Time-of-Flight Rangefinder

ECE 445
Design Review
Team 28
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Introduction

Title: 1D LiDAR Time-of-Flight Rangefinder

We have chosen to pursue this project because our group has a strong interest in optical applications. We are excited to work on this project because we believe our system can easily be extended to many different types of applications such as object detection on cars when reversing, speed detection on cars, or even large terrain mapping. Consequently, not only is the project quite versatile with respect to its practical applications, but it also incorporates topics that we are passionate about.

Objectives:

Two of the main goals of our project are to not only be able to accurately measure the distance to an object, but also be capable of determining if an object is moving and at what speed. Our goal is to design a system that can produce a measurement that is accurate to within 10 cm when limited to objects that are a maximum of 5 m away. After the system is powered on and initialized, the user will be able to choose what type of measurement they would like to take.

Benefits:

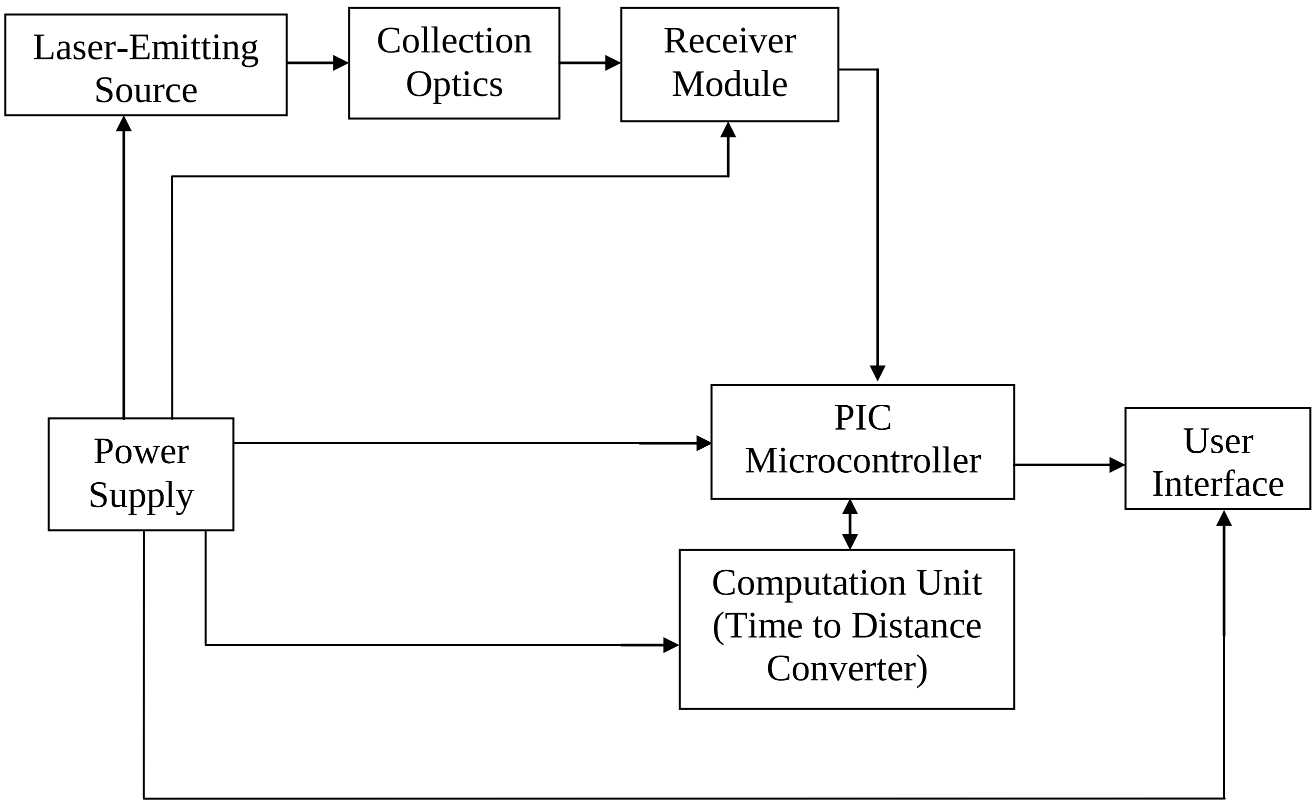
- Can be used in a variety of applications
- Maintains accuracy for objects within the stated range
- Results can be displayed to user within 10 seconds
- Uses safe laser power levels (5 mW)
- Uses visible (red) light to allow users to identify specifically what object they are measuring

Features:

- The design of individual components in our system can be incorporated into more advanced applications. For instance, if 3D spatial modeling were desired, only singular components such as the laser diode or the amplifier circuit need to be changed
- Clear display of results on LCD screen in real-time
- Tripod attachment for easy stabilization
- Frequency filtering to account for environmental noise
- Onboard storage in order to make speed estimates

Design

Block Diagram:



Block Descriptions:

Power Supply:
1. This component consists of a single 5 V power supply and voltage driver chip connected in a schematic layout as shown in Figure 1
2. We chose to use a single power supply in order to eliminate the hassle of turning multiple sources on and off during testing
3. If time permits, we would like to convert our project to using battery power for portability

Laser-Emitting Source:
1. This component of the system consists of a pulsed semiconductor laser diode which will mark the start and stop time for each trip the laser takes to the desired object
2. We will be using a 650 nm, 5 mW laser diode which is safe and easier to distinguish what objects are being pointed at due to the use of visible light
3. The decision to choose our specific laser was made because of its low cost ($9) as well as its very fast rise and fall times (1 ns and 2 ns respectively). These fast response times ensure that we can pulse our laser at high frequencies if necessary.
4. The laser will be pulsed using the FIRE_UP or FIRE_DOWN output from the TDC chip which will generate the necessary 2.7 V needed to turn the laser diode on.
5. We will also need to build a laser diode driver circuit (similar to what is shown in Figure 2) to protect our diode from burning out

Collection Optics:
1. We will position an optical Fresnel lens in front of the avalanche photodiode receiver in order to focus the light to have a higher power density for better reception
2. The lens will be housed in a simple screw ring mechanism that provides adjustability in lens positioning
3. The lens we chose is a Fresnel lens that has an effective diameter of 4 inches (101.6 mm) and an effective focal length of 2.8 inches (71.12 mm) as shown in Figure 3
4. The lens was chosen based on the desire to have high collection efficiency rather than creating a high resolution image and the desire to have as large a lens area as possible to collect the most amount of returning light while maintaining a small focal length to facilitate a physically small system

Receiver Module:
The receiver module consists of an avalanche photodiode, current-to-voltage transimpedance amplifier, and a simple band pass filter

Avalanche Photodiode:
1. We chose to use an avalanche photodiode because it has a much greater sensitivity to low intensity light when compared to an ordinary photodiode
2. The peak sensitivity wavelength of the avalanche photodiode is 620 nm which has a photosensitivity of 0.42 A/W as shown in Figure 4
3. The rise(response) time of our avalanche photodiode, t_r, has a relation with the cut-off frequency f_c as follows:
   $t_r = \frac{0.35}{fc} = \frac{0.35}{250E6} = 1.4$ ns

4. We chose an avalanche photodiode that has as large a receiving area as possible while maintaining a reasonable price. Although the active area is very small compared to the area of the focused light from the Fresnel lens, the lens can only focus light to finite resolution. We must completely illuminate the avalanche photodiode's active area in order to ensure that as much power is collected as possible

Current-to-Voltage Transimpedance Amplifier:

1. This stage consists of a simple current-to-voltage transimpedance amplifier (shown in Figure 5) in order to increase the voltage input to the PIC microcontroller
2. We will design this amplifier on a bread board using an operational amplifier and the appropriate value resistor in order to amplify the voltage by the desired amount

Band Pass Frequency Filter:

1. This component will consist of a resistor-capacitor circuit (shown in Figure 6) in order to filter out the environmental noise from the amplified APD signal
2. Since the frequency the laser diode will be pulsed at is relatively low (~2 kHz), using a band pass filter will isolate the received signal

PIC16F887 Microcontroller:

1. The PIC16F887 microcontroller that we will be using will be the main control of our system
2. It will send start and stop signals to our TDC chip as well as retrieve the calculated data from the chip
3. The PIC will also provide the necessary control to output our final results onto an LCD screen as well as store the appropriate data into onboard storage

Onboard Storage:

1. Onboard storage will also be implemented in our system in order to use multiple distance measurements to generate a speed calculation. The storage that will be used will be on the microcontroller itself in order to minimize acquisition time and maximize output generation
2. Storage will consist of a bank of 8-bit registers on the PIC16F887 microcontroller

TDC GP21 Chip:

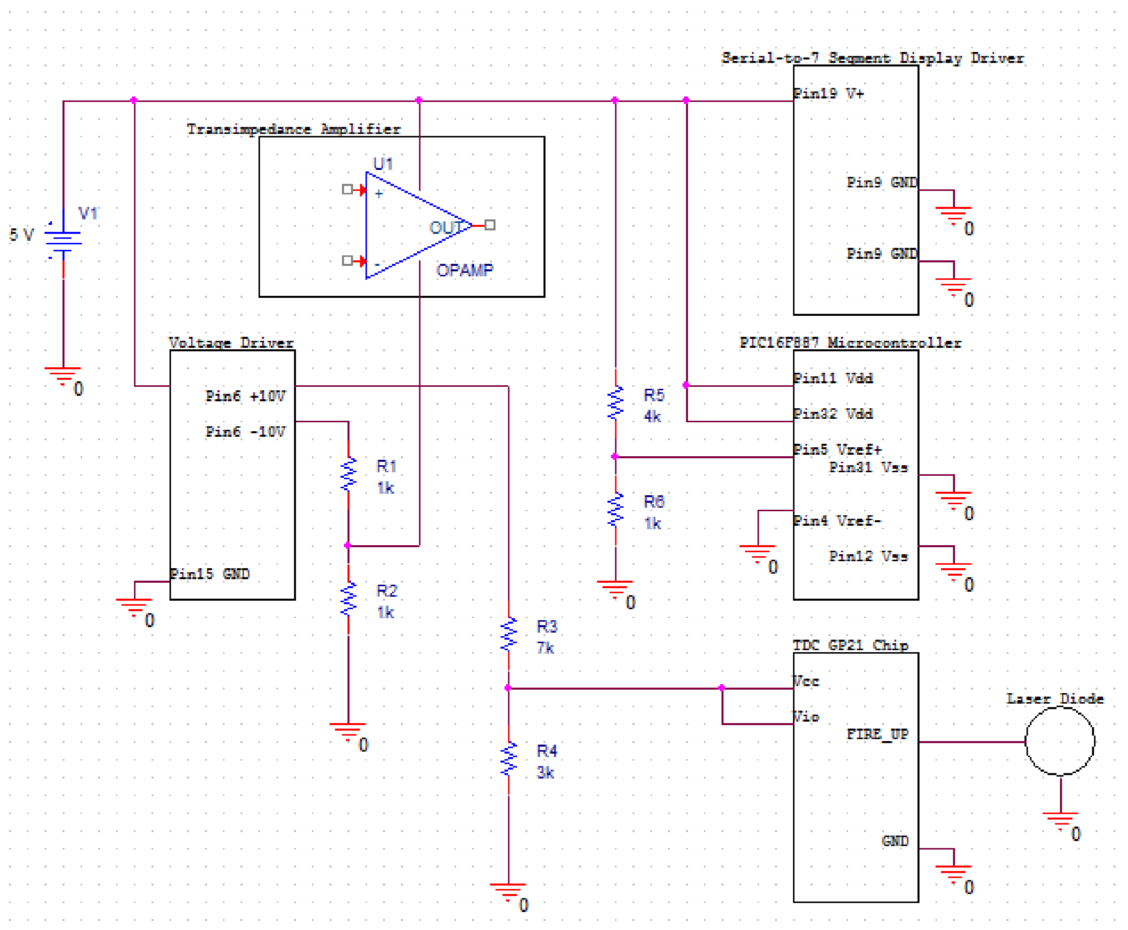
1. The TDC GP21 chip will be performing the time-of-flight calculations and outputting the results back to the PIC.
2. The basic process flow algorithm for our time-of-flight calculations is outlined in Figure 7
3. A simple layout of the pin connections between the PIC and the GP21 chip is shown in Figure 8

User Interface:

1. We will design a simple user interface in order to display the final result to the user. The final result will either be a distance measurement or a speed measurement displayed on an 7 segment LED display
2. The input to the LED display comes from the PIC after all the necessary calculations are made and passes through a BCD to 7-segment driver
3. The schematic of the LED display connecting to the PIC is shown in Figure 9

Figures, Schematics, and Simulations

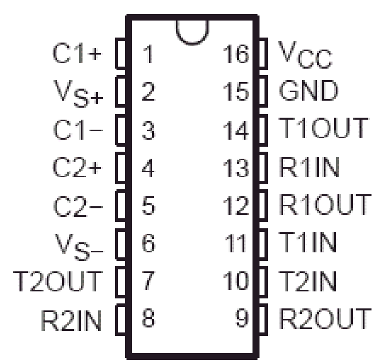
Figure 1



Power Consumption Estimate:

Individual Component Power Consumption:

TDC-GP21:	800mW
PIC:	800mW
MAX232:	842mW
MAX7219CNG:	1066mW
LTC-4627JR:	average 3430mW
Resistors:	~300uW



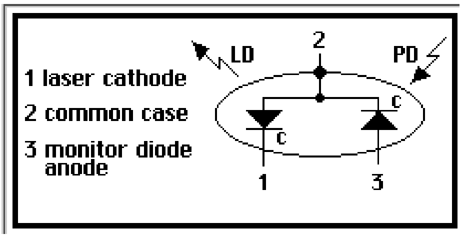
MAX232 PinOut

Power Supply:
9V lithuim Battery 1200mAh

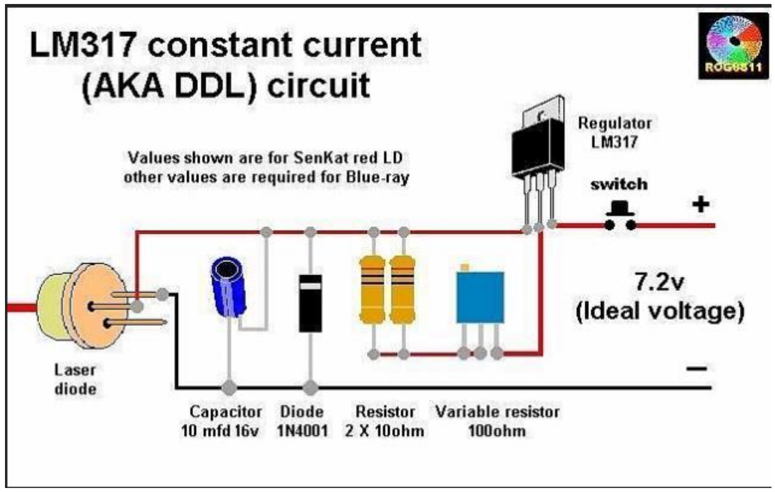
Estimate battery life: 1.2*9/P = $\boxed{\text{1.56 hours}}$

Figure 2

Laser Diode Schematic:

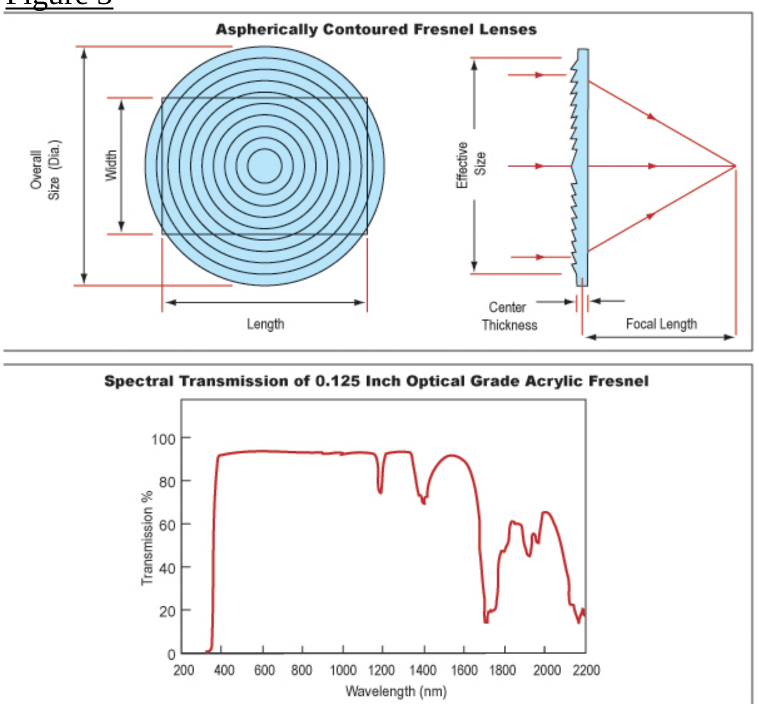


Laser Diode Driver Schematic:



Pin 1: Laser Cathode pin is connected to positive terminal
Pin 2: Common Case pin is connected to ground
Pin 3: Monitor Diode Anode is connected to negative terminal

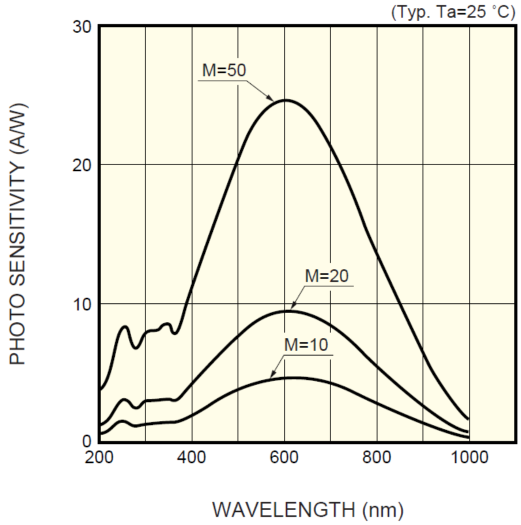
Figure 3



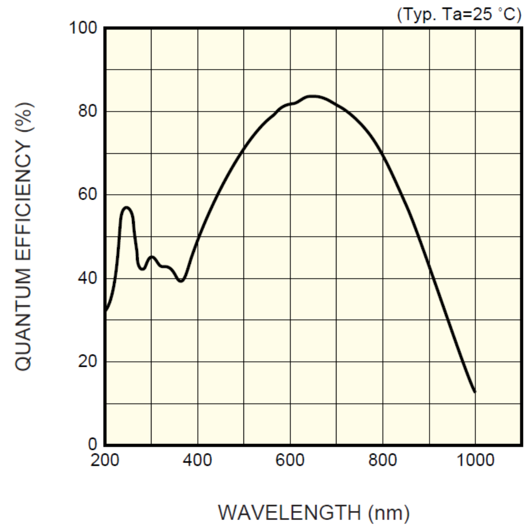
Effective Diameter: 101.6 mm
Effective Focal Length: 71.12 mm

<u>Figure 4</u>

■ Spectral response



■ Quantum efficiency vs. wavelength



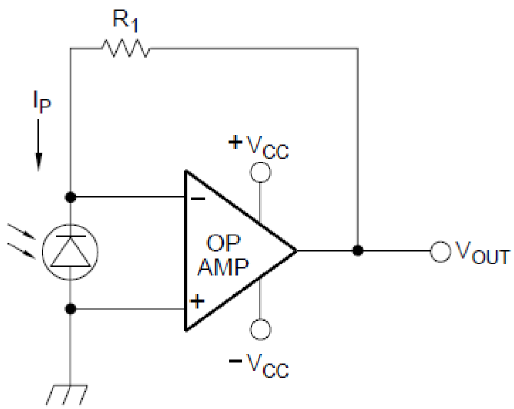
■ Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)

Type No.	Spectral response range λ (nm)	Peak *3 sensitivity wavelength λp (nm)	Photo sensitivity S M=1 λ=620 nm (A/W)	Quantum efficiency QE M=1 λ=620 nm (%)	Breakdown voltage VBR ID=100 μA Typ. (V)	Max. (V)	Temp. coefficient of VBR (V/°C)	Dark *3 current ID Typ. (nA)	Max. (nA)	Cut-off *3 frequency fc RL=50 Ω (MHz)	Terminal *3 capacitance Ct (pF)	Excess *3 noise figure x λ=650 nm	Gain M λ=650 nm
S9073	200 to 1000	620	0.42	80	150	200	0.14	0.2	5	900	3	0.28	50
S9074										400	7		
S5343										250	15		
S9075								0.5	15	100	30		
S5344								1	30	25	120		
S5345								3	100	8	320		

*1: U: UV glass
*2: Area in which a typical gain can be obtained.
*3: Values measured at a gain listed in the characteristics table.

Peak sensitivity wavelength, $\lambda_p = 620$ nm
Photosensitivity when gain M = 1 and λ = 620 nm = 0.42 A/W

Figure 5

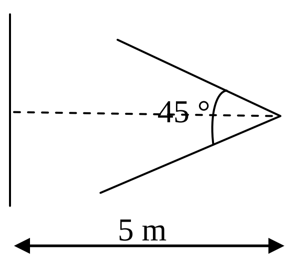


Power Degradation of Light through Air

$P(d) = P_0*e^\wedge(-\alpha*d)$ where α is the attenuation coefficient of the medium

P_0 = 5 mW from the laser diode source
α for air = 10^-5 m^{-1}
For a maximum distance of d = 5 m
P(d) = 4.99975 mW
Very little power is lost when passing through air.
Assume 80 to 90 percent of power is absorbed by desired object.
Therefore, the returning light only has about 1 mW.

Assume a maximum divergence angle when the light bounces of the object of 45 degrees.
Therefore, at 5 m, the radius of the beam of light at the photodiode is



R = 5tan(22.5°)
So the area of the returning beam of light is $A = \pi R^2 = \pi(2.0711)^2 = 13.475\ m^2$

Assuming uniform power distribution, our focusing lens(101.6 mm diameter) will capture

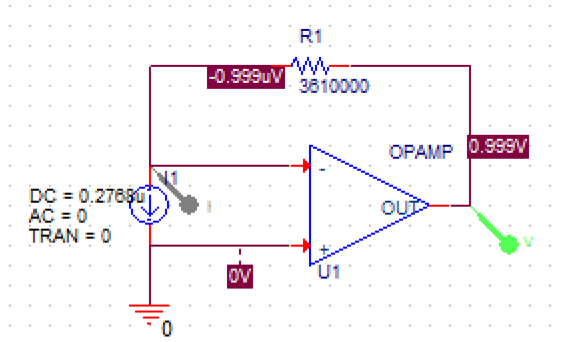
$P = P_0(\pi(0.0508)^2/13.475) = 0.6017\ \mu W$

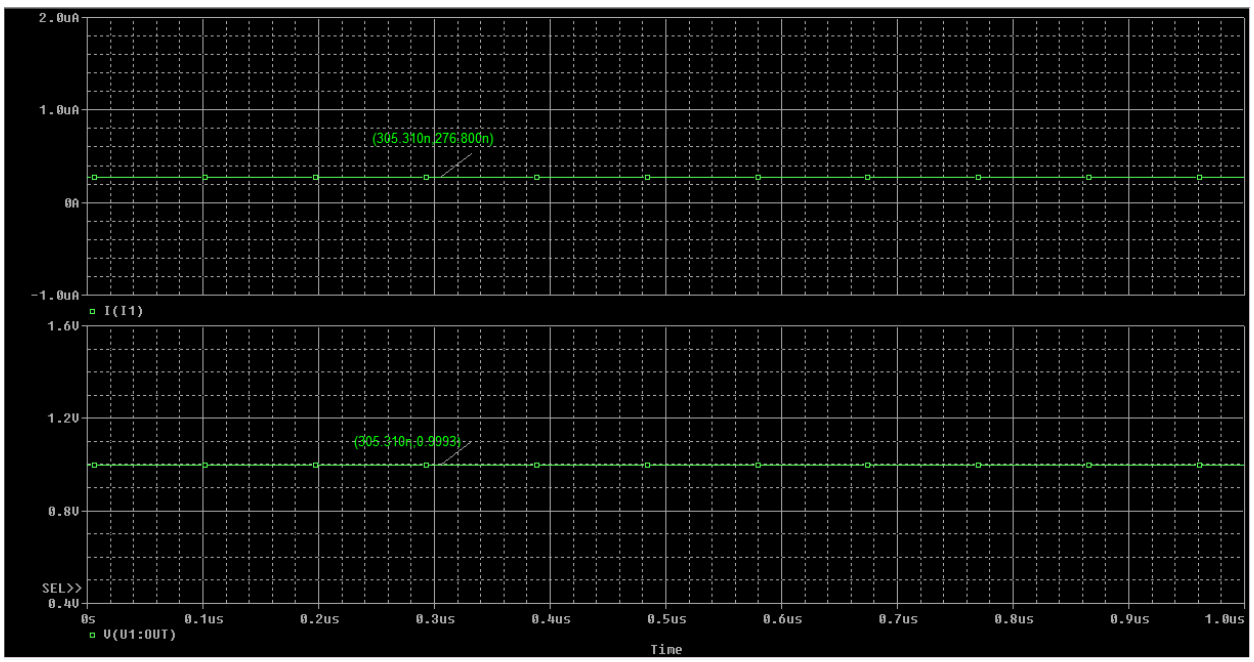
The photosensitivity of the avalanche photodiode is 0.46 A/W.
This 0.6017 μW of incident light on the avalanche photodiode produces a response of about 0.2768 μA.

Using our transimpedance amplifier circuit:

$V_{out} = I_{diode} * R1$
Input voltage to trigger the microcontroller chip is 1 V:

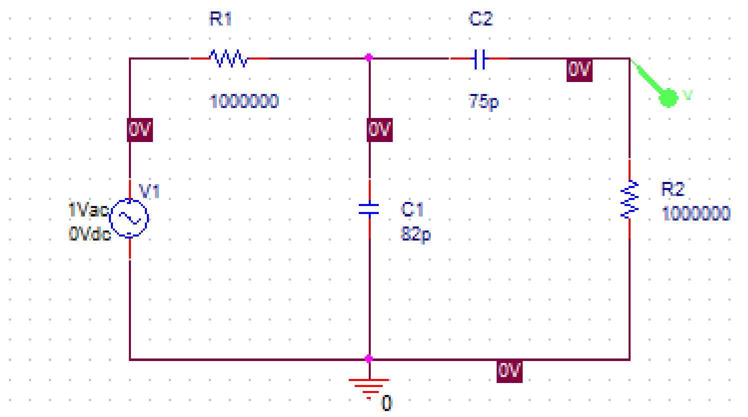
R1 = 3.61 MΩ





We treated the avalanche photodiode as a constant current source of value 0.2768 µA. The simulation confirms our calculation that the output voltage will be gained up to ≈ 1 V.

Figure 6



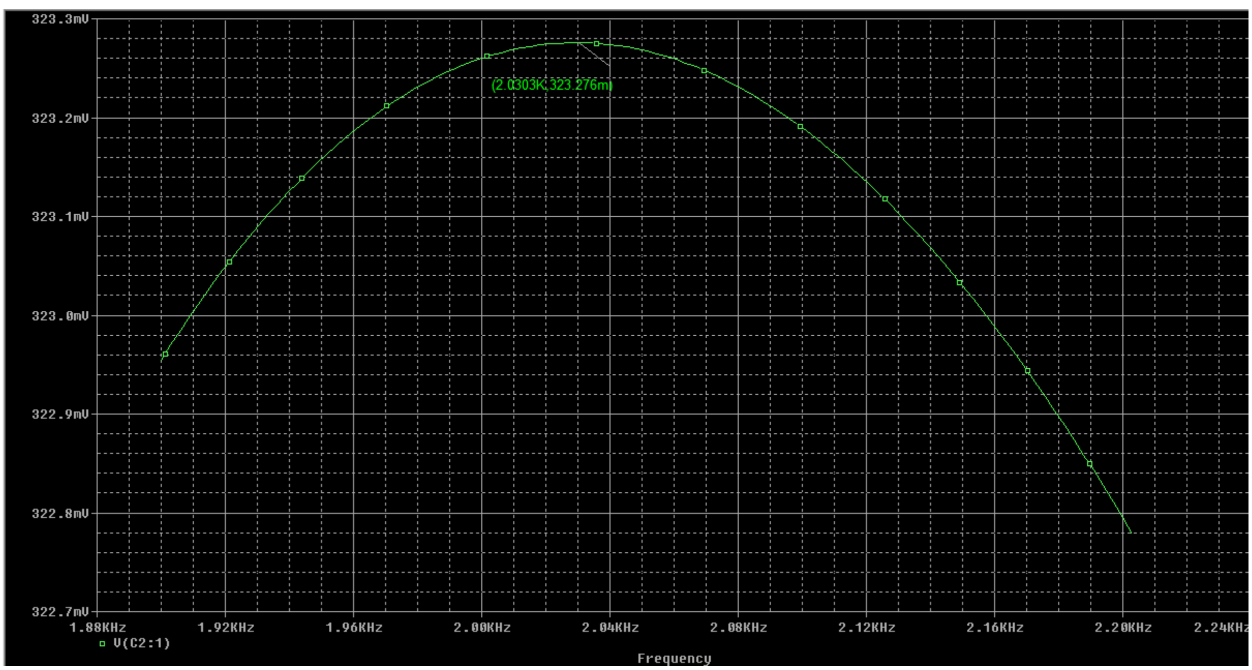
We chose to use a very large resistor value due to the low frequency rates we will be pulsing the laser diode at. We will be pulsing the laser diode at a frequency of 2 kHz.

Low pass filter section:

$C1 = \frac{1}{2\pi * fcl * R2}$ where f_{cl} is the lower cutoff frequency (~1.94 kHz)

High pass filter section:

$C2 = \frac{1}{2\pi * fch * R1}$ where f_{ch} is the higher cutoff frequency (~2.12 Hz)



Our simulation shows a good frequency response between a range of 1.9 kHz to 2.2 kHz which is acceptable since we will be operating our pulsed laser at a frequency of 2 kHz.

Figure 7

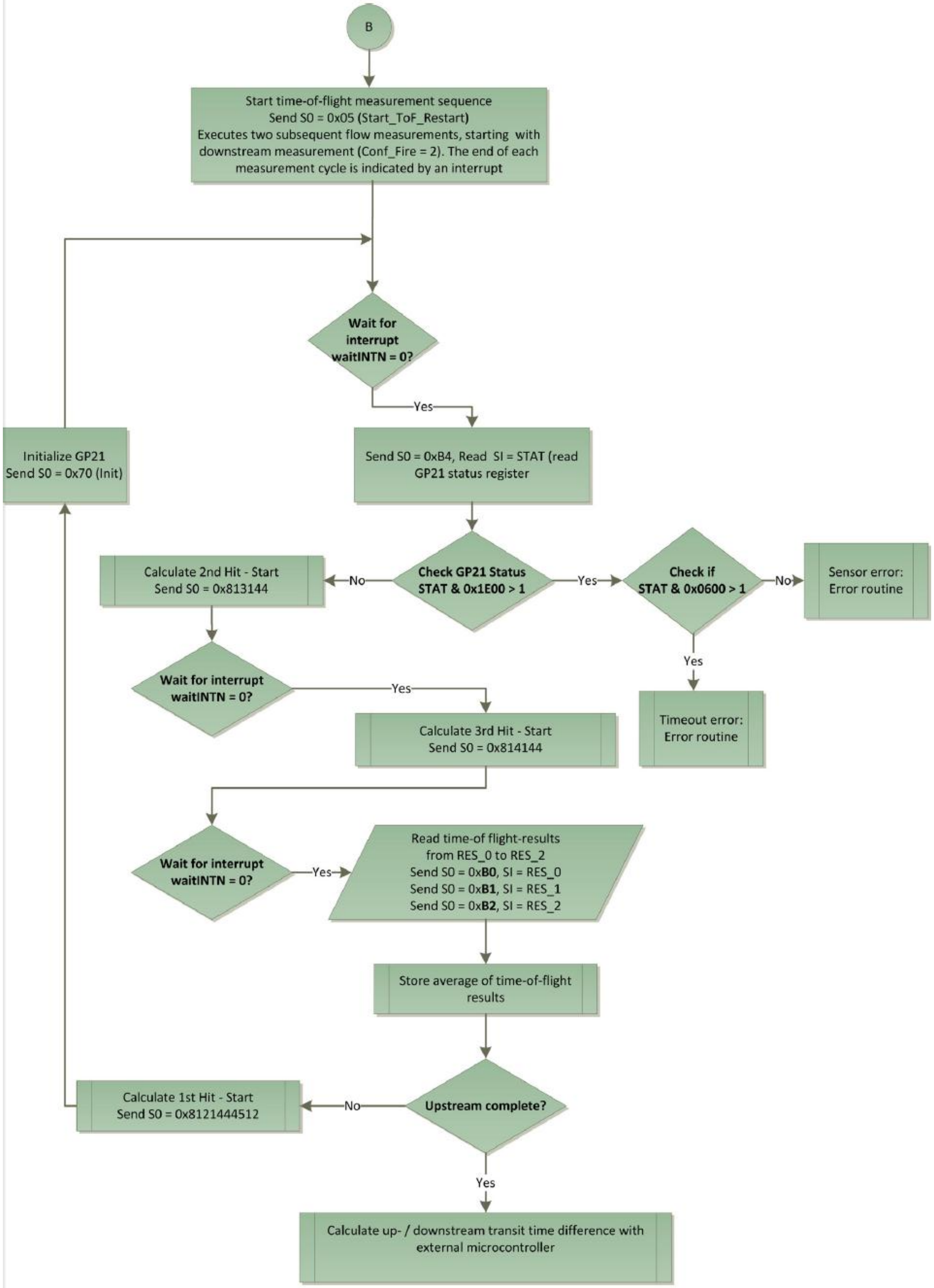

B
Start time-of-flight measurement sequence
Send S0 = 0x05 (Start_ToF_Restart)
Executes two subsequent flow measurements, starting with downstream measurement (Conf_Fire = 2). The end of each measurement cycle is indicated by an interrupt
Wait for interrupt waitINTN = 0?
Yes
Send S0 = 0xB4, Read SI = STAT (read GP21 status register
Initialize GP21
Send S0 = 0x70 (Init)
Check GP21 Status
STAT & 0x1E00 > 1
No
Yes
Calculate 2nd Hit - Start
Send S0 = 0x813144
Check if
STAT & 0x0600 > 1
No
Sensor error:
Error routine
Yes
Timeout error:
Error routine
Wait for interrupt
waitINTN = 0?
Yes
Calculate 3rd Hit - Start
Send S0 = 0x814144
Wait for interrupt
waitINTN = 0?
Yes
Read time-of flight-results
from RES_0 to RES_2
Send S0 = 0xB0, SI = RES_0
Send S0 = 0xB1, SI = RES_1
Send S0 = 0xB2, SI = RES_2
Store average of time-of-flight results
Upstream complete?
No
Calculate 1st Hit - Start
Send S0 = 0x8121444512
Yes
Calculate up- / downstream transit time difference with external microcontroller

Figure 8

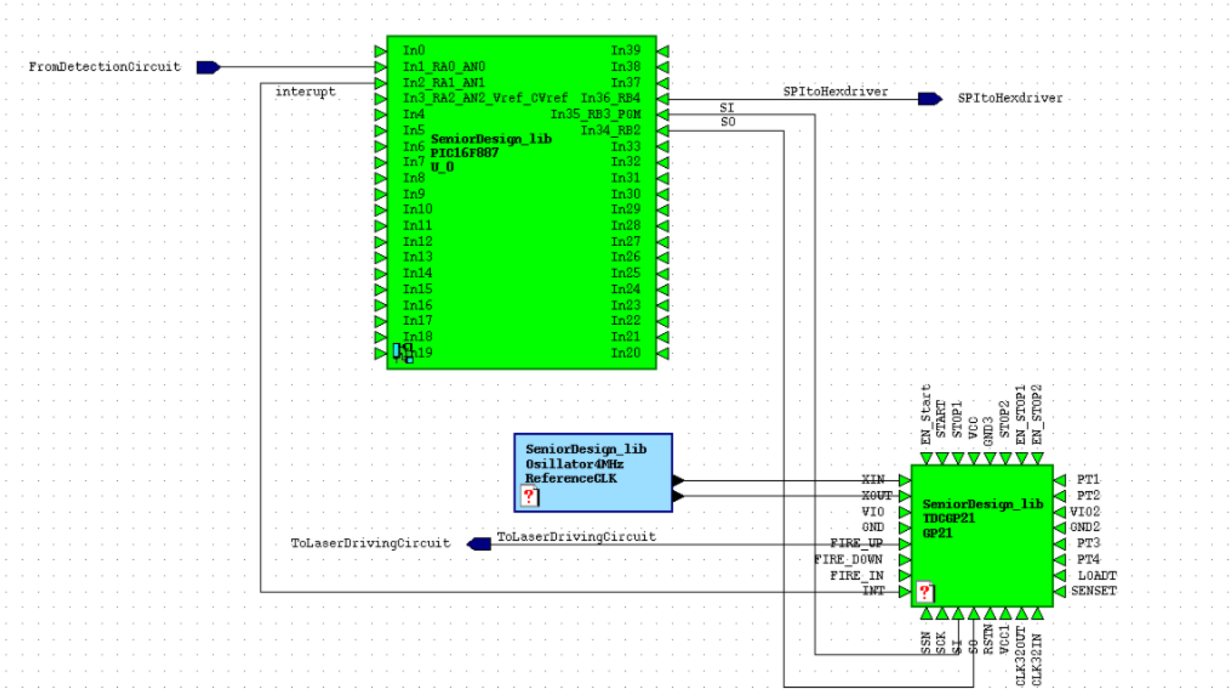
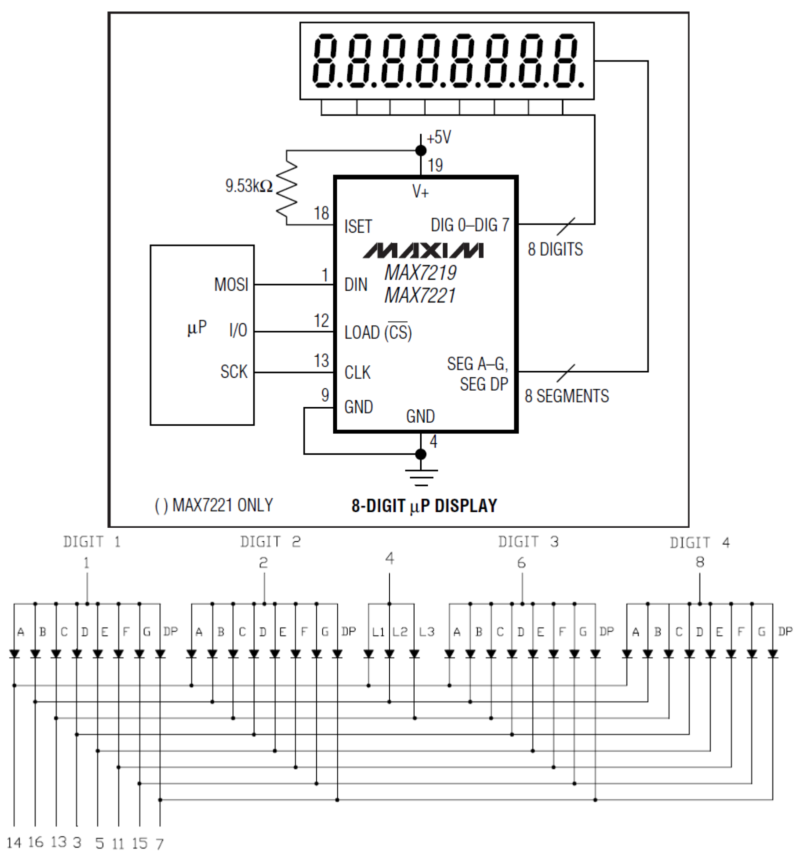


Figure 9



Verification

Testing Procedures:

We will test each of the components in our system in a methodical manner. First, we will start by testing the response of the avalanche photodiode. We will shine the laser on various reflective objects at various distances. We will connect the laser supply voltage to one input on an oscilloscope to mark when the laser is turned on. We will connect the other input signal of the oscilloscope to the output voltage generated by the avalanche photodiode when it receives the reflected laser pulse. From these two signals we will be able to measure exactly how fast the photodiode can respond to a laser pulse.

Our next testing procedure consists of testing the functionality of our microcontroller. We will connect a function generator to the input of our microcontroller and see if it can respond to the frequency at which we will be pulsing our laser. We will also store various values in the registers to see if the microcontroller will output the correct data. Correct data output will be confirmed be connecting our display module to the microcontroller and checking the displays visually.

We must also test the amplifier circuit that we design. We will conduct some simulations using PSPICE in order to calculate what resistor values we need to produce a high enough voltage gain. After acquiring the desired amplifier circuit through simulation, we will move our design to bench testing. We will build our amplifier circuit on a breadboard and make sure the voltage output of the photodiode is amplified to the desired voltage through multimeter measurement. A similar testing procedure will be applied to the verification of our band pass filter as well.

After these components are tested and verified, we will combine them to make sure the entire system is functional. We will test the entire system in its entirety to make sure all the components can work in conjunction with each other. Similar to the testing of the receiver circuit, we will set up a series of tests using many different reflective objects at varying distances in order to test the accuracy and response time of our entire system. We must also make sure our system can measure the speed of objects as well. This requirement will be tested using simple scenarios such as rolling a ball, riding a bike, and possibly driving a car.

Requirement	Verification
1. Laser Diode is operating correctly a. Laser diode is outputting correct amount of power, 5 mW b. Laser diode can pulse at desired frequencies c. Laser diode can pulse at a frequency specified by the TDC chip	1. If the laser diode is outputting the correct amount of power and can pulse at the desired frequencies, the laser diode is functioning correctly a. Shine the laser diode directly onto the functionally tested avalanche photodiode. Using the photosensitivity value of 0.46 A/W, we can predict the desired output of $\approx 0.46 * 5$ mW ≈ 2.3 mA. If the output current of the avalanche photodiode is approximately 2.3 mA, the laser diode is outputting

	the correct amount of power b. Drive the laser diode with the function generator with a known frequency. Shine this pulsing light on the avalanche photodiode. Connect the avalanche photodiode to an oscilloscope to measure the output frequency. If the output frequency closely matches the function generator frequency, the laser diode can be pulsed at specified frequencies correctly. c. Connect the FIRE_UP output on the TDC chip to the laser diode. Set the frequency of the FIRE_UP pulsing to a known value. Measure the output received at the avalanche photodiode with an oscilloscope. If the output frequency closely matches the FIRE_UP frequency, the laser diode can pulse at the desired frequency specified by the TDC chip itself.
2. Collection Optics should be focusing incident light at the correct focal length. The avalanche photodiode should also be detecting the correct frequency of light. a. The Fresnel lens should produce a light point of minimal area at the specified focal point. b. The avalanche photodiode should have a very closely matched frequency response to the frequency at which we are pulsing the light.	2. If the Fresnel lens is focusing the light to the correct focal length of 2.8 inches and the avalanche photodiode is producing a maximum current output when our laser diode is activated, our collection optics will be functioning correctly. a. In order to verify that the Fresnel lens has a focal length of approximately 2.8 inches, we will shine a light source(a lamp) through the lens onto a flat surface such as a wall. The distance at which the lens produces the smallest point of light is the focal length. b. Shine the laser diode at a known frequency generated by the function generator. Check the output of the avalanche photodiode on oscilloscope to compare frequency response.

3. The Receiver Module should amplify the current response to the appropriate voltage level and filter out undesired frequencies. a. Transimpedance Amplifier should be gaining an input current up by the gain factor determined by the resistance R1 of 3.61 MΩ when an object is 5 m away b. Band Pass Frequency Filter should be filtering out any frequencies below 1.94 kHz as well as any frequencies above 2.12 kHz	3. If the amplifier is gaining the current up by 3.61*10^6 at 5 m and the appropriate frequencies are filtered out, then our receiver module is functioning properly. a. Connect a known value current source to the input of the amplifier circuit. Measure the output voltage at the output of the circuit to ensure that the correct gain was achieved. b. Connect a function generator to the voltage input of our band pass filter system. Then, input various frequencies ranging from 1.9 kHz to 2.2 kHz at intervals of 20 Hz. There should a clear response from our system that indicates the passing of signal frequencies between 1.9 kHz and 2.2 kHz. 1. If our band pass filter does not work as a whole, we will break down the filter into the individual low pass and high pass sections and test these separately. Ensuring that both the low and high pass sections are working should ensure that our band pass filter will function as desired.
4. The PIC and TDC Chip will be working if the controller responds correctly to the feedback signal from the receiver module. The TDC Chip will be outputting the correct distance calculation to the PIC. a. PIC Microcontroller should output an interrupt signal to the TDC chip when it receives a voltage response from the avalanche photodiode. b. TDC Chip should send the correct distance calculations to the PIC's onboard storage registers	4. The PIC and TDC chip communications will be working correctly if the interrupts are being received at the correct times and the correct distance calculations are stored in the PIC's registers. a. Send a voltage response into the analog input of the microcontroller and verify that the output signal to the interrupt input on the TDC chip is high. b. Check the PIC's register content using debugging tools or 7 segment displays. The values stored in the registers should be within 10 cm of the actual distance which will be measured physically.

5. User Interface should be correctly displaying the data value stored in the registers on the PIC16F877 microcontroller	5. Write known data values into the registers on the PIC. Confirm that the LED screen displays the correct 7-segment representation of the data stored in the specified register.
6. Power Supply should be outputting the correct voltage levels to each component of the system	6. Measure the voltage levels being supplied to the laser diode, avalanche photodiode, amplifier, PIC, TDC chip, and LCD screen. a. The supply terminals to the operational amplifier in the amplifier circuit should be 5 V and -5 V. b. The supply voltage of the PIC should be 5 V c. The supply voltage of the TDC chip should be 3 V d. The supply voltage to the LED display driver should be 5 V

Contingency Plan:

Quite a few problems may arise during our design and implementation of our project. Our power supply should be reliable due to its simple design. However, we may encounter problems with other components in our system such as the Fresnel lens, the avalanche photodiode, and the TDC chip. The Fresnel lens may not capture our laser diode light as efficiently as desired. If this occurs, one option would be to order a larger lens in order to capture more light. If the avalanche photodiode cannot detect the incoming light at the frequency we have chosen, one possible solution is to decrease the frequency in order to allow a more distinct response from the APD. If the TDC chip happens to burn out unexpectedly, we have ordered replacements. However, we realize that this will be a significant set-back in our project progress.

Tolerance Analysis:

Block Name and Basic Description	**Testing Focus**	**Acceptable Result Ranges Confirming Operation**
TDC GP21 Chip	Generate accurate distance calculations	GP21 Chip should be able to produce a distance calculation that has an error of 10 cm or less for objects located within 5 meters
Avalanche Photodiode	Generate response for objects at relatively long distances	Avalanche photodiode should be able to detect objects up to 5 meters away from source
7-Segment LED Display	Display results to the user within a reasonable time frame	Results should display within 10 seconds after each measurement

Cost and Schedule

Cost Analysis:

LABOR	
Employee	Cost
Chee Loh	$40/hour * 2.5 * 12 hours/week * 12 weeks = $14,400
Xingliang Wu	$40/hour * 2.5 * 12 hours/week * 12 weeks = $14,400
Ping-Wen Wang	$40/hour * 2.5 * 12 hours/week * 12 weeks = $14,400
Total	$43,200

PARTS			
Part	Quantity	Location	Cost
Laser Diode (650 nm, 5 mW)	3 * $9	US-Lasers Inc. (DigiKey)	$27
Avalanche Photodiode (S5343)	1 * $144	Hamamatsu	$144
Fresnel Lens (5 in x 5in)	1 * $48.50	Edmund Optics	$48.50
Voltage Driver Chip (MAX230)	2 * $8.65	MAXIM (DigiKey)	$17.30
Microcontroller (PIC16F887)	1 * $10	ECE Parts Shop	$10
TDC-GP21 Chip	4 * $27.89	ACAM	$111.56
Serial-to-7 Segment Display Driver (MAX7219CNG)	2 * $9.95	Spark Fun Electronics	$19.90
4 Digit LED 7 Segment Display (LTC-4627JR)	2 * $3.60	Lite-On Inc. (DigiKey)	$7.20
Housing Box to Contain Design	1 * $100	Machine Shop	$100
Misc. Circuit Parts(Capacitors, Resistors, etc.)	Many	ECE Part Shop	$50
Total	$535.46		

Grand Total = $43,735.46

Schedule:

Week	Tasks	Members
Week 1(1/29 – 2/4)	-Research use of capacitance to convert to voltage to time measure	Wu
	-Research photodiode receiver and amplifier circuitry	Wang
	-Research photodiode receiver and amplifier circuitry	Loh
Week 2(2/5 – 2/11)	-Research and order parts	Wang
	-Design the receiver circuitry	Wu
	- Complete project proposal	Loh
Week 3(2/12 – 2/18)	-Sign up for design reviews -Design and simulate the band pass filter	Wang
	-Design and simulate the transimpedance amplifier	Loh
	-PIC and TDC chip code reading	Wu
Week 4(2/19 – 2/25)	-Build amplifier and start bench testing	Loh
	-Test and simulate the receiver and transmitter	Wang
	-Program the PIC	Wu
Week 5(2/26 – 3/3)	-Test and simulate the receiver and transmitter	Wang
	-Program the user interface	Wu
	-Debug any amplifier problems and help build and bench test band pass filter	Loh
Week 6(3/4 – 3/10)	-Optimize the calculation speed and find correction factor from device -Test and debugging	Wu
	-Optimize response time of detector -Test and debugging	Wang
	-Optimize the amplifier and noise filtering -Test and debugging	Loh
Week 7(3/11 – 3/17)	-Complete individual report -Combine microchip and user interface	Wu
	-Complete individual report -Interface band pass filter and amplifier to microchip	Wang

	-Complete individual report -Interface receiver and amplifier to microchip	Loh
Week 8(3/18 – 3/24)	-Testing and verification	Wu
	-Testing and verification -Sign up the mock-up Demo	Wang
	-Testing and verification	Loh
Week 9(3/25 – 3/31)	Mock-up Demo	Wu
		Wang
		Loh
Week 10, 11(4/1 – 4/14)	-Work on final design optimization and debugging	Wu
		Wang
		Loh
Week 12, 13(4/15 – 4/28)	-Prepare demo -Prepare presentation and start final paper	Wu
	- Prepare demo -Prepare presentation and start final paper	Wang
	- Prepare demo -Prepare presentation and start final paper	Loh
Week 14(4/29 – 5/5)	Demo and complete the final paper	All

Ethical Concerns

The IEEE code of ethics emphasizes the importance "to accept responsibility in making decisions consistent with the safety, health and welfare of the public, and to disclose promptly factors that might endanger the public or the environment." In order to get an accurate response, some laser rangefinders will use very high powered and high frequency laser diodes (up to 300mW infrared light). One of our main concerns is to reduce the risk of injuring people. In order to accomplish this goal, we chose to use a 5mW visible light laser diode, which will not cause damage to the human eye unless there is direct exposure for a long duration.

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