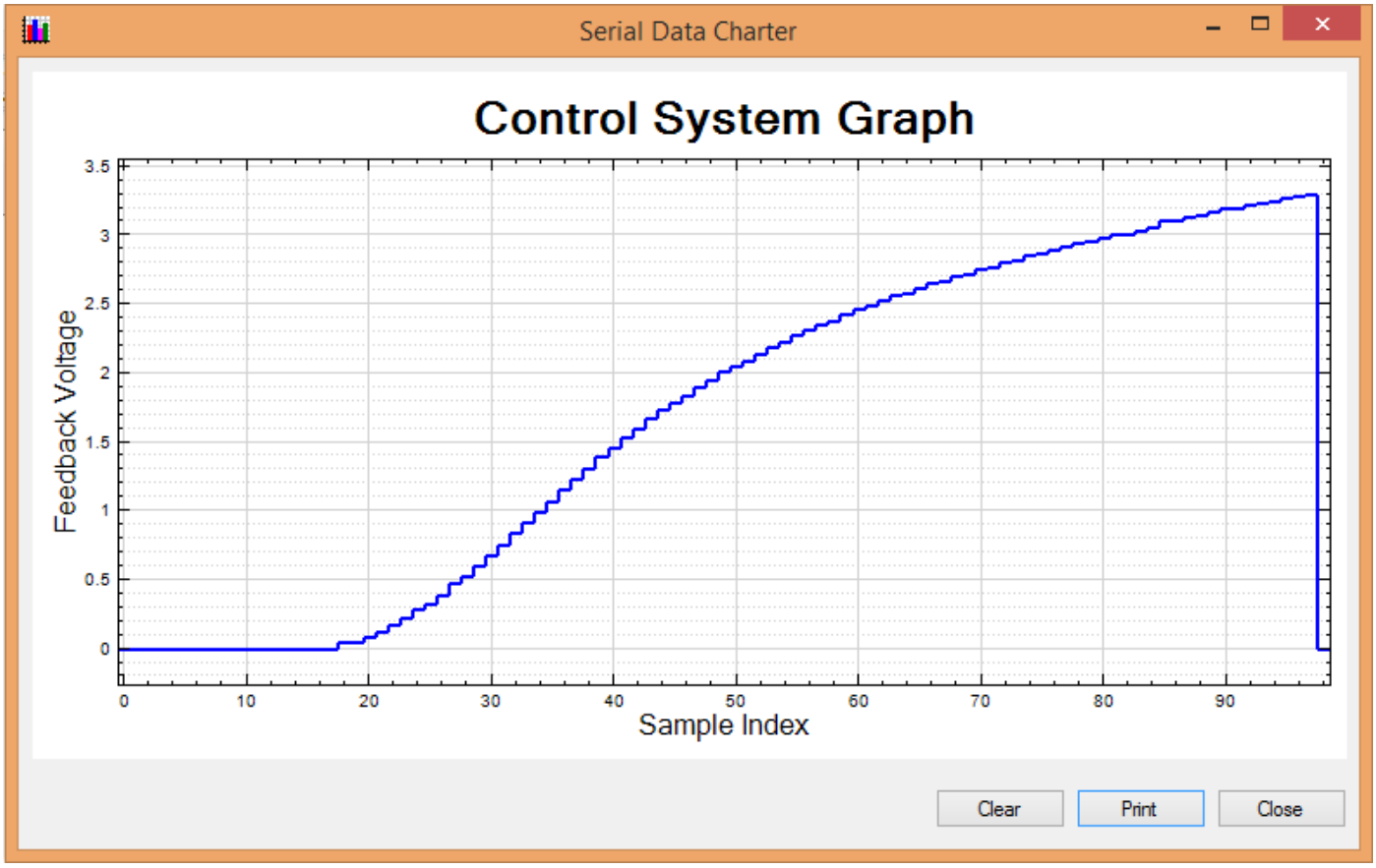

Figure 2: Characterization of light sensor

4.2 Bang Bang

Oscillates back and forth around the setpoint.

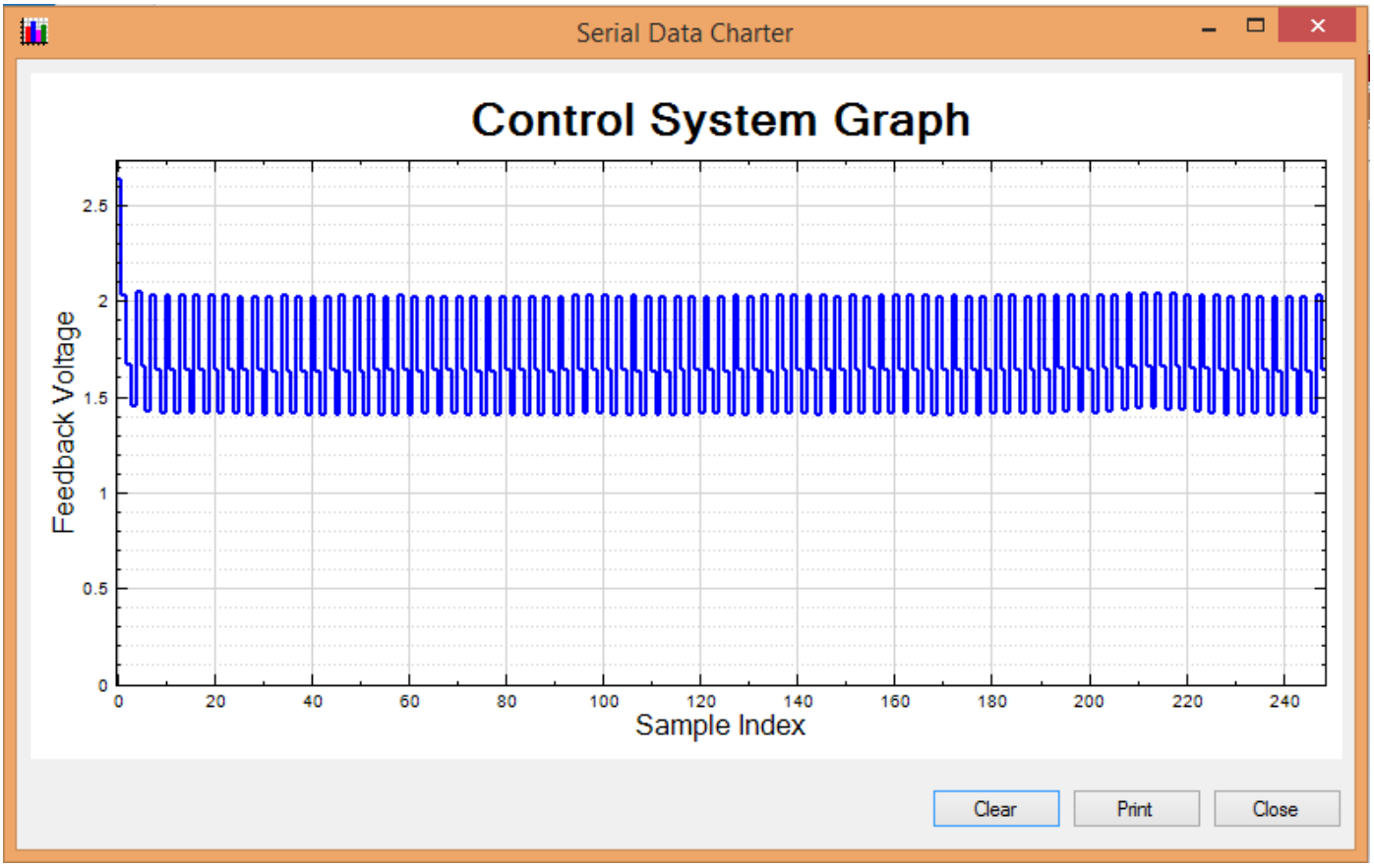

Figure 3: Results using Bang Bang Control: setpoint=1.46 , starting from Vin high

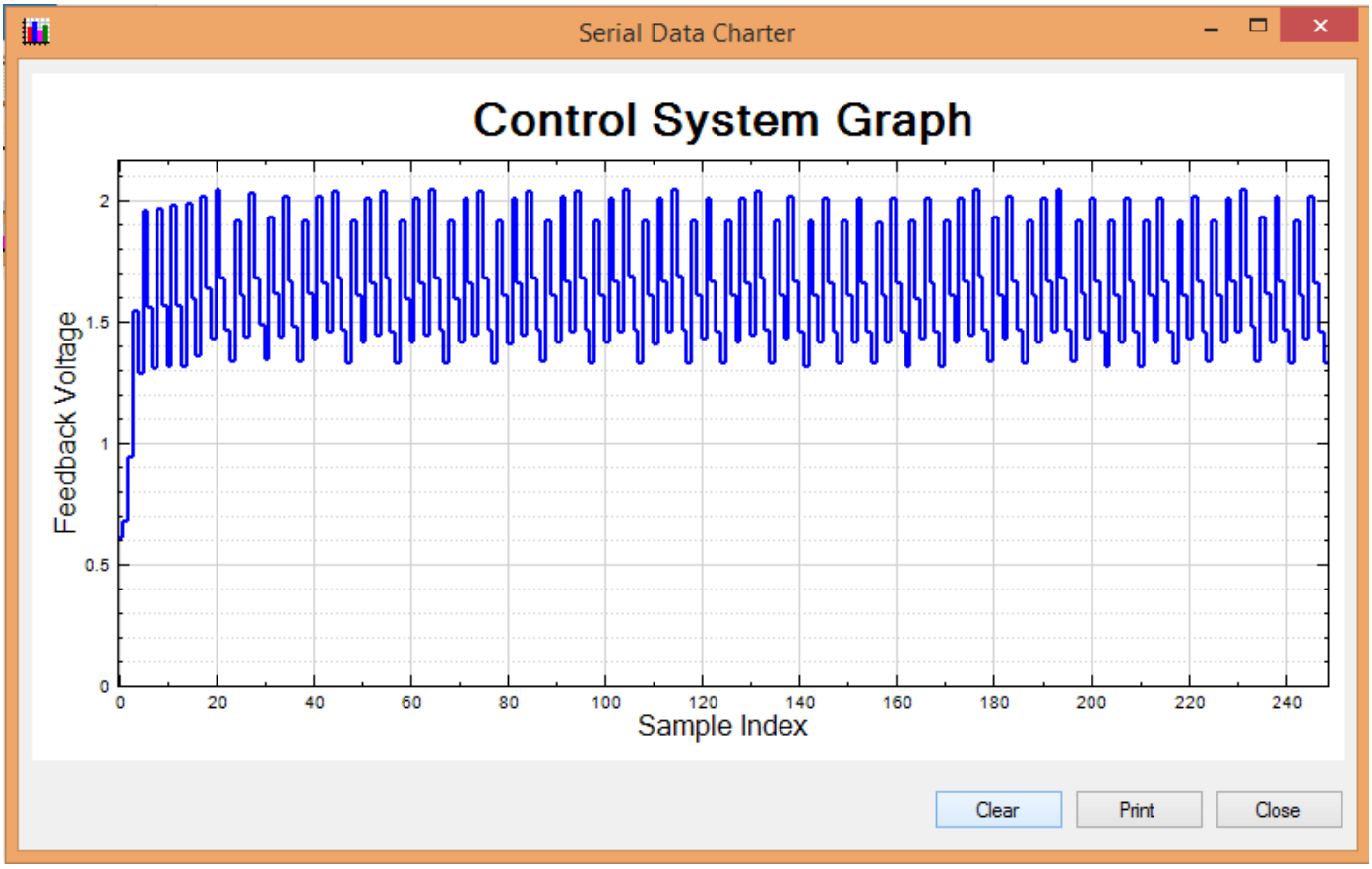

Figure 4: Results using Bang Bang Control: setpoint=1.46 , starting from Vin low

4.3 PID

The following figures show some accurate results:

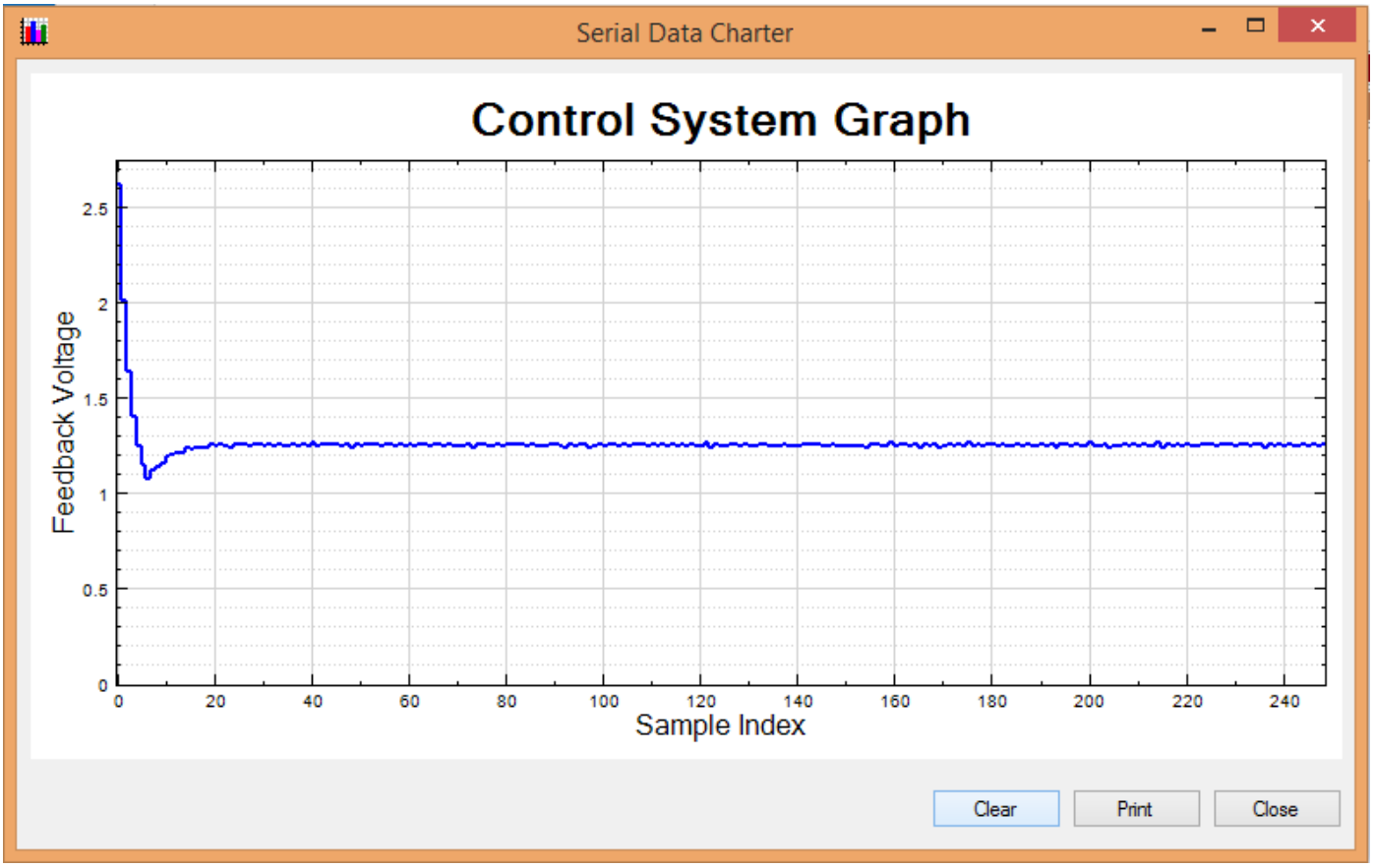

Figure 5: Results using PID Control: P gain = 3.1, I gain = 1.1, D gain = 2.1, Offset = 2 and setpoint = 1.26. (starting from Vin High)

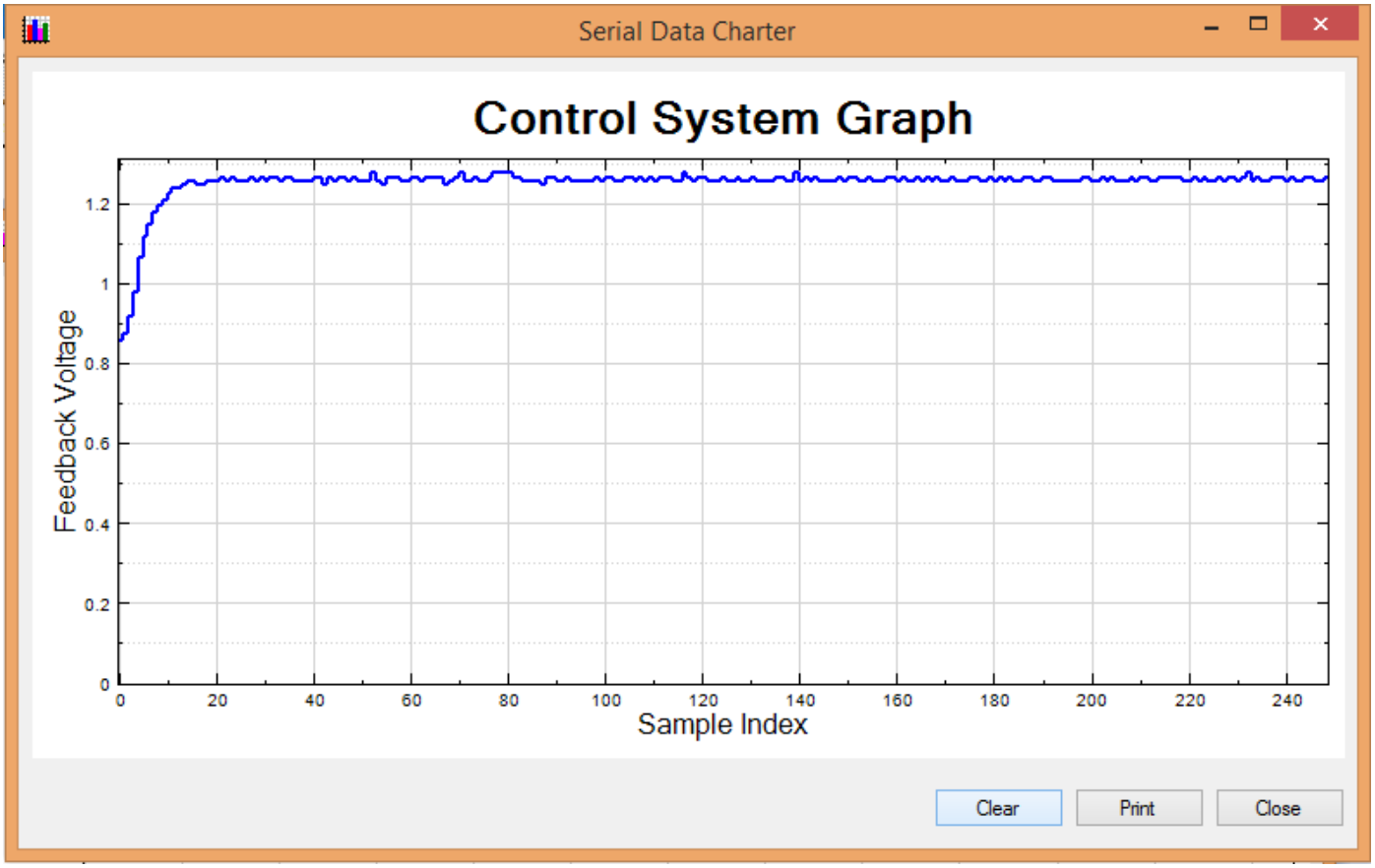

Figure 6: Results using PID Control: P gain = 3.1, I gain = 1.1, D gain = 2.1, Offset = 2 and setpoint = 1.26. (starting from Vin Low)

5 Conclusion

We split up the project tasks in the following manner:

Task	Erik	Caren
Peripheral		✓
Lightsensor Driver		✓
User application	✓	
Integration	✓	✓
Documentation	✓	✓

Table 3: Division of Tasks

5.1 Challenges

- **Tools**: The Xilinx tool chain was quite a hassle to deal with. There was also a problem connecting one of our circuit boards to the Nexys3. Additionally, the UART serial USB connection also caused repeated BSOD's on our computer.

- **Hardware interfacing**: Although we took the same module used in project one for the hardware PWM detection, it did not work. After narrowing down this problem, we swapped the module out and were able to receive reliable results.
- **Typecasting**: In several different places, using the wrong type gave us incorrect values. Making sure each variable was initialize and cast to the correct type took time, and before this was done we received incorrect or imprecise values.
- **Integration**: We divided the project into two different parts, which were both written in a relatively quick amount of time. Given the number of components in this system, however, it was quite a challenge to integrate and fix all the different issues that occurred when they were merged together.

While this project is certainly good practice for the real world, the amount of problems we faced was quite numerous. It is especially frustrating when the roadblocks we faced were not actually involving our code or the algorithms we were using. Instead, much of our time was spent wasted on getting the tools to cooperate. This lead to us spending at least 40 hours each on this project. With that being said, the concept of closed-loop control was quite interesting, and the results we finally achieved were satisfying.