# Final Report

Chee Loh, Ping-Wen Wang, Xingliang Wu

ECE 445 – Senior Design

Spring 2012

TA: Mustafa Mir

2 May 2012

Project No. 28

## Abstract

The goal of this project is to implement a 1-dimensional laser rangefinder system which will not only be able to calculate distances to objects but also calculate the speeds that objects may be moving at. This is accomplished through the use of the time-of-flight method, which determines the time it takes for a laser pulse to be reflected by an object and received at the source. This report will outline project design, verification procedures, and final testing results. An overview of the accomplishments and challenges throughout the project will be described as well as suggestions for future work.

# Contents

# 1. Introduction

The goal of this project is to design and implement a system which can measure the distance to an object from a known source. The system will also be extended to incorporate the calculation of speeds that an object is moving at. Our initial motivation to pursue this project stems from our group's strong interest in optical applications. This report will outline system components, verification procedures that have been performed, and final measurement results. Project accomplishments, challenges, and suggestions for future work will also be described.

## 1.1 Purpose

The purpose of our project is to design a system which can calculate the distance to an object as well as the speed of the object. We believe our system can be extended to many different types of applications such as object detection on cars when reversing, speed detection on cars, or even large 3D terrain mapping. Figure 1 below shows a basic block diagram of our entire system.

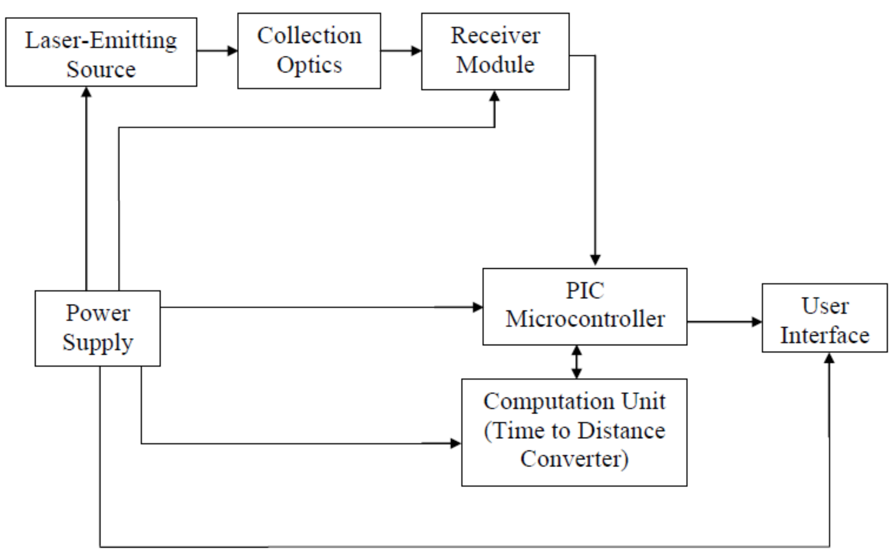


Figure 1

## 1.2 Specifications

Our project had a few design specifications that were addressed throughout the semester. Our goal was 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. Furthermore, after the system is powered on and initialized, the user will be able to choose what type of measurement they would like to take.

## 1.3 Module Descriptions

The project was broken down into individual components in order to implement our design in a more modular fashion. As a result, we were able to focus our attention on one component at a time, simplifying the task at hand.

### 1.3.1 Power Supply

This component consists of a single 4.5 V power supply, voltage driver chip, and voltage regulator. The supply comes from three AA batteries connected in series through a battery holder.

### 1.3.2 Laser-Emitting Source

This component of the system consists of a pulsed semiconductor laser diode module which will mark the start and stop time for each trip the laser takes to the desired object.

### 1.3.3 Collection Optics

The collection optics component of our system consists of an optical Fresnel lens in front of a dual photodiode receiver. The purpose of the Fresnel lens is to focus the returning light resulting in a higher power density for better reception.

### 1.3.4 Receiver Module

The receiver module consists of a pair of photodiodes and a differential amplifier circuit. One photodiode measures the voltage response from the returning laser signal with ambient light incorporated into it. The other photodiode simply measures the ambient light in the environment.

### 1.3.5 PIC16F887 Microcontroller

The PIC16F887 microcontroller that we have used represents the main control of our system. It provides communication with the TDC chip as well as outputs measurement results to a 7-segment display.

### 1.3.6 Computation Unit

The computation unit consists of our TDC GP21 chip. The TDC chip will be performing the time-of-flight calculations and outputting the results back to the PIC.

### 1.3.7 User Interface

The user interface is designed in order to display the final results to the user. Push buttons have also been implemented to offer the user the ability to reset the system, make multiple measurements or single measurements, and to check the status of the TDC chip.

## 2. Design Procedure

The following section will provide a more detailed description of the design process of each component in our system. Original design considerations and alterations will be provided and final design choices will be outlined.

### 2.1 Power Supply

The power supply of our system is responsible for supplying all of our system components with the correct supply voltages in order to function correctly. Careful consideration was made in the design of the power supply in order to ensure safe operating conditions for all system components. We chose to use a single power supply in order to eliminate the hassle of turning multiple sources on and off during testing.

Initially, we were powering our system through provided voltage supply stations that could be easily tuned to 5 V. However, in an effort to make our system more portable and user friendly, we implemented a primary supply coming from 3 AA batteries in series fitted into a battery holder and connected to our breadboard. Although the batteries only supply 4.5 V, this was sufficient in order to power our system.

One of our initial concerns was how to supply the negative terminal on our operational amplifier. We chose to use the MAX232 voltage driver chip for its easy to use chip layout that includes charge pumping capabilities to supply positive and negative 9 V. Later on in our testing, we also realized the need to use a voltage regulator when supplying and sending analog inputs to our TDC chip. To accomplish this we used a simply LP2591ACN-3.3 chip. We chose the DIP version rather than the TO-92 package to ensure that our design remained compact and secure.

### 2.2 Laser-Emitting Source

The laser module used in our system is the “measuring tape” of our system. We tested our initial design ideas with an ordinary laser diode, but we realized that the laser signal needed to be collimated in order actually reach the desired object. We also wanted to ensure that our system was easy for the user to operate while maintaining safety standards.

With these goals in mind, we chose a 650 nm, 5 mW laser module which provided easy operation due to the use of visible light as well as a safe environment due to its relatively low power. The module also provided an attached lens system which collimated the laser beam. Further research revealed that most industrial laser range finders use a very high power laser as well as infrared light. Both of these aspects have been addressed in our design.

Through extensive testing, we found that our PIC’s analog output of 3.3 V was not powerful enough to drive our laser module at full brightness. In order to solve this problem, we implemented a simple NMOS switch in order to switch the laser module supply to our 4.5 V supply when needed. We used the basic law that states when the gate-to-source voltage across a MOSFET is greater than the threshold voltage, the MOSFET is turned on. Therefore, when the

PIC sends a 3.3 V signal to the gate terminal of the NMOS, the channel is opened, allowing current to flow from our 4.5 V supply through our laser module straight to the ground terminal on the source.

Other advantages of our specific laser module include its low cost ($5) as well as its very fast rise and fall times (1 ns and 2 ns respectively). These fast response times ensured that we could pulse our laser at high frequencies if necessary. The laser module also contained an internal current limiting circuit to protect the laser diode when driven. This feature was essential to our design in order to prevent the laser diode from burning out accidentally.

## 2.3 Collection Optics

The collection optics portion of our system consisted of a Fresnel lens. Our original idea was to use a combination of laser pulse frequency modulation and a red-filtering lens. However, we decided that it was much simpler to use a Fresnel lens in order to focus the reflected light back onto our photodiode. Our receiver module would remove unwanted noise from the response signal and we could avoid the use of frequency generation and frequency filtering.

The lens was chosen based on the desire to have high collection efficiency rather than creating a high resolution image. Furthermore, we wanted 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.

## 2.4 Receiver Module

The receiver module consists of a pair of photodiode receivers placed closely together. Our original design idea was to use an avalanche photodiode in order to make use of its very high sensitivity to low levels of light. However, after testing the response of the Hamamatsu S5343 avalanche photodiode, we discovered that its use would bring many more difficulties than we expected.

First, we would need to bias the APD with a very high 150 V reverse bias in order to achieve proper functionality. The high sensitivity of an APD also proved unnecessary as our design specifications only required the detection of objects at a maximum distance of 5 m. Moreover, the high sensitivity actually proved to bring more difficulties to the project because it required the implementation of a temperature control system in order to regulate the APD’s temperature.

Ultimately, we decided to abandon the idea of using the APD because of time constraints and its unnecessary complexity. The final design we agreed upon was to use a pair of regular photodiodes which would pass their voltage responses to a differential amplifier. The OPT101 photodiodes that we chose internally reverse biased themselves which solved one of our concerns.

One of the photodiodes was placed at the focal point of our Fresnel lens, receiving the returning laser signal reflected by the object as well as the ambient light incorporated within it. The other photodiode was placed off center of the Fresnel lens focal point, receiving only the surrounding ambient light. We pass these two measurements into the differential amplifier circuit in order to remove ambient light from our return signal. This procedure ensured that we could recognize return signals accurately without getting false signal readings from ambient light.

## 2.5 PIC16F887 Microcontroller

The PIC16F887 microcontroller was chosen as the main control of our system. Our initial choice of this specific controller was simply because it was provided by the class, making it the most accessible as soon as possible. However, we also wanted to minimize the cost of our product for the consumer. We believed that since our system only required a few analog outputs, communication between the TDC chip, and display of data to 7-segment displays, it was unnecessary to invest in an expensive, high-end microcontroller. Possible alternatives included Arduinos or FPGAs, but our group did not have adequate experience working with these options and felt more confident using a PIC.

The PIC performs a few various tasks. It sends the start signal to our laser module and TDC chip simultaneously. It also retrieves the calculated data from the TDC chip. The PIC also provides the necessary control in order to output our final results onto a 7-segment display. Onboard storage is implemented in our system in order to use multiple distance measurements to generate a speed calculation. The storage that is used is located on the microcontroller itself in order to minimize acquisition time and maximize output generation.

## 2.6 Computation Unit

The computation unit of our system consisted of the TDC GP21 chip. Initial design ideas to perform the time-of-flight measurements consisted of creating some assortment of latch logic. However, after additional research, the group felt this approach was too difficult. Furthermore, many more reference projects implementing the use of a TDC chip were available online.

We found that the TDC chip had many desirable features with respect to our project as well. The TDC chip is specified to have a very high resolution of 45 picoseconds which would allow us to measure distances with great accuracy. The calculation that the TDC chip performs is also accomplished in a very short time of a few milliseconds. This feature was essential if our design was to be implemented into a commercial product.

The TDC chip performs its measurements by charging an internal capacitor at the start of a signal pulse. When the returning signal is received, a stop signal is triggered and the voltage across the capacitor is measured instantaneously. The capacitor voltage results in a time calculation which can easily be converted to a distance.

## 2.7 User Interface

The user interface was designed to provide the user with many measurement options and an easily interpreted display. Both the distance measurements as well as speed of the object are displayed on the 7-segment display simultaneously. The input to the LED display comes from the PIC after all the necessary calculations are made and passes through the BCD to 7-segment driver. The alternative idea of using an LCD screen to make the display even more versatile was considered, but time constraints prevented the group from pursuing this suggestion.

Four push buttons are also available: a reset system button, a multiple measurement averaging button, a check status button, and a raw time display button. These buttons provided the group an easy way to continuously test our system after modifications were made and offered end users a multitude of options to choose from.

# 3. Design Details

The following section will go into further detail on the final design choices that were made. Schematics of the circuit layouts along with specific design values and data will also be described.

## 3.1 Power Supply

The primary 4.5 V supply voltage is fed into the MAX232 voltage driver chip which doubles the input voltage to positive and negative 9 V. Our intentions were to use the charge pumps on the MAX232 in order to generate a -4 V minimum voltage to supply to the negative terminal on our operational amplifier.

The power supply component also includes a LP2591ACN-3.3 chip which provides a 3.3 V regulated supply in order to power our PIC16F887 as well as our TDC GP21 chip. Initially, the PIC was powered by our 4.5 V supply, but we realized that the TDC chip could only handle 3.3 V analog input signals. Therefore, in order to voltage limit the output signals from the PIC to the TDC we simply supplied our PIC with only 3.3 V.

Unlike the voltage supplied directly from the wall outlet, the battery system provided a very clean supply. By summing the individual component power consumptions and using the simply equation shown in Equation 3.1.1, we were able to calculate an estimated lifetime of our system running on a single set of batteries.

$$t = P_{battery}/P_{consumed} \tag{3.1.1}$$

where $P_{battery}$ is listed as 6.75 Wh and $P_{consumed}$ is the total power consumed by our system. $P_{consumed}$ was calculated by totaling the values shown in Figure 2.

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

Figure 2

Solving for the system lifetime, t, we calculated that our system would successfully run with our battery system for about 58 minutes. Although this result may seem like an unreasonably short lifetime, we are assuming that the system is continuously running at full power consumption. We expect the user to only run the system for a few minutes at a time, extending the system lifetime considerably.

Figure 3 below outlines the power supply layout to all the main components of our system.

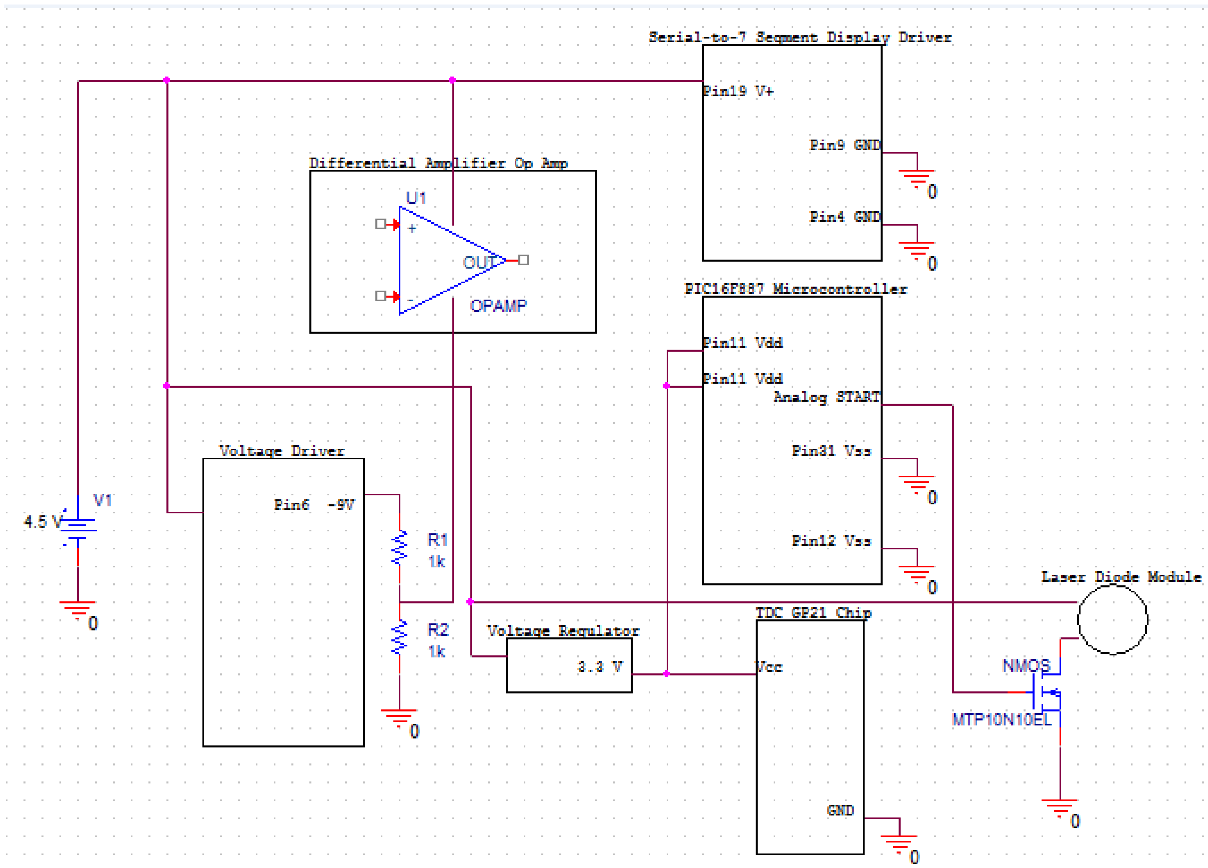


Figure 3

A simple voltage divider rule was applied to the output of the MAX232 voltage driver in order to supply the negative terminal of our differential amplifier op amp with -4.5 V. The negative terminal voltage level is calculated using Equation 3.1.2.

$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right) \tag{3.1.2}$$

where $V_{out}$ is the voltage supplied to the negative terminal, $V_{in}$ is -9 V, and both R1 and R2 have been chosen as 1 kΩ.

## 3.2 Laser-Emitting Source

The laser-emitting source consisted of a laser module and a simple source circuit in order to supply the proper voltage to it. We discovered that the 3.3 V output from the PIC was not sufficient in order to give our laser module maximum brightness on the target. As a result, we designed a simple circuit shown in Figure 4 below.

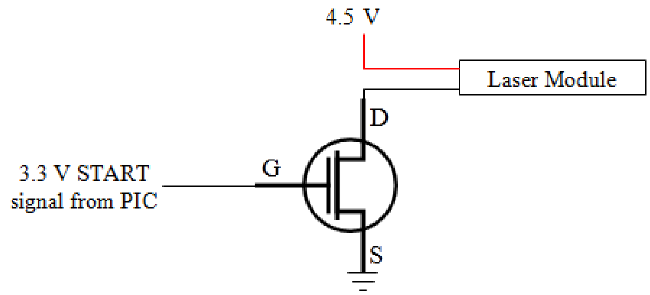


Figure 4

The gate-to-source voltage of our NMOS is 3.3 V when a start signal is sent and approximately 0 when no signal is sent. Consequently, when the start signal is sent from the PIC, the gate-to-source voltage exceeds the threshold voltage of 0.7 V of our NMOS. When this occurs, the NMOS is turned on, allowing current to flow from our 4.5 V supply through the laser module to the grounded source terminal.

## 3.3 Collection Optics

The collection optics consisted of a Fresnel lens which focused the return laser signal back onto a photodiode. Since the manufacturer of the lens specified that size of the lens as well as its focal length, we did not need to calculate them manually. As shown in Figure 5, the Fresnel lens focuses all incoming light to a point located at its focal length. Figure 6 shows the actual layout of our system. The lens is mounted with the receiving end facing the direction of returning light. The focal length specified by the manufacturer was 2.8 inches so we made the mounting system adjustable. The lens is positioned 2.8 inches in front of the receiver module back panel to ensure that the incoming light is focused directly onto the photodiode.

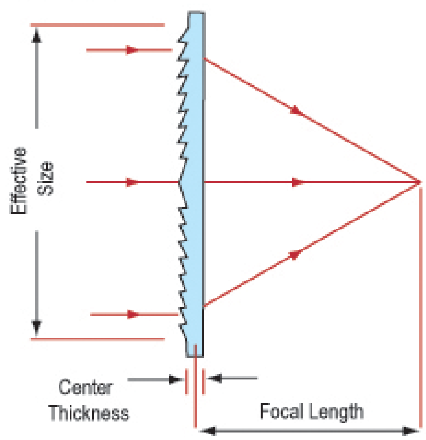


Figure 5

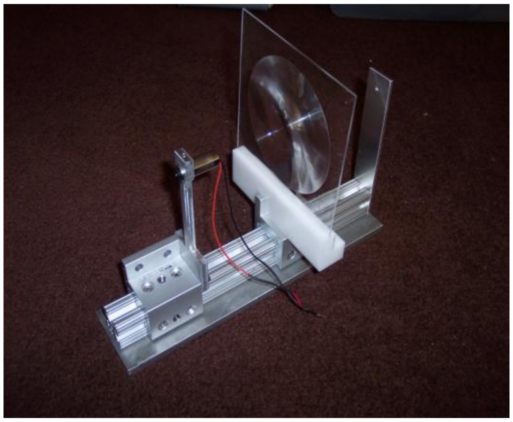

Figure 6

## 3.4 Receiver Module

The receiver module consisted of a pair of photodiodes as well as a differential amplifier circuit. The differential amplifier circuit was equipped with a high speed operational amplifier in order to achieve a response time that was as fast as possible. The circuit layout of the differential amplifier is shown in Figure 7.

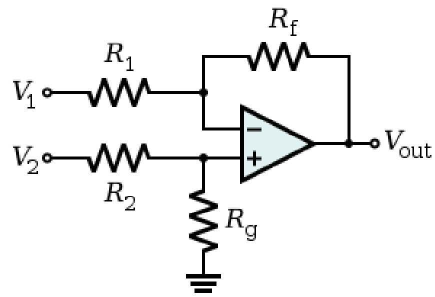


Figure 7

The voltage $V_1$ represents the voltage output from a single photodiode which measures the level of ambient light in the environment. The voltage $V_2$ represents the voltage output from the other photodiode which captures the ambient light as well as the light from the returning laser signal. The two voltage measurements are then passed to the differential amplifier circuit. The differential amplifier acts as a filter which subtracts out the ambient light signal from our total return signal response.

Using the two basic laws of KVL and KCL, we derived an output voltage equation shown in Equation 3.4.

$$V_{\text{out}} = V_2 \left( \frac{(R_f + R_1)\, R_g}{(R_g + R_2)\, R_1} \right) - V_1 \left( \frac{R_f}{R_1} \right) \tag{3.4}$$

Through empirical testing in a relatively controlled environment, we found that the optimal differential gain required to achieve a clear stop signal was 4. Using the resistors that we had available, we chose $R_1$ and $R_2$ to be 2 kΩ and $R_f$ and $R_g$ to be 8 kΩ. This resulted in our final circuit shown in Figure 8.

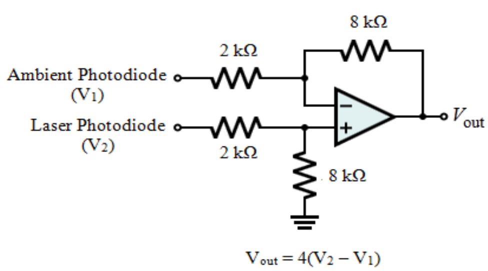


Figure 8

## 3.5 PIC16F887 Microcontroller

The PIC16F887 provided the main control of our system. The PIC operates at an internal clocking frequency of 8 MHz in order to read and display measurements in the shortest time possible. Using the PIC's internal clocking also eliminated the need for any external clocking circuitry. The PIC's supply voltage is limited to 3.3 V which is in turn used as a reference voltage for its analog outputs. This was an essential design choice because the TDC chip can only except analog input signals at 3.3 V.

The PIC is not only responsible for reading the stored data from the TDC chip measurement, but also writing this data to a 7-segment display through an LED display driver. The PIC outputs the calculated measurement from the TDC chip through a serial peripheral interface(SPI) to a pair of 4-digit common cathode LED displays.

Several optimizations had to be made in the PIC's calculations in order to get the appropriate order of measurements. The first calculation that had to be made was to convert the output measurement from the TDC chip, which was in units of time(μs), into units of length(m). To do this, we simply used Equation 3.5.

$$D(m) = c(m/s)*t(\mu s) \tag{3.5}$$

D represents the final distance calculation to be display for the user while c represents the speed of light($3x10^8$ m/s) and t represents the amount of time that has elapsed from the start of the laser pulse to the received return pulse.

Several other adjustments had to be made in order to retrieve a measurement that was in the correct order of expected results. We had to subtract 17 meters off of each measurement in order to have our measurements report on the correct scale of distances.

A complete schematic of the interconnections between our PIC and the rest of the entire system can be viewed in Figure A.1. A completed copy of the PIC's code can be found in Figure A.2.

## 3.6 Computation Unit

The computation unit in our system is composed of the TDC GP21 chip. The TDC chip is the component that performs the actual time-of-flight measurement. This task is accomplished by using an internal capacitor on the chip. When a start signal is sent to the TDC chip, it begins charging this internal capacitor. When the return laser pulse is received, a stop signal is sent to the chip, triggering the capacitor to stop charging. The TDC chip then measures the voltage on this internal capacitor and using the RC time constant relationship it can calculate the appropriate time-of-flight measurement.

One note that should be made is that the TDC chip requires very precise external clocking oscillators in order to initialize and function properly. The chip requires two external oscillators connected with corresponding capacitors. One external oscillator is a 32.768 kHz crystal while the other is a 4 MHz ceramic. Both oscillators needed to be connected with the appropriate 10 pF capacitors as shown in Figure 9.

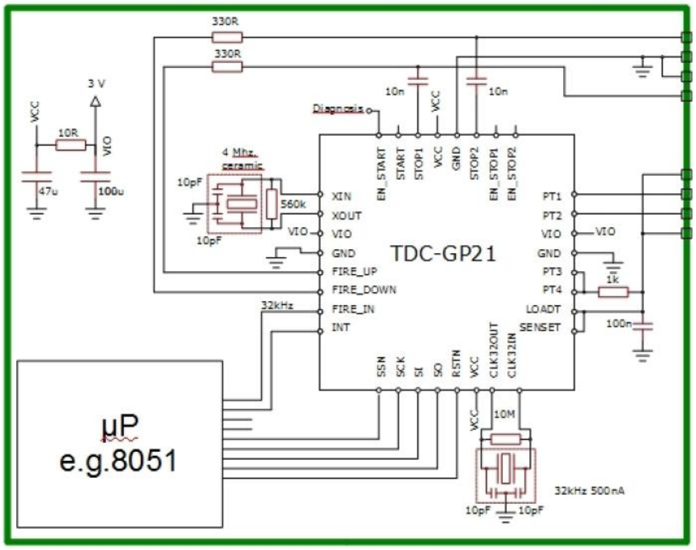


Figure 9

The TDC chip in our system operates in Measure Mode 2 which only supports calibrated measurements. The results are given in the form of equation 3.6.1 shown below.

$$\text{Time} = \text{reg0} * T_{ref} * 2^{ClkHdiv} \quad (3.6.1)$$

The data stored in reg0 is represented by Equation 3.6.2.

$$\text{reg0} = \text{CoarseCount} + \frac{\text{Stop ch1} - \text{start}}{Calibrate\ 2 - calibrate\ 1} \quad (3.6.2)$$

In order to calculate the time-of-flight between the rise of the laser pulse to the first hit on the photodiode, the TDC calculation must be set to Hit1 – Start. When using Measure Mode 2, the registers on the TDC chip must be initialized as shown in Figure 10.

| | |
|---|---|
| reg0: 0x22242801 | // measure mode 2. Reference clock divide by 4, auto calibrated |
| reg1: 0x21020001 | // Calculate 1st stop ch1 - start |
| reg2: 0x20000001 | // default setting |
| reg3: 0x01000001 | // enable time out interrupt |
| reg4: 0x20000001 | // default setting |
| reg5: 0x00000001 | // default setting |
| reg6: 0x00001001 | // disable interrupt source |

Figure 10

The measurement range is characterized by Equation 3.6.3 and Equation 3.6.4.

$$t_{min} = 2 * T_{ref} * 2^{ClkHdiv} \quad (3.6.3)$$

$$t_{max} = 2^{14} * T_{ref} * 2^{ClkHdiv} \quad (3.6.4)$$

where $T_{ref} = \frac{1}{4Mhz} = 0.25$ µs and ClkHdiv = 2.

As a result, $t_{min}$ = 2 µs (including circuit delay), $t_{max}$ = 16.384 ms, Resolution = 45 ps.

## 3.7 User Interface

The user interface of our system provides both an easy way to test and debug our design as well as various option for the end user to choose from. Two 4-digit 7-segment displays allow the user to view both the distance to an object as well as its relative speed simultaneously. We have also incorporated the use of four push buttons that the user can choose from. Each of the four push buttons offers a single function: system reset, display and averaged distance measurement, display the status of the TDC chip, and display the raw time measurement outputted by the TDC chip.

The functionality of each push button was defined when coding the PIC. The PIC simply defines the four functions and monitors when the button is pushed. When the button is pushed the signal to the PIC becomes high and the code enters the appropriate conditional loop. After the loop has completed the desired task, the output is finally displayed on the 7-segment displays.

A hex code interpretation of our 7-segment display driver(MAX7219CNG) is shown in Figure 11 below.

| Data Hex | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-segment character | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | - | E | H | L | P | Blank |

Figure 11

## 3. Design Verification

The following section will describe bench test verification results that confirm the functionality of the components within our system. The Requirement and Verification Table shown in Table 4 of Appendix C will also be examined.

### 3.1 Power Supply

In order to verify the correct operation of our power supply the group was required to ensure that the components in our system were supplied with the proper voltage. We measured the voltage at the supply terminals of our operational amplifier, the supply to the PIC and LED display, and the supply to the TDC chip.

Figure 12 shows the verification of the power supply on the operational amplifier used in the differential amplifier. The positive supply voltage is maintained at 4.52 V while the negative supply voltage is maintained at -4.311 V. These values are both acceptable and verify the correct supply of voltage to the op amp.

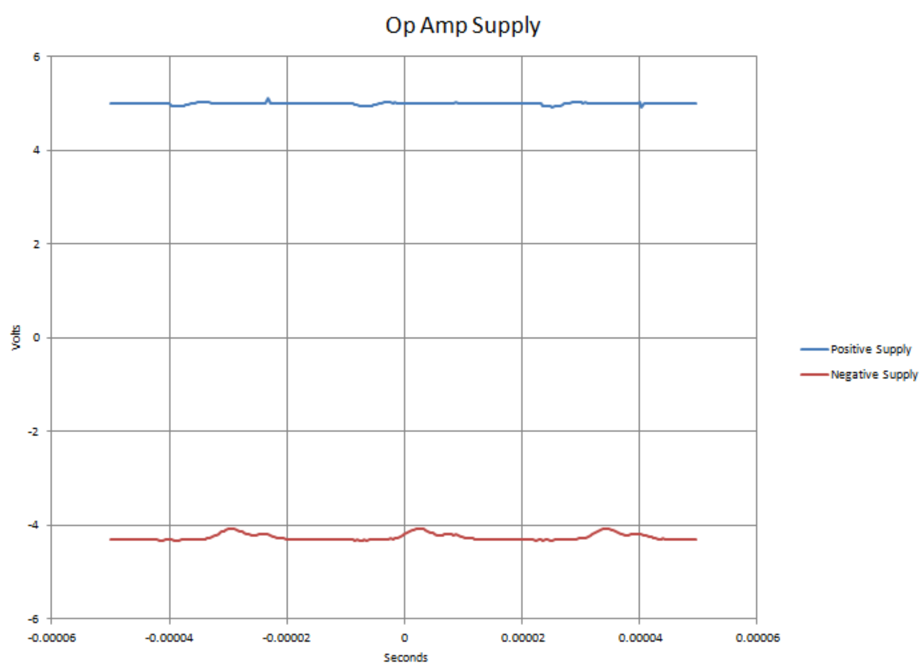


Figure 12

Figure 13 shows the verification of the LED display supply. The voltage is maintained at 4.505 V which is within specifications. Finally, the output of the voltage regulator that was supplied to our TDC chip and PIC was measured and shown in Figure 14. The average voltage level was 3.295 V with a minimal voltage ripple of 69 mV. This is an acceptable value specified for our design.

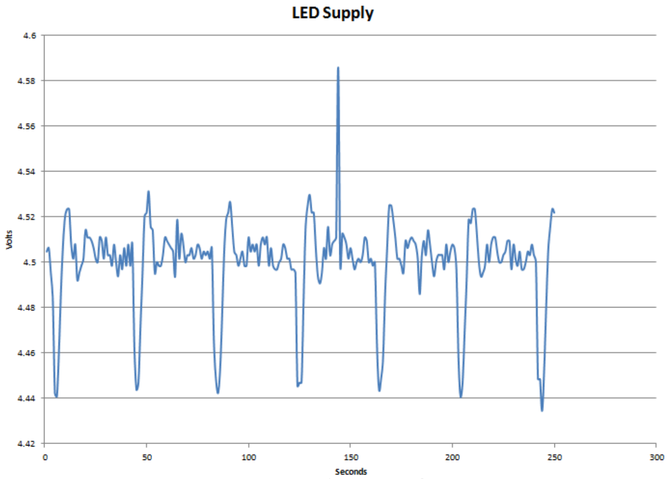


Figure 13

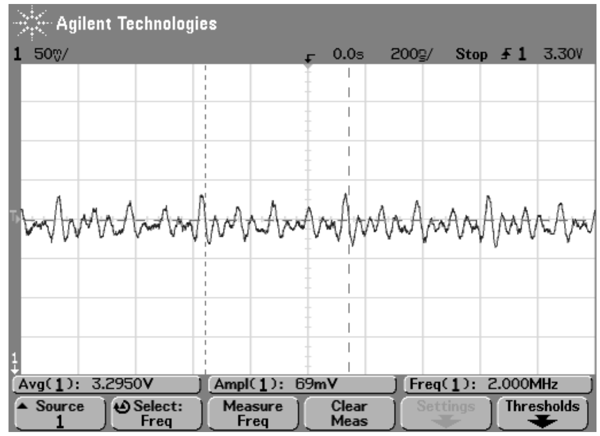


Figure 14

## 3.2 Laser-Emitting Source

The driving frequency of the laser diode was confirmed by the output of the receiving photodiode. We calculated the total time between each measurement completed from our PIC's source code. The total measuring time was approximately 22.284 ms which corresponds to a resulting laser frequency of approximately 44.875 Hz. The frequency of the output measured from our receiving photodiode is shown in Figure 15 which confirms the correct frequency response.

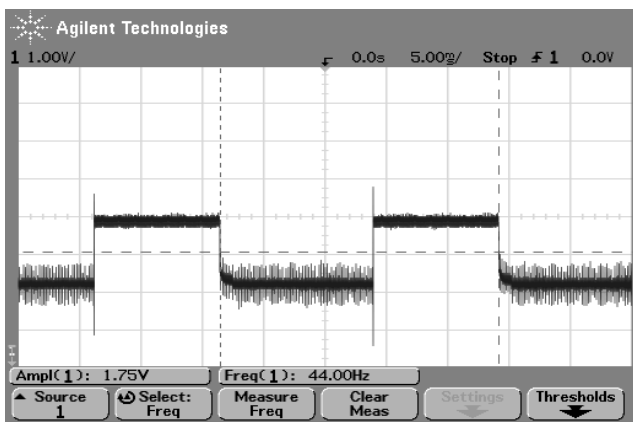


Figure 15

The correct operation of the laser module at a 4.5 V supply was verified visually. When supplied with a test voltage from the voltage regulator output of 3.3 V, the laser module only produced a very dim laser signal. However, when the laser module was sourced with our primary supply of 4.5 V through our NMOS switch, maximum laser intensity was produced. This result confirmed that the laser module was functioning correctly at 4.5 V.

## 3.3 Collection Optics

The Fresnel lens focal length needed to be verified physically. The focal length of the Fresnel lens was specified to be 2.8 inches which is equivalent to 71.12 mm. As shown in Figure 16, we verified this focal length to be about 7.5 cm or 75 mm which is acceptable. The image shows that the lens produces a focused image of the overhead fluorescent light in the room.

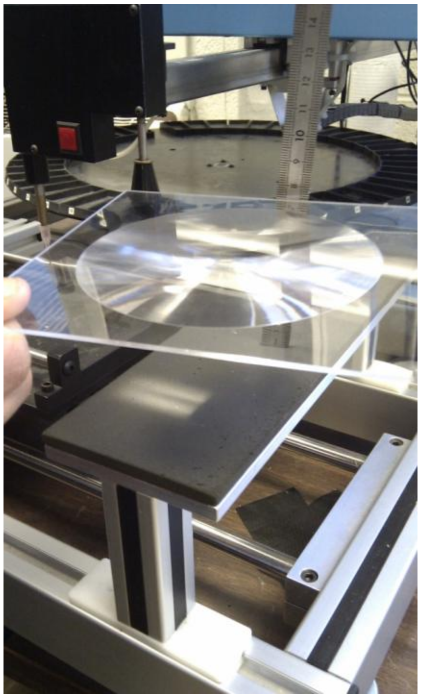

Figure 16

The proper operation of the photodiodes was verified through the same verification test of the laser module shown in Figure 15. The photodiodes produced a very closely matched frequency response to the actual frequency at which the laser was pulsed.

## 3.4 Receiver Module

The receiving photodiode had to be verified to respond to our laser module even in the presence of ambient light. Figure 17 and Figure 18 show the output of the differential amplifier circuit when the laser is on and off respectively. In order to verify that the receiver module was working properly, the differential amplifier output had to reach a minimum of 2 V in order to trigger the stop on the TDC chip when the laser is on. The differential amplifier output was also required to not exceed the minimum threshold voltage of 2 V when the laser was no on. Both of these characteristics are confirmed by the figures, completing our verification of the receiver module.

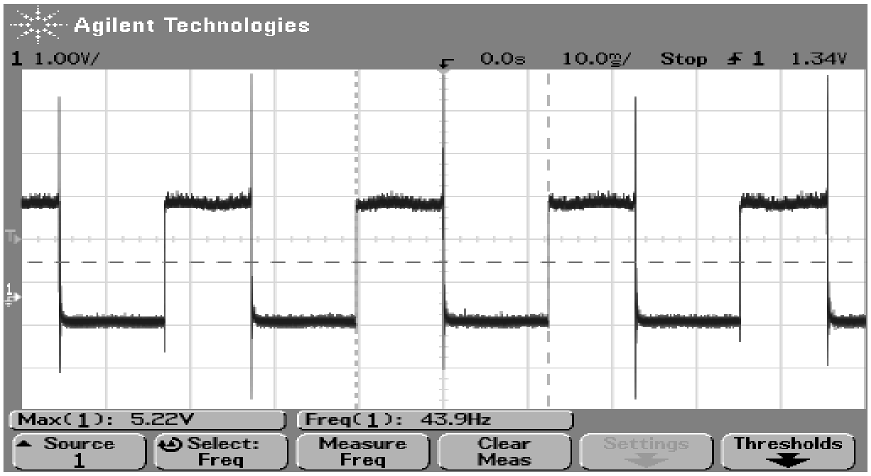


Figure 17

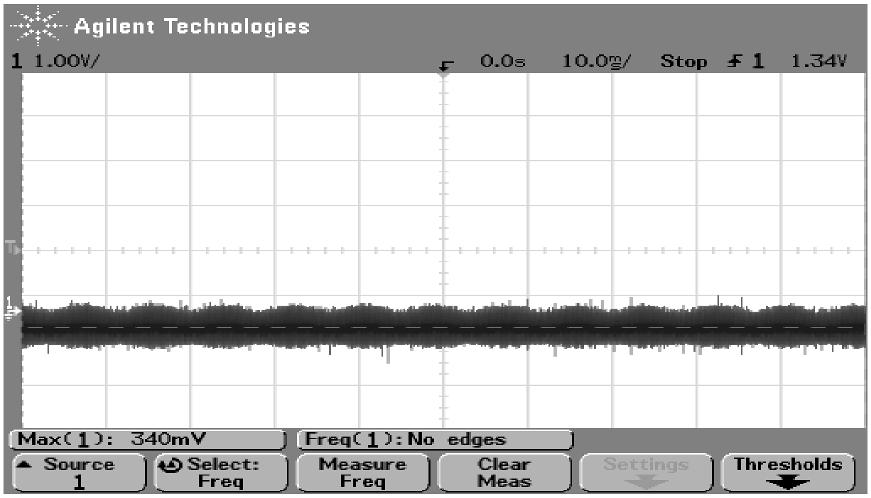


Figure 18

### 3.5 PIC16F887

Correct functionality of the PIC16F887 was ensured through the various testing of all the other components in our system. The verification of our 7-segment display, user push buttons, and frequency response of the laser pulses suggested that the PIC was working properly.

These tests demonstrated that the PIC could indeed read data from the TDC GP21 chip as well as write the data to the 7-segment display. The PIC also demonstrated that it could send start signals to the NMOS switch at the correct and expected frequency as well. Finally, the PIC could interface properly with the four push buttons that were provided to the user. All four push buttons functioned as desired.

## 3.6 Computation Unit

The computation unit was functionally verified through extensive measurement testing as well as checking the status register within the TDC chip itself. The bit organization of the TDC status register is shown in Figure 19.

| ADR | Symbol | Bits | Description | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | STAT | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 - 6 | 5 - 3 | 2 - 0 |
| | | | EEPROM_eq_CREG | EEPROM_DED | EEPROM_Error | Error short | Error open | Timeout Precounter | Timeout TDC | # of hits Ch2 | # of hits Ch1 | Pointer result register |

Figure 19

The status register on the TDC chip was checked after successful measurements were displayed on the 7-segment display as well as when no display was present. When checking the bit value at address 4, x0011 corresponded to a successful measurement while x0408 corresponded to a measurement period that timed out. By periodically checking the TDC's status register, we were able to verify that the TDC chip was functioning correctly and as expected. A flow chart of our time-of-flight measurement technique using the TDC chip can be viewed in Figure B.1.

## 3.7 User Interface

The user interface was verified to be functionally correct. We wrote known data values directly to the 7-segment display driver and displayed the results on the 7-segment displays. The LED screen displayed the predefined data values correctly, confirming proper operation. Figure 20 demonstrates one instance of a correct test output.

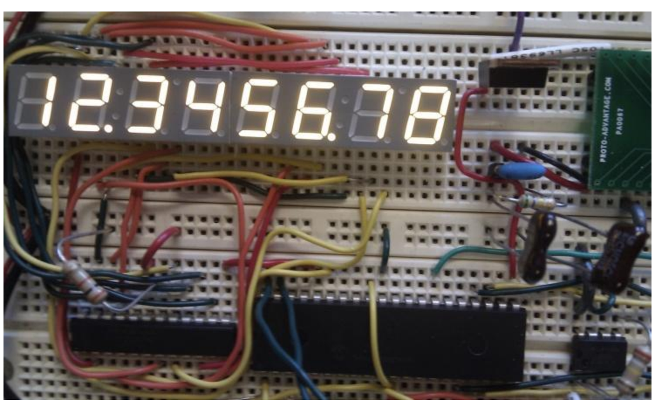


Figure 20

## 3.8 Consistent Components

One final verification that our group wanted to address was that our components had to maintain a high degree of consistency. One way to accomplish this was to require that the components have very fast response times. Therefore, any deviations from the typical response time would only result in errors of a few fractions of nanoseconds, not affecting the accuracy of our measurements by more than a few centimeters. Unfortunately, we were unable to satisfy this requirement of our design. Figure 21, 22, 23, and 24 below show the delays through various components in our system. Clearly, the delays are in the order of microseconds, failing to meet the requirement. As a result, small variations in these response times produced large variations in the final measurement calculations that were displayed.

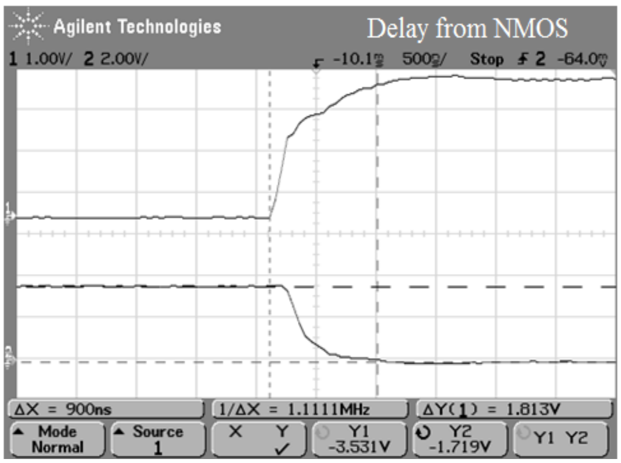


Figure 21

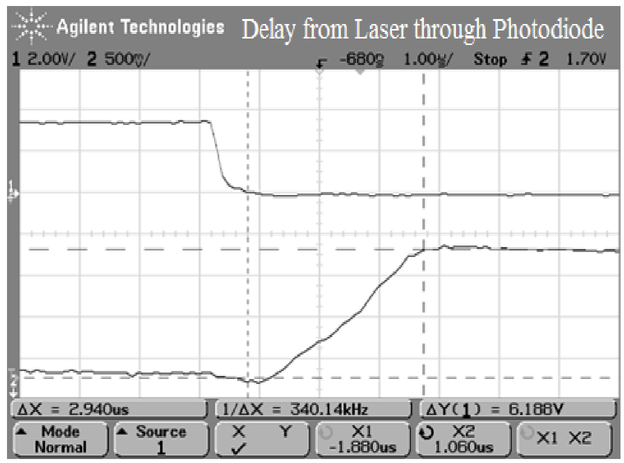


Figure 22

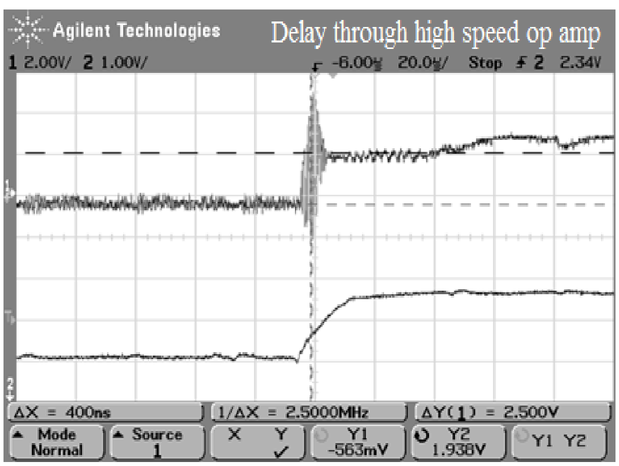


Figure 23

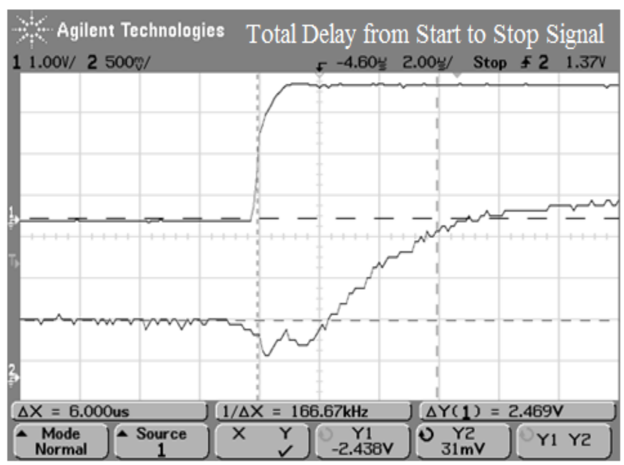


Figure 24

A final tabulation of a 1200-point average of measurements at various distances can be seen in Figure 25.

| Distance | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 | Test 10 | Test 11 | Test 12 | 1200 Point Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.02 | 2.85 | 1.35 | 3.97 | 5.25 | 1.29 | 2.94 | 3.13 | 2.07 | 1.02 | 1.1 | 1.43 | 2.942 |
| 2 | 2.21 | 0.78 | 0.82 | 1.44 | 1.48 | 2.04 | 0.85 | 2.74 | 1.68 | 0.78 | 1.59 | 1.61 | 1.802 |
| 3 | 1.35 | 1.79 | 1.37 | 1.17 | 3.7 | 0.2 | 1.75 | 2.06 | 3.61 | 3.73 | 1.17 | 1.73 | 2.363 |

Figure 25

It is clear that the measurement values fluctuate greatly at various distances confirming our suspicions.

## 4. Costs

Below is a complete outline of all the parts that have been purchased towards the completion of our project as well as an estimated total labor cost.

### 4.1 Parts

**Table 1 Parts Costs**

| Part | Manufacturer | Retail Cost ($) | Quantity | Cost ($) |
|---|---|---|---|---|
| Laser Module (650 nm, 5 mW) | Aixiz Lasers | $5.00 | 1 | $5.00 |
| Photodiodes (OPT101) | Texas Instruments | $6.88 | 2 | $13.76 |
| Fresnel Lens (5 in x 5in) | Edmund Optics | $48.50 | 1 | $48.50 |
| Voltage Driver Chip (MAX232) | MAXIM | $8.65 | 2 | $17.30 |
| Microcontroller (PIC16F887) | Microchip | $2.45 | 1 | $2.45 |
| TDC-GP21 Chip | ACAM | $27.89 | 4 | $111.56 |
| Serial-to-7 Segment Display Driver (MAX7219CNG) | Spark Fun Electronics | $14.48 | 2 | $28.96 |
| 4 Digit LED 7 Segment Display (LTC-4627JR) | Lite-On Inc. | $3.96 | 3 | $11.88 |
| Voltage Regulator (LP2951ACN-3.3) | Texas Instruments | $0.56 | 1 | $0.56 |
| High-Speed Op Amp (LMH6732MA-ND) | Texas Instruments | $6.38 | 2 | $12.76 |
| System Mount | Machine Shop | $100.00 | 1 | $100.00 |
| Misc. Circuit Parts(Capacitors, Resistors, etc.) | ECE Part Shop | $50.00 | Many | $50.00 |
| **Total** | | | | **$402.73** |

**Table 2 Original Design Scraped Parts**

| Part | Manufacturer | Retail Cost ($) | Quantity | Cost ($) |
|---|---|---|---|---|
| Avalanche Photodiode (S5343) | Hamamatsu | $204.10 | 1 | $204.10 |
| Laser Diodes (650 nm, 5 mW) | U.S Lasers | $9.00 | 6 | $54.00 |
| **Total** | | | | **$258.10** |

### 4.2 Labor

**Table 3 Labor Costs**

| Employee | Cost ($) | | | |
|---|---|---|---|---|
| Chee Loh | $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 | | | |
| Xingliang Wu | $40/hour * 2.5 * 12 hours/week * 12 weeks = $14,400 | | | |
| **Total** | | | | **$43,200** |

**Grand Total** = $43,860.83

## 5. Conclusion

We believe that we have completed the project to the best of our abilities. We have designed, built, and verified correct functionality of almost all of the physical components in our system. All of the software coding and communication between the PIC and TDC GP21 have been completed and verified as well. The only disappointment that we have is that the project was not able to achieve the accuracy standards that were outlined in our design specifications. However, our group views this project and Senior Design as an invaluable learning opportunity. We have learned a great deal about proper engineering documentation and testing techniques. We also recognize the importance of planning well thought out and organized design ideas.

### 5.1 Accomplishments

Many accomplishments have been achieved upon the completion of our project. Our group was able to achieve successful communication with the TDC GP21 chip. This was a very significant accomplishment as proper breadboard layout and internal chip initialization took quite a bit of effort. The group was able to achieve successful transmission, reception, and interpretation of optical signals. This was another huge milestone as all members of our group had limited experience designing and testing with optical transmissions. The group was also able to achieve successful calculation algorithms as well as a properly functioning user interface and display.

### 5.2 Uncertainties

We believe that most of the inaccuracies in our final measurements were a direct result of inconsistencies in delay times of various components in our system. Although we believe that improving the response times of the components to the order of nanoseconds would improve much of these inaccuracies greatly, we are unsure whether this would be sufficient when compared to industry standards. We believe that consumer laser rangefinders maintain very high accuracy measurements by using a combination of raw time-of-flight measurements as well as other techniques such as laser frequency modulation or laser triangulation.

## 5.3 Ethical considerations

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.

## 5.4 Future work

Some suggestions for future work should be considered. As mentioned previously, improving the response times of remaining components would improve measurement accuracy. Future groups may consider upgrading the TDC chip to the TDC-GPX chip for improved resolution. Exchanging the ordinary photodiodes in our system for an avalanche photodiode may be considered to increase the maximum distances that can be measured, but this choice requires significant monetary investment and process control.

## References


[1] Photodiode/Phototransistor Application Circuit, Photodiode_circuit.pdf(application/pdf Object). [Online]. Available: http://physlab.lums.edu.pk/images/1/10/Photodiode_circuit.pdf (Accessed: 11 March, 2012)

[2] US-Lasers – Red Visible Laser Diodes. [Online]. Available: http://www.us-lasers.com/vilasdio.htm (Accessed: 11 March, 2012)

[3] Si APD S5343 to S5345, S9073 to S9075. [Online]. Available: http://sales.hamamatsu.com/assets/pdf/parts_S/S5343_etc.pdf (Accessed: 11 March, 2012)

[4] Fresnel Lenses – Technical Images. [Online]. Available: http://www.edmundoptics.com/products/displayproduct.cfm?productid=2040 (Accessed: 11 March, 2012)

[5] Time-to-Digital-Converter Preliminary Datasheet. [Online]. Available: http://www.acam.de/uploads/media/DB_GP21_en_04.pdf (Accessed: 11 March, 2012)

[6] Monolithic Photodiode and Single-Supply Transimpedance Amplifier. [Online]. Available: http://www.ti.com/lit/ds/symlink/opt101.pdf (Accessed: 1 April, 2012)

# Appendix A – PIC16F887 Schematic and Final Code

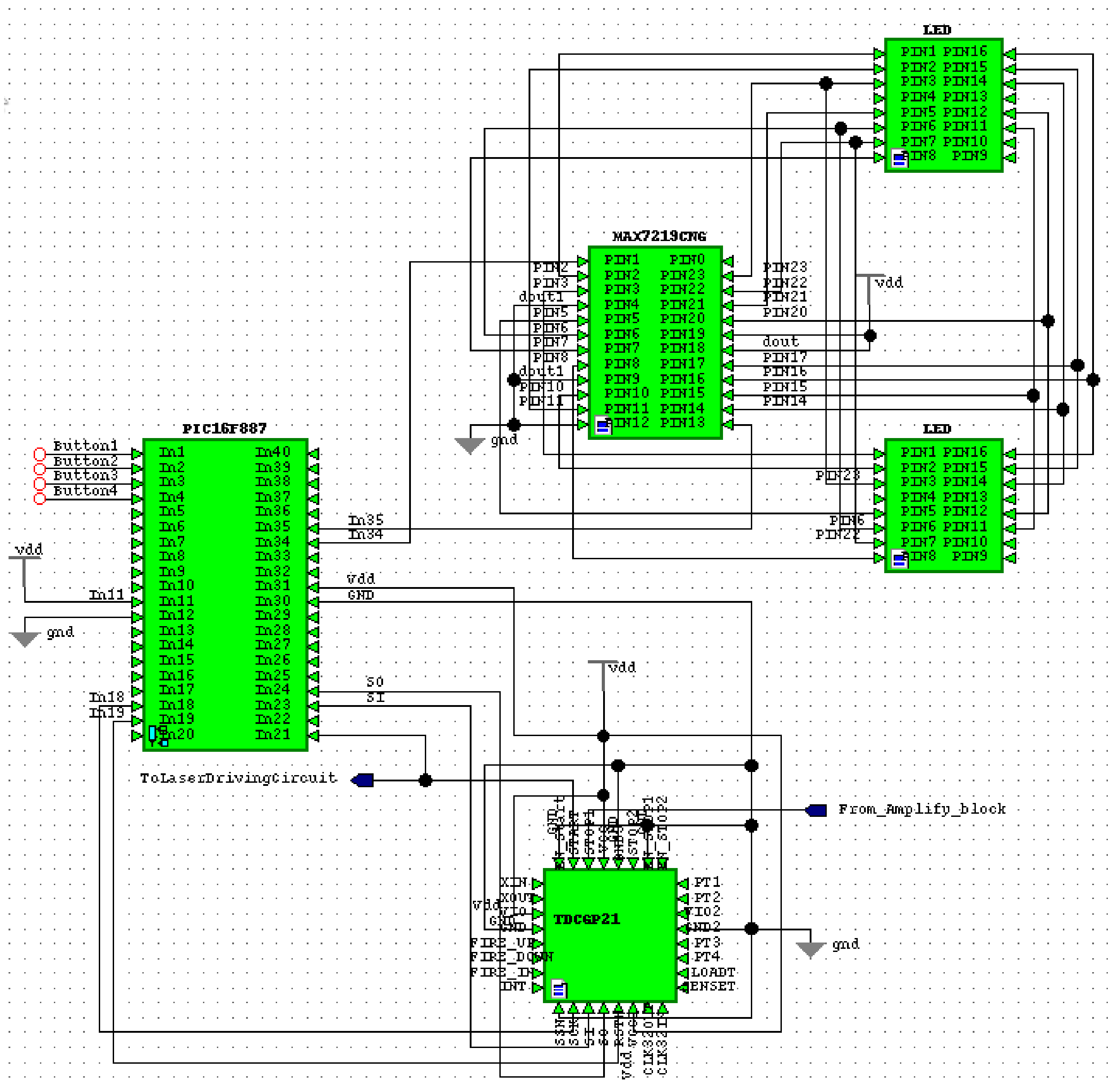


Figure A.1

```
#include <16F887.h>
//#FUSES
INTRC,NOWDT,NOPUT,NOMCLR,NOPROTECT,NOCPD,NOBROWNOUT,NOIESO,NOFCMEN,NOL
VP
#fuses INTRC_IO,NOWDT,PUT,NOLVP
#use delay(clock=8M)
//#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7, ERRORS)
#include <stdlib.h>
#include <max7221.h>
#include "tdcgp21.h"

#define SPI_MODE_0  (SPI_L_TO_H | SPI_XMIT_L_TO_H)
#define SPI_MODE_1  (SPI_L_TO_H)
#define SPI_MODE_2  (SPI_H_TO_L)
#define SPI_MODE_3  (SPI_H_TO_L | SPI_XMIT_L_TO_H)

#define measure_mode_1     pin_a0
#define measure_mode_2     pin_a1
#define measure_mode_3     pin_a2

//int32 calib_result;
//float correction_factor;
float result0;
float result1;
float speed;
int hit_count = 0;



//==========convert 32bit to 16 bit integer 16 bit faction====
float Bit32ToFloat(int32 number)
{
      float result, temp;
      int32 temp0;
      int i;
      temp0 = number;
      result = 0.0;
      temp = 1.0;
      for(i = 0; i<16;i++)
      {
            if((temp0&0x00010000)!=0)
            {
                  result += temp;
            }
            temp *= 2.0;
            temp0 = temp0 >> 1;
      }
      temp0 = number<<1;
      temp = 0.5;
      for(i = 0; i<16;i++)
      {
            if((temp0&0x00010000)!=0)
```

```
          {
               result += temp;
          }
          temp /= 2.0;
          temp0 = temp0 << 1;
     }
     return result;
}

//============drop any data greater than 500 ns==============
float confine(int32 data)
{
   float result, temp;
   int i;
   int32 temp0;
   result = 0.0;
   temp0 = data & 0x00007FFF;
   temp = 125.0;
   for(i = 0; i < 14; i++)
     {
          if((temp0 & 0x00002000) !=0)
               result += temp;
          temp /= 2.0;
          temp0 = temp0 <<1;
     }
     return result;
}

//============================================
void main()
{
float temp;
int check;
int32 i;
int32 result;
temp = 0.0;
//int i;
     init_7221();
     delay_ms(10);

//====================test writing to LED==============
/*while(1)
{
convert_to_max_high(56.78);
convert_to_max_low(-1.23);
}*/

//initial start pin and rtns pin of tdc chip
output_low(something);
output_low(start);
delay_us(100);
output_high(PIN_D4);
```

```
delay_us(100);
output_low(PIN_D4);
delay_us(100);
output_high(PIN_D4);


setup_spi(SPI_MASTER | SPI_MODE_1 | SPI_CLK_DIV_4);
output_high(SSEL); // Initialize Slave Select to inactive level
delay_ms(100);

gp21_send_1byte(0x50);  // Power on Reset to GP21
delay_us(500);          // 500 us wait for GP21

      //----------- read-write communication test --------------
      gp21_wr_config_reg(0x81, 0x12345678); // Config reg 1

      // Opcode 0xB5:  Read content of highest 8 Bits of write
      // register 1, to be used for testing the communication.
      //    result = gp21_read_4bytes(0xB5);
      //    convert_to_max(result);

      //initialize TDC measure mode 2, Hit1 - start. Auto calibrate
      //tref = 1/4Mhz, divclk = 4, time  = reg0 * 1us
      gp21_wr_config_reg(0x80,0x22242801);//reg0
      gp21_wr_config_reg(0x81,0x21020001);//reg1
      gp21_wr_config_reg(0x82,0x20000001);//reg2
      gp21_wr_config_reg(0x83,0x01000001);//reg3
      gp21_wr_config_reg(0x84,0x20000001);//reg4
      gp21_wr_config_reg(0x85,0x00000001);//reg5
      gp21_wr_config_reg(0x86,0x00001001);//reg6

      gp21_send_1byte(0x70);      //init tdc
      gp21_send_1byte(0x03);      //calibate
      delay_ms(10);
      result = gp21_read_4bytes(0xB0);

      while(1)
      {
            output_low(start);
            gp21_send_1byte(0x70);      //initialze tdc
            output_low(start);          //start tof
            delay_ms(10);
            output_high(start);
            delay_ms(10);

            output_low(start);
            delay_us(20);


            /*result = gp21_read-_2bytes();
            convert_bit_max(result);
            delay_ms(500);
```

```
			result = gp21_read_4bytes(0xB0);
			convert_bit_max(result);
			delay_ms(500);		*/



			while( input(measure_mode_1) &&
input(measure_mode_2)&&input(measure_mode_3) )
			{;}
			if(input(measure_mode_1) == 0)
			{
			temp = 0.0;
			for(i=0;i<100;i++)
			{
			//distance and speed measurement. higher 4 bits dist lower
4 bits speed
			result = gp21_read_4bytes(0xB0);
			temp += confine(result);
			output_low(start);
			gp21_send_1byte(0x70);		//initialze tdc
			output_low(start);		//start tof
			delay_us(20);
			output_high(start);
			delay_ms(10);
			output_low(start);
			delay_us(20);
			}
			temp /= 100.0;
			if(hit_count == 0)
			{
				result0 = temp * 0.1499 -17.00;
				if(result0 < 0)
					result0 = 0.0-result0;
				convert_to_max_high(result0);
				speed = 0.0;
				hit_count = 1;
			}
			else if(hit_count == 1)
			{
				result1 = temp * 0.1499 - 17.00;
				if(result1 < 0)
					result1 = 0.0-result1;
				convert_to_max_high(result1);
				speed = (result1- result0)/1.20;
				hit_count = 2;
			}
			else
			{
				result0 = temp * 0.1499 -17.00;
				if(result0 < 0)
					result0 = 0.0-result0;
				convert_to_max_high(result0);
```

```
                speed = (result0 - result1)/1.20;
                hit_count = 1;
            }
            convert_to_max_low(speed);
            }
            else if(input(measure_mode_2) ==0)
            {
            //print status reg
            result = gp21_read_2bytes();
            convert_bit_max(result);
            }
            else if(input(measure_mode_3) ==0)
            {
            //print raw data of TOF
            result = gp21_read_4bytes(0xB0);
            convert_bit_max(result);
            }
        }
}
```

Figure A.2

## Appendix B – Time-of-Flight Process Flow

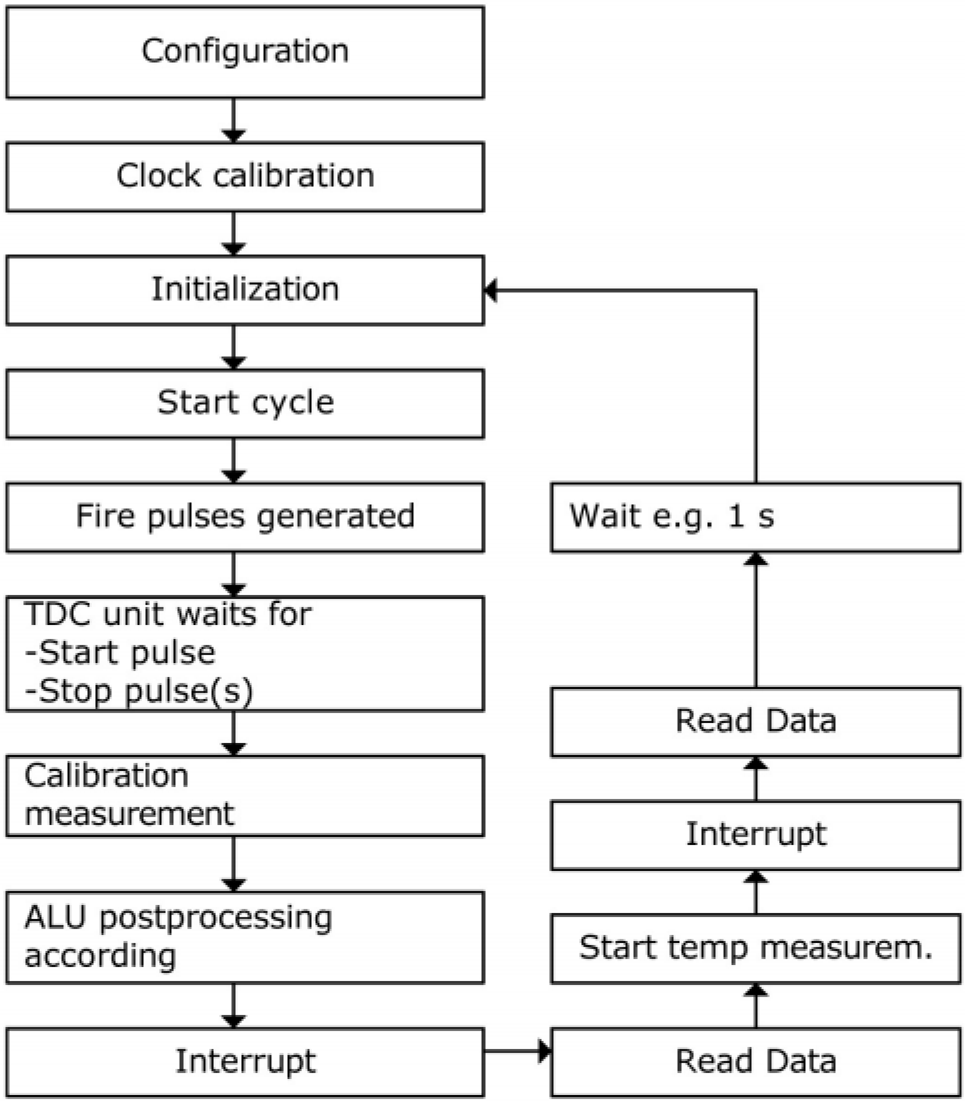


Figure B.1

## Appendix C – Verification and Requirements Table

**Table 4**

| Requirement | Verification | Verification Status |
|---|---|---|
| 1. Laser Module is operating correctly<br>a. Laser Module is operating correctly at 4.5 V supply<br>b. Laser Module can pulse at desired frequencies<br>c. Laser Module can pulse at a frequency specified by the PIC | 1. If the laser module is operating correctly at the specified supply voltage and can pulse at the desired frequencies, the laser module is functioning correctly<br>a. Check supply voltage to laser module and verify that laser is outputting full brightness.<br>b. Drive the laser diode with the function generator with a known frequency. Shine this pulsing light on the photodiode system. Connect the output from the photodiode system 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.<br>c. Calculate the time delay of each laser pulse from the PIC code. Measure the output received at the photodiode system with an oscilloscope. If the output frequency closely matches the frequency calculated, the laser diode can pulse at the desired frequency | Verified |

| | | |
|---|---|---|
| | specified by the PIC itself. | |
| 2. Collection Optics should be focusing incident light at the correct focal length. The photodiodes should also be detecting the correct frequency of light.<br>a. The Fresnel lens should produce a focused image at the specified focal point.<br>b. The photodiodes 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 photodiodes are producing a correct frequency response when our laser diode is activated, our collection optics will be functioning correctly.<br>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 focused image of light is the focal length.<br>b. Shine the laser module at a known frequency generated by the function generator. Check the output of the photodiode on oscilloscope to compare frequency response. | Verified |
| 3. The Receiver Module should amplify the voltage differential between the two photodiodes as well as not trigger a stop signal when the laser is not pulsed.<br>a. Differential Amplifier should be gaining the voltage differential from the two photodiodes to a minimum of 2 V to trigger the stop on the TDC when the laser is pulsed(within a 5 m distance). | 3. If the differential amplifier is gaining the voltage up to a minimum of 2 V when the laser is pulsed and is producing an output voltage lower than 2 V when no laser is pulsed the receiver module is functioning properly.<br>a. Measure the voltage response of the differential amplifier circuit when the laser is pulsed and an object is within a 5 m distance. If | Verified |

| | | |
|---|---|---|
| b. The stop signal to the TDC should not exceed the minimum threshold voltage of 2 V when the laser is not pulsing. | the voltage is amplified to a minimum of 2 V, the differential amplifier is functioning correctly when receiving a laser signal.<br>b. Measure the voltage response of the differential amplifier circuit when the laser is not being pulsed. The TDC chip should display a status of “time out” because the stop signal from the differential amplifier does not exceed the 2 V minimum. | |
| 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.<br>a. TDC Chip should send the correct distance calculations to the PIC’s onboard storage registers.<br>b. TDC works on Start-Stop Measure Mode 2. It can measure the time difference from the rising edge of the start signal to the rising edge of the first stop signal. | 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.<br>a. Write a value into Register 0 on the TDC chip. Read the data from the register immediately after. Check the correct writing and reading of various values.<br>b. Use the PIC to generate start and stop signals. Increment the delay time between start-stop. Read from the TDC chip and print out result onto 7-segment display. | Verified |
| 5. User Interface should be correctly displaying the data value stored in the registers on the PIC16F877 microcontroller | 5. Write known data values to the MAX7219CNG 7-segment display driver. Confirm that the LED screen displays the correct 7-segment representation of | Verified |

| | | |
|---|---|---|
| | the data. | |
| 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 module, photodiodes, differential amplifier, PIC, TDC chip, and 7-segment display.<br>a. The supply terminals to the operational amplifier in the amplifier circuit should be at least a minimum 4 V and -4 V.<br>b. The supply voltage of the PIC should be 3.3 V.<br>c. The supply voltage of the TDC chip should be 3.3 V.<br>d. The supply voltage to the LED display driver and 7-segment display should be at least a minimum of 4 V. | Verified |
| 7. Components should be chosen to have very fast response times (~ 1-3 ns ideally) in order to minimize propagation delay and delay inconsistencies | 8. Incomplete - Photodiodes and PIC signal response times are not fast enough to produce valid and consistent results. | Not Verified |