Portable Sensing Field Device

Temperature and Ranging Tool

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Chapter 1: Introduction

1.1 Executive Summary

With the ever increasing rate of the evolution of today's technology, many once simple devices require more demanding solutions for added convenience. The portable sensing field device is a handheld unit that can wirelessly measure both range and temperature of distance targets. This device attempts to solve traditional and inconvenient methods of measuring distance and temperature; such as measuring tape and expansion\contraction thermometers. This added functionality could be an invaluable tool for certain people working in many different industries. This extended ability enables the user to taking measurements in applications where previous methods would prove to be very impractical or physically impossible.

The motivation for doing this project for senior design was mostly due to several of the team member's avid interest and desire to learn more about the world of optical engineering and well as small signal analysis. There are very few optics classes available to undergraduate students in the electrical engineering field, so this project is a way to explore what we would have not otherwise been able to do. Since this project will encompass many different fields of electrical engineering, it is a worthy challenge and will use most, if not all of the skills that we as engineers have acquired over the past 4 years of training.

As the idea of the portable sensing field device has further developed and changed, there have been many alterations to the original plan as well as several complications were encountered. The sensing device will be a small handheld device with some sort of LCD. It will have a triggering mechanism for turning the device on and off, as well as mode selection buttons that will control various functions. We undertook this project knowing the challenges of building a laser range finder and are fully confident in our abilities to get the job done in a minimal cost and effective way. The sensing device will consist of several different sub-modules that each carries their own separate function. There will be an IR laser, photo-sensor, IR sensor, a laser sub microcontroller, a main microcontroller, main power system, triggering unit, and its containment structure.

1.2 Motivation

Like mentioned before, the main motivation behind the sensing device is the core interest of the subject of optical engineering from several of the members. Building such a device will develop invaluable skills that can be applied to a wide variety of real life situations. Although this is not a new idea, and has been done plenty of times before, the skills and satisfaction that one gets out of building it yourself, are invaluable. The fact that laser range finders are now commercially available for relatively low prices does not change the complexity of building one yourself. Time-of-flight based rangefinders are extremely complex and require the designers to be extremely precise in their actions. The devices that are currently on the market that achieve a similar function usually only tell the range of the target. We chose to add IR temperate to our design as well. This is a device that does not already exist, so if properly constructed, could have some potential for future applications.

The concept of range finding is a fairly simple thing to do using tradition methods. Using ultrasonic or IR LEDs make this task fairly simple. But you are very limited in range as these methods are best suited for robotics and short range detection. We sought out on this project to create a device that can detect long range objects using an IR laser beam using the time of flight method. This is perhaps this most challenging to the range methods, as well as the most costly. One of the most difficult design hurdles that we must overcome in doing this project is the ranging photo detector circuit. The nature of the part that is required uses very high voltages which are very sensitive to temperature changes; which requires external compensation as a correctional factor. The other most difficult part in designing this device is the optical lens system that is required. Since we deal with very low power reflected light, we need an optics system that is able to focus every little bit of received light onto the photo detector. Like mentioned before, we knew as a group going into this that it would be a difficult task to achieve. We are however, confident and determined to achieve our goals.

Another strong driving force, for several group members, behind wanting to build such a project is the core concepts and experience that one is exposed to in designing such a gadget; making it an excellent senior design project. The portable sensing field device has a heavy emphasis on optics and lasers. Optical engineering is a highly sought after field for many employers and this project proves to serve as valuable resume builders. ACAM and Transducer's Direct, the manufacturer and supplier of one of our components, are interested in publishing our work on their company websites, so that large source of our motivation for this project.

From what we could tell, there hasn't been a senior design group in the past that has attempted to do a laser ranging and temperature sensing device. So on top of this being a great engineering experience, this is a unique project to the eecs senior design library. While this tends to distinguish our group from those in the past, this may also prove to be more difficult because there is less information for us to compare. While there are previous works that we were able to find throughout the internet, they are numbered and not quite what we are trying to do.

Due to the complexity of this project, we inquired a mentor that we can talk to for advice. Since this project has optics and lasers in the device, we consulted a person from the CREOL program when designing certain parts. While we could design the optics system ourselves, there may be more efficient ways in doing certain parts that we may need to consider.

1.3 Goals and Objectives

The main goal, above all, for this project is to create a lightweight, portable, handheld device that is able to accurately measure both range and temperature of distant objects. The design has been done in the most efficient way in reference to both power consumption and hardware design. Effective engineering principles and values are applied throughout the entire design to achieve the best possible solution using the least amount of parts to attain maximum results. The final device is simple and straightforward. It is designed so that it is self-explanatory in its operation and simple for any one, from any background to use.

As a group we decided that we want to be able to both range and temperature sensing. We also though that it would be very interesting to have some kind of video processing system that can overlay the range and temperature readings on the screen as you actively view it. This requires a camera and some kind of active LCD screen. After research, we come up with a method of display the readings on the screen using microcontroller. We focus on designing around Nokia 5110 LCD which is an advanced display graphic LCD 84x48. Using this graphic LCD, we are able to display both results of range finder and thermometer perfectly.

One major goal of the portable sensing field device is achieving function laser distance calculations. Realizing this goal is a monumental task worthy of the efforts of 4 highly trained UCF engineering students. Due to the extremely high speed of the velocity of light and measuring a bounce back from many meters away, precision hardware timing will be essential for success. All amplifiers and switching circuitry must be high quality and made specifically for high speed/high frequency applications. Even there had been error occurred in calculation and calibration, we complete the device with these goals have been done perfectly:

- The sensing device is lightweight portable.
- Device is dependable and predictable in its measurements and calculations.
- It is able to take min/max temperature reading when continually measuring.
- It is able to simultaneously display and actively update both temperature and distance readings LCD screen.
- It is able to report to LCD a null value when target is out of range.
- It is able to report an estimated degree of accuracy for both temperature and distance.

- The device has a method of predicting remaining battery life.

1.4 Requirements and Specifications

The following requirements and specifications are the guiding constraints that we consider when designing every sub-system of the device. The conditions listed below are all physically possible in terms of current technologies and are within the capacity of a focused engineering undergrad. These requirements are discussed in further detail in the succeeding sections. The portable sensing field device have achieved following:

- It is able to take range readings using IR laser light; achieving distance measurements of at least 50 meters (164 feet, 55 yards) (roughly half a football field).
- Entire mass of device, including all circuitry and enclosure weight less than 2.5 lbs.
- It is able to measure temperature using emitted infrared energy over the temperature range of -20°C to 500°C.
- Achieve a temperature reading at distances of at least 20 feet.
- Have functional operation in the ambient temperature range of -40°C to 160°C.
- It is able to sustain function battery life of at least 1 hour of continuous use (1 hour of hand-trigger initiated readings).
- Have an LCD output with data update of no more than 1 second.
- It is able to be held with one hand; e.g. not excessively bulky in its package design.
- Have trigger/button reading functionality (device takes reading by operator pushing trigger/button).
- For the temperature measurement, have a distance to spot ratio of at least 10:1.

1.5 Risks and Challenges

As with any project that the designer does not have hands on experience with, there is an inherent risk involved with attempting such project. Since the portable sensing device deals with several different small signal responses electromagnetic transmission, there are multiple points of possible failure are associated with designing such a device. However, largest risk in the project will be when it comes down to choosing and purchasing the parts required for the design. I say this because as students, we lack much of the hands on experience and real world skills that would enable an engineer to pick the right part for the job. Of course, this project represents a significant investment in the development of those “real world” skills. As we research the parts required for the design, we have gained an understanding if the part is going to work for what we're trying to do, but there are always may be unforeseen circumstances that may render that part unusable for the application.

There is also a great risk in accepting such a project due to the fact that we are designing a laser range finder. This project is usually regarded as one of the most complicated methods of distance measurement; as well as the most costly. I have represented a large risk in undergoing such a goal. The main reason why laser range detection is usually considered to be such a difficult thing to implement is because you are sending out some pulse of (usually infrared) light over a large distance and hoping to receive a small part of that light back. This requires the use of a properly selected and sensitive optics system, very sensitive photo detection hardware, and exceptionally low noise electronics. The analog electronics part of the design is thought to be the most difficult portion. Once we have a stable analog voltage that properly represents the incident light on the photodiode, digitizing this quantity and manipulating it using in C code is not that hard to do.

There is another significant risk is associated with designing the power system of the device that we experienced. Since this device have several different active loads on the battery supply, we need some method of calculating the different current draws from each load. Since the current draw on the battery is going to be dynamically changing due to use of different functions on the device, this was a difficult task to do. It has been taking very hard time to design a power system when you do not have the entire module system yet designed and do not know what the entire current draw will be under maximum conditions. To approach this problem, we design the power system concurrently as we design the other functions. Finally, we have more than one method of getting the job done.

Since out portable sensing device have a laser built into it, there is a personal safety risk for ourselves and those around us when operating this device. In 2010 the National Institute of Standards and Technology did a study regarding effects of infrared laser light on the human eye. They found that power levels of only 20mW in the 800nm range could cause substantial retinal damage. Much of the risk associated with infrared laser light is not so much the power level, but the fact that the human eye cannot see infrared light so a person would not know when they are being exposed to retina damaging power levels. When dealing with high powered laser's it is essential that the designer wear protective eye wear to avoid any bounce back or wanted reflections that might penetrate the eye. However, as the designer of this device, we of course focus on keeping the power level of the laser low enough so that it is in the government sanctioned bracket of safe operation for extended exposure. Most of the damaging effects of these lasers would only be for point blank exposure. Since the operator of the device will only be exposed to the bounce back off a distance object, the power level will be greatly reduced and safe for absorption by the eye. Another issue of personal safety arises when it comes to the power system and potential combustion of the battery. One particular issue that comes to mind is the exploding Li-ion batteries that Apple was plagued with on their MacBook's and iPods in 2006. As of Wikipedia, Li-ion batteries can suffer from thermal runaway and cell rupture when overheated and/or overcharged. Such effects can lead to thermal combustion, violent explosions, and release of harmful gases. Since a Li-ion battery pack may be one of the possible choices due to its recharging abilities and specific energy density, this is something that we must consider. Whatever battery we do chose, we must also make sure that is rated to function in the range of operation conditions for the device.

In summary, the portable sensing field device represents both a technically and administratively demanding undertaking. The inherent risks accompanying the range device is great; as well as crafting a tool that is safe for both the operator and those around. Achieving these goals and overcoming said risks, indeed mandates the full cooperation of all members of the group.

1.6 Block Diagram

Presented in figure 1 is the generalized block diagram describing the overall sub-module operation of the portable sensing field device. One can see that the device is split up into its separate main functions. The sensing devices are all fed into the microcontroller where they are turned into a digital representation and processed using C code. Each of the sensing devices, although shown as a simple block, represents detailed circuits that are too confusing to show in a single schematic representation. Each of these modules, both research and design, will be discussed in great detail in the following sections.

In being a group project, each person is assigned an individual subsystem to both research functionality and come up with a possible design. The core functionality of the sensing device revolves around the TDC chip and the main microprocessor. This is where all the post processing of sensor data will be done and output to the LCD. The APD sensor circuit is by far be the most sensitive and we spend the most time on designing and critiquing during prototype testing. Since this is system need to communication with all the separate modules at the same time, there is a central clock pulse that ensures synchronous data transfer. In **figure 1.6.1**, although not shown, there is a synchronous clock pulse going to the APD module. The output from the TDC and the IR temperature circuit both communicate with the MCU using the SPI (Serial Peripheral Interface). The output from the IR temperature circuit is analog and is converted to a digital representation within the MCU.

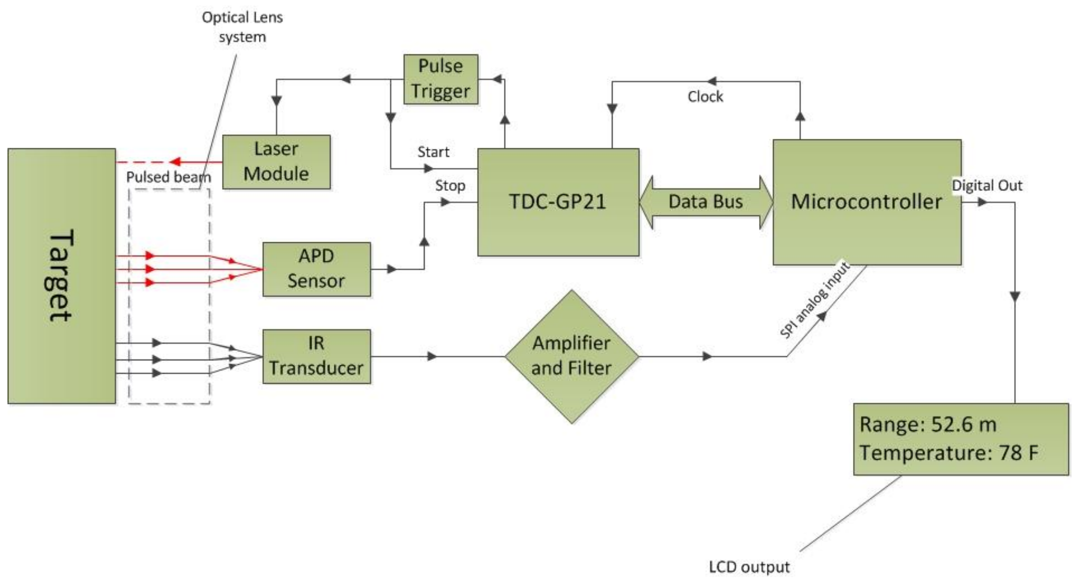

Figure 1.6.1

Since there are two photodiode, we have two separate lenses. An optics system must be used because when we send out the pulsed IR laser beam (for the ranging system) very much of the power will be lost due to absorption and reflections from the target. However, there is a very small fraction of a diffuse reflection that makes it back to the source. This is where the APD sensor becomes a fundamental necessity. The APD's ability to pick up on such small levels of radiation makes it the ideal part to use for a laser range finder. The lens focuses that small amount of light onto a very small (~.2mm) area on the APD. The geometry and lens placement is extremely important. The lens system for the IR thermometer is necessary for the same reason. The IR temperature device does not rely on a laser beam from the source though. This picks up on the very small amount of IR energy that all matter emits when above 0°K.

Chapter 2: Research

2.1 Distance Ranging System

2.1.1 Theories of Operation

Most methods of finding the distance to an object rely on a very simple principle, sending a pulse of something out, and finding the time that it takes to receive the bounce back. Once the time round trip time is known, then the distance can be calculated using the fundamental laws of speed and motion. This very simple concept is employed by several hundred different species of animals throughout the world and is the main mechanism that is used in all modern range finding devices. In general, there are 3 main methods of finding range that are in use today. They are as follows:

- SONAR (Ultrasonic ranging)
- RADAR - radio detection and ranging
- LIDAR (Laser\Infrared)

Each of these has their unique advantages and applications and will be discussed.

SONAR RANGING

SONAR – or sound navigation and ranging, is a type of echolocation used to find objects. It works by sending out a ping of some frequency, either audible or inaudible, and listening to find the ping back after it hits and object. Best known for being used by the US navy in submarines and boats, SONAR is most effective when used in water. This is due to the fact that ultrasonic sound moves much faster while in water versus air. Making it particularly effective for finding boats and submarines where other methods of location would be ineffective.

Shown in **figure 2.1.1** is the overall method of SONAR. The sender sends out a ping of some magnitude, it hits some object, the reflected wave of lesser magnitude goes back to the receiver and the round trip time is found. When using sonar in the air for consumer electronics, the ping is usually in the ultrasonic range so that it is inaudible to humans.

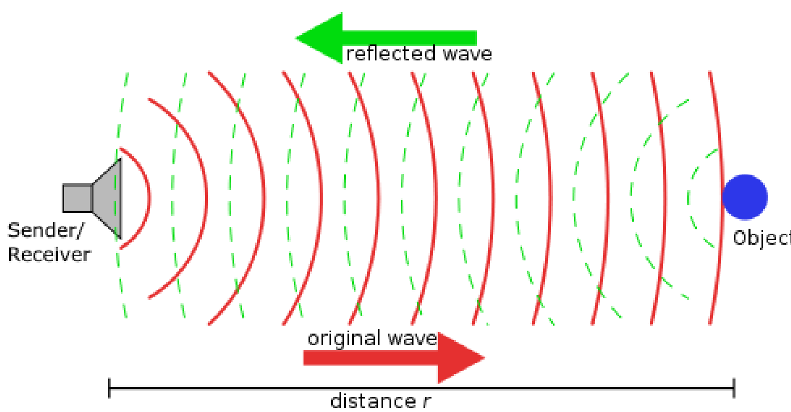

Figure 2.1.1
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Since sonar only requires a speaker and sensitive microphone, it is generally the most cost friendly method of finding range. This of course has its trade off. When using sonar in the air, it is limited in range. Most sonar sensors are limited to about 10 feet (3 meters), making it an effective sensor for a robot or short range motion sensor.

RADIO DETECTION AND RANGING (RADAR)

Radar is extremely widespread and probably the most common method of ranging used today. Like the name suggests, radar uses radio waves to track objects around the source much like sonar uses sound waves. One obvious advantage of using radio waves is their inherit ability to penetrate through many common materials. Depending on the frequency of the radio waves that are being used, generally radio waves bounce off metals and carbon fiber materials, making radar particularly useful for the detection of aircrafts, planes and other large metal structures.

Radar propagates in a radial manor. All objects at a certain radius distance from the source will be exposed to the radio waves. The waves will either pass through the objects or be reflected.

Radar detection systems, while having the furthest range, are not the best choice for the scope of this project. Since they work in a radial manor, finding the line of sight distance from the source to an object may be difficult. Radar systems are also generally the most expensive of the ranging methods and one will also encounter legal issues when implementing a ranging system using this method due to local laws in place from the FCC.

LIDAR (Optical/Infrared)

The next most common and best choice for a long distance point and detect ranging system is the LIDAR method. LIDAR – light detection and ranging, works very much like radar but is using light (laser/infrared) instead of radio waves. One advantage that matches the scope of this project is the fact that light propagates in a line of sight manor. This would allow the user to point the device at the target, emit light, and receive the reflected beam. Due to the properties of light, LIDAR will reflect off all objects that are not transparent. This is unlike radar which requires some kind of metallic or very dense material. This property is one of the reason we chose LIDAR to be our range finder method. Ideally, the user should be able to point the device at any object and receive some portion of the original transmitted wave back.

So the question comes down to, what wavelength of light does one use to achieve the greatest distance in range? While all wavelengths in the optical and infrared spectrum should work, infrared is the best choice because it is not visible and is less prone to noise interference from optical radiation. To achieve the greatest distance, a laser is also a necessity. Since a laser concentrates the photonic energy into a small beam, the light travels much farther than traditional methods.

The concept of using a laser to determine the distance to an object has been around for some time now. Laser range finders are in use by the military, hunters, golf courses and many other practical applications. They are generally sold as a hand held device that one looks through and shows a number in meters as to how far the target or interest is. A properly calibrated, professional, military grade range finder can detect distances of up to 20 km.

There are several different methods of using a laser to determine distance. Each of which will be discussed.

TRIANGULATION METHOD

The triangulation method of laser ranging uses trigonometry and Pythagoras theorem to determine the distance to the object. By projecting a laser beam at the target and using a CMOS imaging sensor as the transducer device that is spaced at a known distance from the laser, a triangle will be formed and trigonometry can be used to find the distance. **Figure 2.1.2** shows the overall geometry of this method.

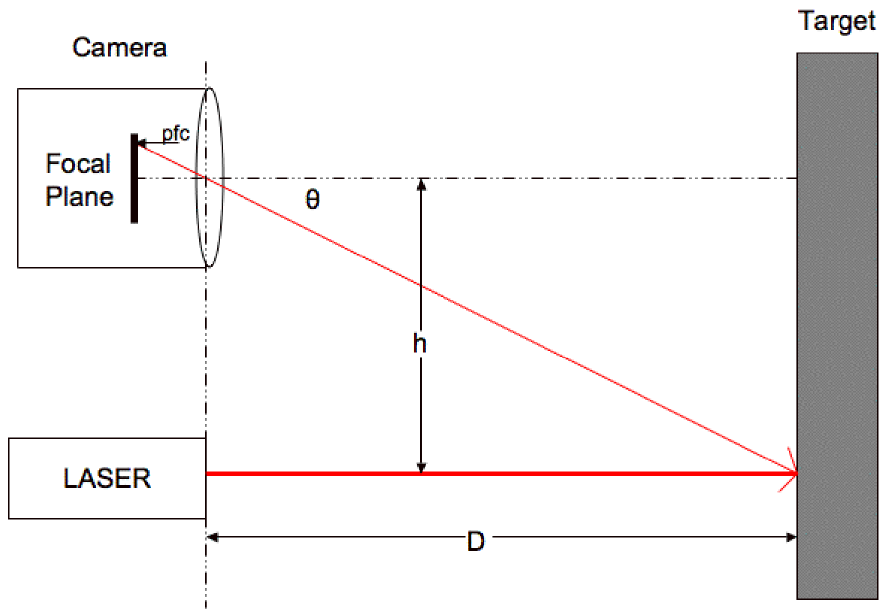

Figure 2.1.2
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The imaging sensor is used to determine the angle at which the reflected beam comes back at. Knowing angle Θ and knowing the preset distance (h) between the laser and sensor, we can find the following equation as the horizontal distance:

Triangulation distance equation:

$$D = \frac{h}{\tan \Theta}$$

Although this method, simple as it is, has a great weakness. As the distance (D) gets larger, it becomes increasingly more inaccurate. This is due to the fact that Θ becomes so large that the sensor cannot properly measure the angle. Since the distance is inversely proportional to the tangent of the angle, the measurement becomes greatly skewed. This method can achieve distance calculations of up to about 200 cm (2 meters) with a percent error of about +/- 5%. Considering the project goal requires greater distance measurements, this method is largely unsuitable for the project function.

LASER PHASE SHIFT METHOD

The phase shift method of measuring distance works by sending out a sinusoidal modulated laser pulse to the target. The receiver sensor picks up on a small amount of the bounce back light which is modulated as well from the original pulse but it is out of phase. The phase difference of the two signals is the round trip time of the light. While this method allows is usually easier to implement due to the fact that you do not have to measure the time of the laser in the air, it is usually not as accurate and requires more optics parts. For this project we want to focus more on the electronics and less on the optics. This method allows for greater distance measurement than triangulation, but is less accurate.

TIME OF FLIGHT METHOD

We use time of flight method to design our device because it is the most favorable method of laser ranging and also offers the farthest range calculations. This is the method that is used most often in commercially available laser range finders. Just as the name suggests, it works by measuring the time of flight of the sent out laser pulse. Once the time is known, the distance can be calculated. Since it relies on the bounce back from the laser, the laser intensity as well as the target reflectivity is of great importance.

Due to the extreme velocity of light, using normal methods of comparing two signals may prove to be very difficult. However, through the use of a specialized analog to digital converter, we are able to find the difference of the signals that can be used to determine the distance. Using just a laser and receiver sensor, this method will only be able to receive light from a few meters away. But through the use of precision optics and lens to magnify the received light, this method has the possibly of being able to take range calculations of over 20 km. The quality of the receiver transducer is also very important and will be discussed in later sections.

2.1.2 Laser Design

WAVELENGTH: IR VS. OPTICAL

Because of the nature of the light produced by a laser, we found that laser ranging could be done with practically every wavelength available with relatively similar performance; however, depending upon the application, there are different reasons to use the different wavelengths of light. Initially we were interested in using a laser that produced light in the visible spectrum and were considering either a blue, green, or red laser module. We found that power output options were very similar across all three types of lasers, and beam radius was very similar as well. We found nothing in our research that could determine if using one color was more beneficial than the other, so our deciding factor came down to price. While the blue and green light producing modules we considered were relatively inexpensive when compared to their laboratory grade counterparts, they still couldn't compare to the low prices of the red laser modules we found. For this reason, we began forming our device around the red laser.

While we were doing all of our initial research to determine which laser to use as the building block for our device, we completely overlooked the possibility of false activation of our sensor due to similar wavelengths of light. After we had already chosen a red laser, we realized that it was reasonably possible for our sensor to become activated by other sources of red light in the area, which would lead to false reading and therefore poor results. To circumvent the issue, we looked into the possibility of using Infrared lasers because of their relatively unique wavelengths when compared to visible light. The wavelength that we chose to use was 780nm, which is considered "near IR" and not completely IR. A laser of this wavelength is essentially invisible to the human eye in normal daylight conditions; however it could still be visible to the human eye in dim conditions, perfect for testing, and could possibly help avoid receiving any false positives when running the device. We would therefore also need specialized sensor, one that would have a peak performance ability at our desired wavelength.

Another thing to consider when using an IR laser is the potential danger the laser posed to the individual that would be using the product, as well as the general public around the user. Using lasers in the visible spectrum are generally much safer and tote lower ratings on the laser scale. This is due to the human blink reflex caused by incoming intense light sources. IR lasers do not trigger the blink reflex because they are not visible by the human eye, and can therefore cause severe retinal damage, including permanent blindness. To try and nullify the potential dangers as much as possible, a pulsed beam laser would have to be used. This would avoid the possibility of anyone's eyes being affected by a normal continuous beam laser, though proper safety equipment would still have to be used when developing the device.

POWER

Choosing the correct laser for this application is extremely important; and while theoretically laser ranging can be done with almost any commercially available laser, the overall performance of the device will depend heavily on the quality of the laser. Perhaps the most important aspect to consider is the power output of the laser. Because the light from the laser will be required to reflect off of many different surfaces, the laser module must have sufficient power output to capture the return pulse with as little loss as possible. Some surfaces will easily absorb 50% or more of the power from the laser and therefore return a severely diminished pulse. If you consider the scattering that will likely occur after the beam reflects off of the surface, it isn't unlikely that the returning beam of light will have less than 10% of the original pulse's power.
While there are other ways to improve the range and effectiveness of the laser/receiver through optics, having a large enough power output will improve the overall accuracy and prevent the possibility of false readings on your receiver.

Beam Diameter

While wavelength and power specifications are the most important factors to consider when buying a laser, you must also consider the beam diameter and scattering properties of the laser itself in order to avoid severely limiting the range of the device. As discussed in the section regarding power, scattering and diffraction can have a devastating effect on the integrity of the returning beam. However scattering and diffraction also occur prior to reflection as the laser light is traveling through the medium. Most midrange lasers share a very common beam diameter, and the modules are constructed in such a way that the scattering or diffraction of the beam in the air is miniscule and can be ignored. However, because one of the main goals of this project is to create a low-cost solution, we had to consider that more inexpensive lasers can sometimes produce of very poor quality beam with a large beam diameter, which makes both the initial and return beam much more susceptible to diffraction and scattering. Even if laser has a very large power output, the beam diameter and diffraction properties could nullify any of the usual benefits of using such a high powered laser.

2.1.3 Optical Sensor

The optical sensor of the range system is of great importance in achieving our range goal. The optical sensor is responsible for receiving the minuscule bounce back of light after it has hit its target. Using the wrong kind of sensor will have dire consequences on the range and all options must be considered.

Photodiode

A photodiode is a semiconductor device that is responsible for converting light into either a current or voltage. A standard photodiode is very similar to a basic PN diode except for the fact the packaging has an open window to allow light to get in and there are different levels of doping on the semiconductor material as well. Photodiodes work by exploiting the photoelectric effect.

The photoelectric effect says that when a photon of sufficient energy is absorbed by a material, it excites an electron of the material and causes it to break free of its atom. The free electron moves without bounds and causes a current to move in the material. The photoelectric effect is most active in very short wavelengths of light, such as the visible or ultra-violet range.

Photodiodes have several important performance parameters that describe the response of the part and must be considered when making a decision. One that is very important for this project is the responsivity of the photodiode. Responsivity is defined as the ratio of the output current per measure of light, which are usually watts. Shown below in **figure 2.1.3**, this is typically expressed in A/W and often shown in a graph versus wavelength.

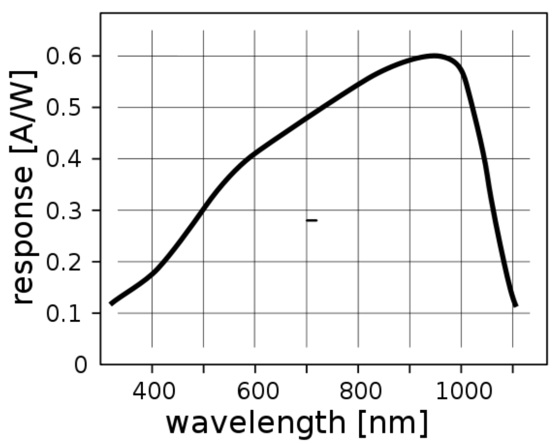

Figure 2.1.3
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One can see that the maximum output per watt occurs with light having a wavelength of about 950 nm. Since the range device will be using an infrared laser we will have to choose a photo detector that is tuned to have the maximum responsivity at the same wavelength.

Another performance parameter of photodiodes that is worth talking about is dark current. Dark current is the amount of current that moves through the diode even in the absence of light. In standard PN diodes this is known as the leakage reverse bias current. This current increases with both temperature and the voltage that is applied to the junction. This is an unavoidable phenomenon and must be accounted for when calculating the output current from the diode.

The photodiode has a huge variety of applications in electronics. Although a standard photodiode would work for the range finder, it is not the best part as they are not typically used to measure extremely low light intensities. The range would be very limited in using a standard photodiode. The photodiode is the basis for several other more sensitive and advanced photo-detectors which will be discussed. Since the photodiode outputs a photocurrent, most, if not all, photodiodes require the use of a transimpedance op-amp circuit to turn the current into a voltage for use in the rest of the circuit. There are many factors that must be considered when choosing the right op-amp. This will be further discussed in later sections.

PHOTOTRANSISTOR

The phototransistor is a simple device that is very closely related to the photodiode. It is basically just a NPN or PNP junction with an exposed window on the packaging so that light is able to hit the base region of the transistor. It works using the same method as the photodiode but the advantage of using this part is that it has a built in gain associated with the output. This is useful if you want to reduce the amount of parts needed for a project to reduce the size. Although this part has a larger output signal, the sensitivity of this device is the same as the photodiode and is not the best part to use for extremely sensitive light detection.

AVALANCHE PHOTODIODE

Of all the photo-detector parts available, the avalanche photodiode (APD) is defiantly the best choice to use for a laser range finder. APD's are ideal for applications that require high sensitivity and fast response times.

APD's are basically normal photo-detectors that have a built in gain stage that works using the avalanche breakdown mechanism. When a photon is absorbed by the junction and an electron breaks free, an electron-hole pair is generated. This electron moves through the substrate colliding with neighboring electrons which creates an "avalanche" of electrons and a large current. The APD must be powered by a large reverse bias voltage (100-200V) in order to have substantial gain apparent. In having a large reverse bias voltage, there is an equally large electric field present in the diode. So when electron-hole pairs are created as incident photons are absorbed, they are quickly swept away by the electric field to the anode; thus creating a very sensitive and fast response. This method of detecting light is so sensitive that an avalanche photodiode properly calibrated is able to detect as small as 100 photons, which is a very small amount of electromagnetic radiation. **Figure 2.1.4** shows the movement of electrons and holes during this operation.

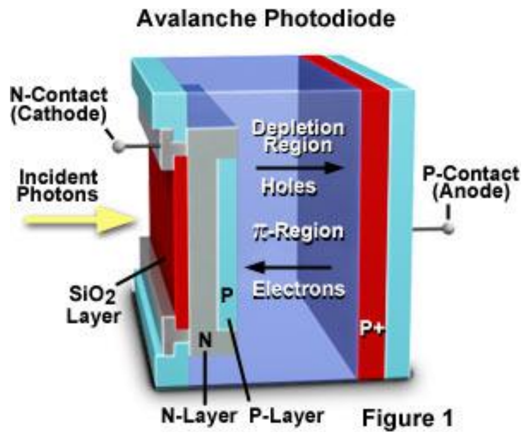

Figure 2.1.4 (Reprinted with permission from Hamamatsu)

The Japanese company Hamamatsu had a surplus of information available about APD's. They specialize in photo-detector devices and are one of the few manufactures that produce APD's. The decision of using an APD in our design brings up some very important questions regarding the specifications of which APD to purchase. We must consider the following:

- Internal Gain
- Photosensitivity/Quantum efficiency
- Active area of sensor
- Peak wavelength sensitivity
- Reverse Bias operating voltage
- Dark current
- Noise
- Cut-off frequency
- Temperature effects

The gain of all APD's is heavily dependent on the reverse bias voltage. This is due to the nature of the avalanche breakdown effect that the APD exploits. In general, for all APD devices, the gain increases with an increasing reverse bias voltage. However, if the reverse voltage continues to increase, there will be a significant exiting photocurrent, proportional to the incident light that causes a large voltage drop across the APD internal resistance and load resistance. When this happens, the voltage across the avalanche layer of the diode decreases, causing the electric field to decrease, this results in an output photocurrent that is no longer dependent on the input light. By operating at such a high gain, the device is no longer useful because the photocurrent is skewed.

Another very important element that has a large effect on the gain of the device is the diode temperature. It's well known that when an electron absorbs photonic energy, it starts to oscillate in all directions contained in its atomic lattice. When enough energy is absorbed, it will break free of its atom and cause a current. It is also well known that electrons are not at rest even before the light hits it, due to the oscillations from the device temperature. As the temperature increases the accelerated carries will collide with the lattice before ionization which causes a decrease in overall gain. The variations of temperature must be either considered for ahead of time and adjusted for using the APD power supply or the device must be temperature constant. The temperature variations of the device are indicated via the datasheet using a measure of V/°C.

The next factor we must consider regarding APD design is the photosensitivity and quantum efficiency. The photosensitivity is defined as the amount of photocurrent that comes out for every watt that goes in. Also known as responsivity, it is usually measured in A/W. Since the gain changes as a factor reverse bias voltage, and the responsivity must be given at some gain, the responsivity is indirectly affected by the reverse voltage. Manufactures will typically give an expected responsivity within some reverse voltage range along with the expected gain. The quantum efficiency (QE) is closely related to the photosensitivity (responsivity) of the device. Quantum efficiency, expressed as percentage, is defined as how effective the photodiode is at creating electron-hole pairs for every photon that hits its surface. It is related to the photosensitivity by the following:

$$QE = \frac{S * 1240}{\lambda} * 100\ (\%)$$

Where S is the photosensitivity and λ is the wavelength in nm.

The peak wavelength sensitivity is the wavelength of incident light that gives the peak responsivity. Incoming light with the peak wavelength will output the largest amount of current for every watt that is absorbed by the diode. This very important design parameter determines which wavelengths of light the diode responds to. Since we chose to use the ranging device in the infrared range, we must select an APD that has a peak output response at or around the same wavelength. Obviously, this is going to be a factor of whichever laser we use. Since the IR lasers available range anywhere from 780 nm to 1000nm, we have a wide range of choices for the laser and APD wavelength sensitivity. Hamamatsu Photonics has a listing of 6 different APD's that operate in the 800-900 nm range that have various different parameters associated with them.

The next parameter that must be discussed is the effect of dark current in the APD. This was briefly discussed in section 2.1.3 when talking about general photodiodes, but in the case of a high sensitivity APD this factor becomes even more important. Since the range finder will be dealing with very small signal currents, due to the minuscule amount of light that it takes in, the smallest effect of an unwanted current could skew the output drastically. The dark current in an APD results from the fact that the device must be operated under reverse bias voltage. Shown in **figure 2.1.5** is the overall geometry that describes the multiplied carriers and movement of dark currents.

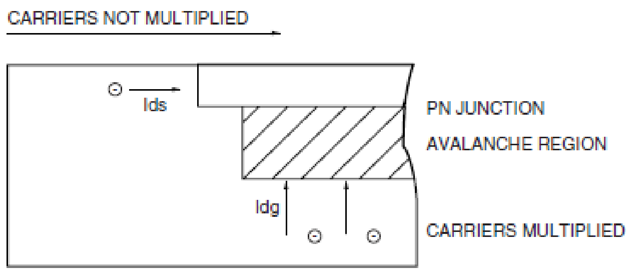

Figure 2.1.5: Reprinted with permission from Hamamatsu

The dark current is composed of two parts: the surface leakage current (IDS) and the internal current (IDG) moving in the silicon substrate. Since the surface current does not inside the silicon substrate, it is not multiplied by the gain factor. The internal current however, moves inside the substrate and is subject to the multiplication gain factor, which causes ID to increase to a significant value.

$$Id = Ids + M * Idg$$

The total dark current is shown in the above equation. M is the multiplication gain factor that depends on the biasing of the diode, as well as the temperature.

The last descriptive characteristic of the APD, and perhaps the most important, is the amount of noise that the device generates. Since the APD is a semiconductor diode device, it is subject to what's called shot noise. This results from the ionization from the charge carries during the avalanche breakdown process. Since APDs exhibit the avalanche process, their total noise is generally greater than that of a standard photodiode. This is one of the disadvantages of using an APD, but depending on their application, their high sensitivity and quick response usually make up for the excess noise.

$$In^2 = 2q\,(I_L + Idg)\,BM^2F + 2qIdsB$$

q: Electron charge

I_L: Photocurrent at M=1

Idg: Dark current component to be multiplied

Ids: Dark current component not to be multiplied

B: Bandwidth

M: Multiplication ratio (gain)

F: Excess noise factor

The equation above shows the shot noise (In) of an APD. As you can see, it is a factor is dark current and the gain, so as you increase the reverse bias voltage on the circuit to achieve a larger gain, this also increases the shot noise on the output. The excess noise factor (F) is the additional noise contribution that comes from the avalanche process. It is described by the following equation:

$$F = Mk + \left(2 - \frac{1}{M}\right)(1 - k)$$

Where M is the gain and k is the atomic ionization rate. Hamamatsu offers several APD with extremely low shot noise, but of course, these products are much more expensive. **Table 2.1.1** shown below is a listing of several APDs that met the optical pass-through requirement as well as the moderately cost friendly items.

Manufacturer	Part Number	Active area mm	Peak wavelength (λ) nm	Peak sensitivity (A/W)	Max dark current (nA)	Temperate coefficient (V/°C)	Typical breakdown voltage (V)	Unit Price $
Hamamatsu	S9251-05	0.5	860	0.52	2	1.85	250	91.00
Hamamatsu	S9251-02	0.2	860	0.52	1	1.85	250	83.00
Hamamatsu	S6045-02	0.5	800	0.5	1	0.4	200	100.00
Hamamatsu	S6045-01	0.2	800	0.5	0.5	0.4	200	91.00
Hamamatsu	S5139	0.5	800	0.5	1	0.65	150	83.00
Hamamatsu	S2383-10	1.0	800	0.5	2	0.65	150	136.00
Hamamatsu	S2382	0.5	800	0.5	1	0.65	150	83.00
Hamamatsu	S2381	0.2	800	0.5	0.5	0.65	150	76.00
Pacific Silicon	TO52-S1	0.5	900	0.6	1.5	1.55	200	93.10

Table 2.1.1

One can see that compared to other parts required thus far, the APD is the most expensive item. This is because APDs are made for a small market and there are only a few manufactures that make them. Hamamatsu defiantly had the most available and a lot of supporting documentation. The Hamamatsu S2381 APD seems to be the best part for the job. It passes IR radiation at 800 nm peak. This is well within the IR range and scope of our goal. It also boasts an impressive dark current of only 0.5 nA, temperature coefficient of 0.65 V/°C, low reverse bias of 150 volts, and most affordable at $76.00.

2.1.4 Target Reflectivity

The target that the device is attempting to find the range of will be the key factor that determines how much reflected light the device will be able to receive. This will be an important design parameter that must be considered when choosing parts to use because the power of light received will define the output voltage response. This is due to the responsivity of the APD which is defined as A/W. So for a gain of 100 the responsivity might be 50 A/W; if incident light is present on the device and within its pass band wavelength, the output photocurrent will be I=R*P. The photocurrent output is equal to the responsivity multiplied by the power of the incident light.

When a laser pulse is send out from the device, the received power will be a factor of several different absorption and/or scattering mechanisms. The incident power will dissipate due to the following:

- Reflections (Specular and diffuse)

- Refraction
- Absorption (propagation medium and target)

So if we were to use a laser with an incident power of 25mW, we will get a very small amount of that reflection back; possibly a 1uW or lower. In undergoing a detailed analysis of these power loss mechanisms, we should be able to come up with an estimate of what the power of the reflected light should be given a known surface material. Naturally, this is going to change dynamically depending on the target material, air conditions, and distance to target.

The reflective ability of the target can be split up into two different categories; the specular and diffuse reflections. The specular reflection is the direct reflection from the incident light that would occur and be most apparent on a shiny surface. When a mirror is hit with a laser beam, almost all the power is reflected that the same angle that is came in at; however, in the opposite direction. The specular reflection of a surface is governed by the law of reflection, which says that the incoming ray and the reflected ray make the same angle with respect to the normal vector. For the rangefinder device, measuring the specular reflection would be difficult. Since in non-ideal conditions, the incident ray will be coming in at some arbitrary angle, so the specular ray will be going out at some proportional angle that is going in the complete other direction. The amount of specular reflection depends heavily on the material and whether it is shiny or not; so it is possible to have a very minimal specular reflection. The primary mechanism of reflection that is most desired for optimal response of the range finder is the diffuse reflection. Diffuse reflection is a secondary effect that occurs due to the “roughness” of a surface. When an incident ray hits some surface, the microscopic pits and irregular texture of the surface causes the ray to split and be reflected in all directions. The diffuse reflection, also known as spectral scattering, is advantageous for the particular application of a laser range finder because the light can be measured from any angle; independent of the incident ray. A Lambertian surface is defined as a surface that exhibits ideal diffuse reflectance with little or no specular reflection. In an ideal Lambertian reflection, the illumined surface will have an equal measure of diffuse reflected radiant flux (power) from all directions surrounding the surface. Generally matte and non-glossy surfaces exhibit the best Lambertian reflection. Some examples of high efficiency Lambertian surfaces include plaster, drywall, fibrous material, unfinished wood, and polycrystalline material such as marble. Surfaces that demonstrate ideal Lambertian reflections obey the Lambertian Cosine Law.

Lambert’s Cosine Law:

$$I(\Theta) = I_{\circ} * \cos\,\Theta$$

I is the radiant intensity (W/sr) and Θ is the angle between the incident angle and the surface normal. The radiant intensity can be converted to radiant flux (W) by multiplying by a factor of 4π. The result of this equation shows that for a Lambertian surface, the diffuse power reflected is proportional to the incident angle to the ray. The maximum reflected power occurs when the cosine is equal to 1; e.g when the incident ray is incoming on the surface normal Θ=0°. It should be noted that this is for the ideal case of a perfect Lambertian surface; which we will not encounter in real applications. There will likely be a total reflection consisting of both diffuse and spectral effects. Shown in **figure 2.1.6** is the basic operation of spectral and diffuse reflection.

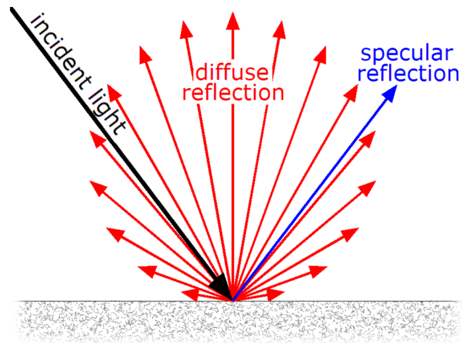

Figure 2.1.6 (Reprinted from Wikipedia under the GNU Free Documentation License)

Figure 2.1.6 shows the reflection mechanisms of a real surface that the sensing field device may target. In summary, the functional operation of the ranging device relies on how much of the diffuse reflection is present given a pulsed laser on some surface. Which it is better to have an ideal Lambertian surface, this is not likely and there will be a combination of both specular and diffuse reflections.

While the reflectiveness of the target surface determines how much light will bounce back to the transmitter, the absorption is also a crucial property that determines the amount of radiation that is absorbed by the electrons of the material and dissipated usually as heat or mechanical energy. When a laser beam is sent out from the source, the power is absorbed by the surrounding air as it propagates to its target as well as the target material. The surrounding air tends to attenuate the power of the laser over extended distances. This is due to the absorption of photonic energy by oxygen and the other impurities in the air that we breathe. This can usually be neglected at short ranges (less than 1 meter), but for extended ranges, this becomes the primary mechanism of laser power dissipation. The absorbance a characteristic quantity of the material in question and determines how much of the electromagnetic energy is absorbed. The Beer-Lambert law, used often in identifying unknown chemicals, relates the absorption of light at some wavelength to the material in which the radiation is propagating. The absorption is thus shown to be the following:

Beer-Lambert Law for Gases:

$$A = -\ln \frac{I}{I_{\circ}}$$

$$A = \alpha L$$

This relation shows how radiation is attenuated in a gas. α is called the absorption coefficient and is a factor of the material. For atmospheric air, $\alpha = 0.000241 cm^{-1}$. L is the one way length in centimeters to the target of interest. Since we will already know the incident power of the ray (i.e. the power of the output laser), we need to solve these equations for the final power. Given that we are designing this device to achieve at least 50 meters (5000 cm), we will use this as the distance to the target for the calculation.

$$P(x) = P_{\circ} * e^{-.000241x}$$

Our generalized power attenuation by atmospheric air equation is shown above. If we assume our incident laser power to be 25mW and at a distance of 5000cm, the attenuated power as it hits its target given by 25*e^-1.205=7.5mW. So over the course of 50 meters, there is a 78% power loss by just the air absorption. This seems like a lot of power lost, but in retrospect the whole reason for using an APD device is for detecting extremely small amounts of light, so this loss is to be expected. The graphical results of this equation are shown in **figure 2.1.7**.

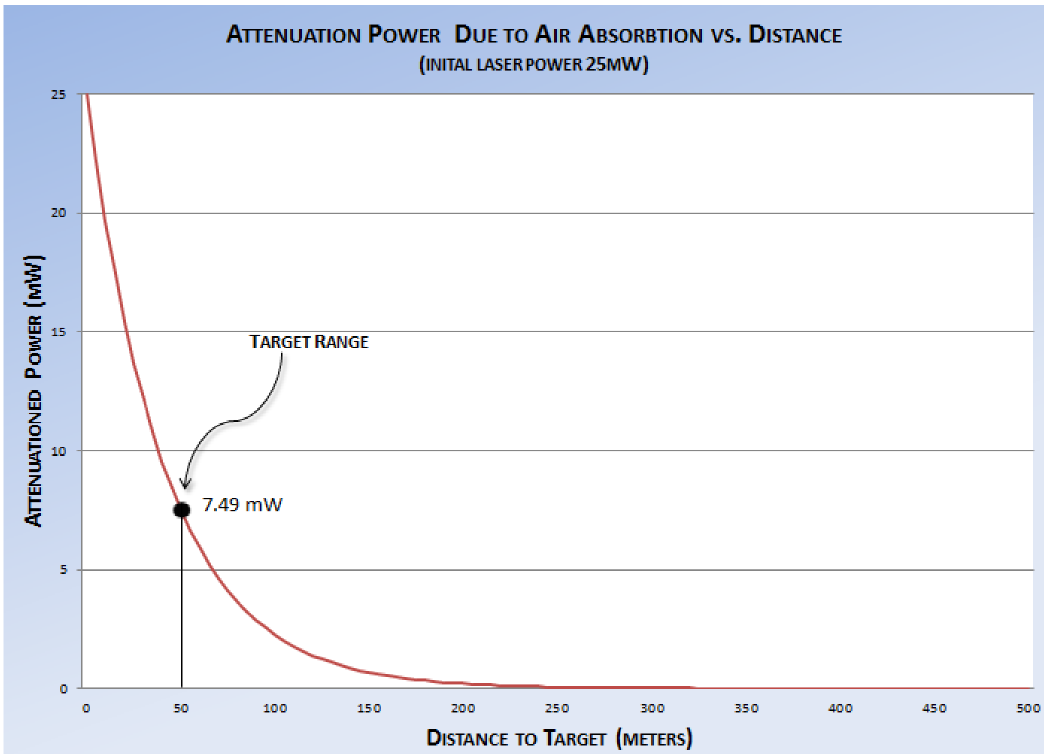

Figure 2.1.7

2.1.5 Optical Lens System

An optical lens system must be used by the device in order to achieve extended distance and temperature readings. This makes the lens system one of the most important parts of the design. When the IR laser sends out a pulse, it gets refracted when it hits its target causing light to go in all directions. There is, however, a small amount that comes back to the source and hits the lens. What we need is a lens that is able to take light that hits from any angle and can focus it to a single point that is on the APD sensor. The lens must be small enough to fit into a handheld device, and it also must have a reasonably small focal length. Most simple lenses are classified as either convex (bulging outwards from the lens) or concave (depressed in towards lens). The lenses ability to either converge or diverge light is also a fundamental factor of the design and will be discussed below.

The diverging lens does exactly what the name implies. It diverges a collimated beam of light into all directions. When a uniform beam of light passes through this type of lens, it is spread very wide. This is not the type of lens that we should use for the scope of this project. Since we need our incoming light to be focused onto a single target, we need a converging convex lens. By using a converging lens, we are able to take that small amount of reflected light that comes back from the target and focus its power onto the photodiode.

For this project, the two types of lens that we have the option of using are Plano-convex and a Fresnel lens. These are both converging lens that will take the small amount of light that incident on its surface and focus it into a collimated beam that will be incident on the photo sensor. A Plano-convex lens is rounded on the side that takes in the unfocused light and flat on the side that focused it into a regulated beam. They are usually made of materials like BK7, Fused Silica, Sapphire, or CaF2; there are also several different parameters associated with the performance of these lenses that differ depending on the application. In choosing the right lens for the job, we must consider the Lensmaker's equation:

Lensmaker's equation:

$$\frac{1}{f} = (n-1)[\frac{1}{R1} - \frac{1}{R2} + \frac{(n-1)d}{nR1R2}]$$

The Lensmaker's equation elates the focal length (f) to the index of refraction of the material (n), the lens thickness (d) and the radii of curvature of both sides of the lens (R1,R2). One should note that this equation is only valid when the surround matter is air (n=1). This works fine for the scope of our project because we are not designing this for underwater use or anything outside of standard terrestrial based measurements. One should also notice that the focal length of the lens is not dependent on the distance or angle of the incoming light. So no matter how far, or on what angle the incident light is, it will be focused on the same point from the back of the lens. Knowing this, we are able to choose a lens with a small enough focal length so that it is compact in the final design and properly focuses incoming light onto the photo sensor so we can measure the maximum amount of light. Shown in **figure 2.1.8** is the geometric considers of a Plano-convex lens.

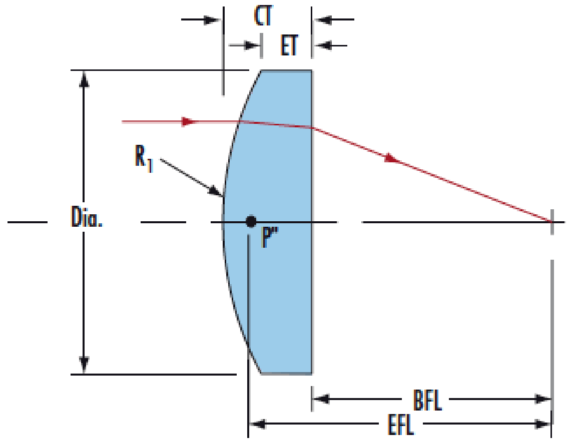

Figure 2.1.8: Waiting permission of use from Edmund Optics

For the range finder, the most important characteristics will be the lens diameter, focal length and the optical pass band coating. The optical pass band coating is an anti-reflective paint that goes over the front of the lens. This coating acts as an optical filter, allowing only wavelengths of interest to pass through the lens. Doing this will filter out the radiation sources that we do not care about and only let through the IR wavelength. The diameter of the lens is important because having a larger surface area will allow the lens to capture more incident light that is being reflected off the target source. However, we do not want a lens that is too large because the project enclosure will get too large and the lens gets much more expensive with increasing diameter size. For most range finders available, the lens diameter is somewhere in the range of 26mm (1 inch).

The NT62-586 plano-convex lens from Edmund Optics provides specifications that fit our objectives. With a diameter of 25.40mm (1.0 inch), an effective focal length of 50.8mm and a near infrared optical coating, the NT62-586 fits both the optical requirements and has a focal length small enough to fit in a compact enclosure. The anti-reflection coating performance graphics characteristics are shown in **figure 2.1.9**.

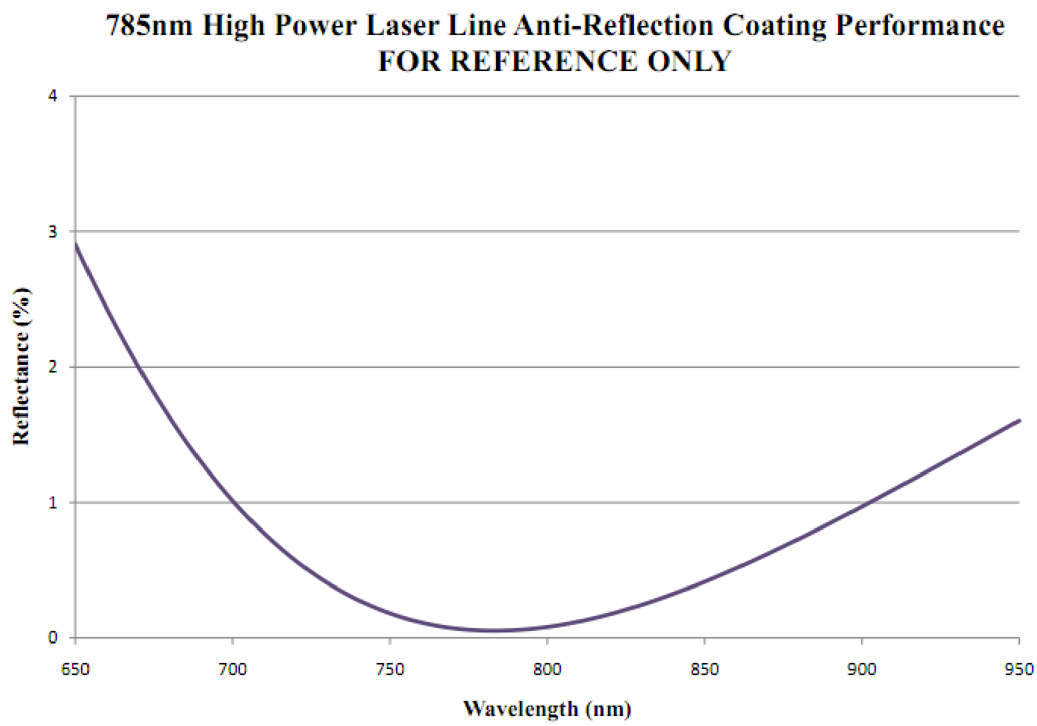

Figure 2.1.9: waiting permission of use from Edmund Optics

2.1.6 Environmental Conditions

Atmospheric Considerations

Due to the ever changing conditions in which the ranging device will operate in, the response will vary. The thermal-sensitive nature of all semiconductor devices greatly influences the design and requires that methods be put in place to compensate for such situations. Since this project requires that a laser propagate across a distance, there are several environmental factors to consider that may attenuate the power. These include but are not limited to:

- Propagation distance
- Atmospheric pressure
- Humidity conditions
- External radiation
- Unwanted dust/particles in air

Shown in section 2.14, the distance that the laser has to propagate directly effects the power level that comes back to the device. To summarize, this was due to the absorption of the laser power by the air molecules and impurities themselves; as well as the power lost from absorption/reflection off the target. Referencing back to 2.1.4 again, the absorption coefficient of the air was directly related to the air density of the atmosphere. To summarize in the following equation:

Ideal gas law:

$$\rho = \frac{P}{RT}$$

So the air density (ρ) changes with both atmospheric pressure and temperature. So assuming constant temperature, as the pressure goes down (device operation at high altitude), the density will decrease. If the density decreases, there will be less 'stuff' around that the laser will be absorbed by. Therefore, there will be less power absorbed under such conditions.

The humidity level of the air is also something that one must consider when attempting to send a laser over a distance. In having a higher level of water content in the air, you are essentially adding an 'impurity' to the existing absorption coefficient. In doing so, the coefficient will increase significantly and cause more of the laser power to be lost. This same principle will apply for most atmospheric weather conditions; such as rain, snow, fog and hail. Any one of these conditions will increase the absorption of the laser and cause your received light to be much smaller.

The external radiation that is present in close proximity to the target will influence the amount of noise that goes into the device. Since we will have an optical filter that should filter out most of the unwanted light that comes in, the effect should be minimal; however, unwanted light that has the pass band wavelength will still get through. We are most likely going to use a wavelength of about 780nm. So our optical filter will only allow light of that wavelength to pass. So this should limit the light that goes in to only the reflected light from the laser; but there is going to be a small amount of residual ambient IR light of the same wavelength that passes that will cause noise. Since our IR laser light will be pulsed as a square wave, this may cause the reflected pulse to have a ripple or noise markings on the high portion of the pulse. Further electronics filtering may be required to properly decipher the signal.

Ideal Operating Conditions

The ideal operating conditions for operation of the range finder are as follows:

- Dry air, low humidity (room conditions)
- Temperature of 20°C (room temperature)
- Distance of less than 2 meters.
- Stable base of operation
- No external radiation (sunlight, room lights, etc.)
- Lambertian surface for best diffuse reflectivity (paper, white drywall)
- Angle normal to target surface (perpendicular to target)

These are of course 'ideal' conditions and we will most likely not have these conditions under normal device operation. These are the conditions that we will use during prototype testing while in the lab.

2.2 Infrared Temperature System

2.2.1 Theories of Operation

Temperature is one of the most important principle parameters that we need to monitor and control in most of engineering applications like cooling, heating, drying, and storage. Therefore, we increase the ability of our ranger finder by giving it a temperature measuring function. There is a diverse array of sensors that could be used to measure the temperature. All of those sensors infer temperature by sensing some physical changing characteristics. There are four different principles that are used as basic functions what we consider for our thermal measuring device:

1. Mechanical
2. Thermo-junctive
3. Thermo-resistive
4. Infrared radiation

MECHANICAL

The first principle that we consider to design our temperature measuring device is the change in temperature causes mechanical motion. From the physical point of view, most materials expand by rising temperature. Solids, liquids, and gases are the temperature sensitive materials that are used to construct mechanical thermometers. Liquid in glass thermometer, for example, uses mechanical temperature measuring principle to operate. The **figure 2.2.1** below is example of typical glass thermometer, the mercury glass thermometer

Figure 2.2.1: Mercury glass thermometer
(Reprinted from Wikipedia under the GNU Free Documentation License)

We learn that liquid in glass thermometer is used much less frequency today than formerly, but it is the sensor that visualizes the most frequently for temperature measurement. It is well-known for portability, low cost, wide range, compatibility with most environments. Its range of temperature is as low as 70 K to as high as 1000 C; however, the survey stated that most of the frequently cases are from -35 C to 260 C. Liquid in glass thermometer's accuracy is only moderate, but into detail; there are liquid in glass thermometers go to millikelvin temperature range

As the temperature increases, the liquid (mostly mercury or alcohol) expands, moving up the tube. The temperature scale is calibrated in purpose being read the temperature measurement directly.

THERMAL-JUNCTIVE

The second principle that we consider to design our temperature measuring device is thermal-junctive. In fact, the most popular temperature device that uses thermal-junctive principle is thermocouple. A thermocouple is made up of two different metals; they are joined together at one end where produces a *thermo-junction voltage* in millivolts related to temperature difference. This is called the *Peltier Effect.* It is a type of temperature sensor that is used widely to measure and control, and covert heat into electric power.

Moreover, we learn that the *Thompson Effect* is used to develop thermocouples as well. The changing in temperature of the junction causes the voltage to change too. The difference in voltage will be measured by the input circuits of the electrical controller. The measurement of the output is a voltage proportional to the change in temperature between the junction and free end.

The thermal-junctive also could be developed by combining both of *Peltier Effect* and *Thompson Effect.* From theory, we hold one junction that temperature is given, then measure the voltage and temperature at the sensing junction. The output voltage that is generated is directly proportional to the change in temperature. This combination is called the *Seebeck Effect.*

THERMO-RESISTIVE

Thermo-resistive is another important principle that we consider to design our thermal temperature device. It states that the electrical resistance of a material change when there is a change in temperature; that resistance change is measured to provide the difference in temperature.

There are two different thermo-resistive measuring devices:

1) Resistance temperature detectors
2) Thermistors

Resistance temperature detectors

Resistance Temperature Detectors, RTDs for short, are either fine wire wound or coil on a substrate. RTDs are widely made of platinum, so they are often called platinum resistance thermometers (PRTs). RTDs operate on the principle that the electrical resistance of a metal changes essentially linear and repeatedly with temperature changes. Moreover, we figure out that RTDs have a positive temperature coefficient which meant the resistance increase with temperature.

We learn that there are some advantage that RTDs have like linear resistance with temperature, wide range of temperature, and good stability which are what we want for our thermometer. However, some disadvantages like a small resistance change with temperature, a bit slower to respond than other thermal measuring devices, and external circuit power required. RTDs are divided in many categories; however, carbon resistors, film, wire-wound, and coil elements types are the most common used.

- *Carbon resistors* are available widely, and they are very cheap. They work best at low temperatures; are the most useful temperature devices at extremely low temperatures. This advantage has made carbon resistors being useful for many years.
- *Film thermometers* have an extremely thin layer of platinum in each of them on their substrates, about one micrometer. Film thermometers are low cost and fast respond. Film thermometers are better in performance than carbon resistors; however, they have the strain gauge effect and somewhat stability issues.
- *Wire-wound thermometers* have more accuracy result and wider temperature range than carbon resistors and film thermometers. In industry, coil elements have widely replaced wire-wound elements. The coil diameter gives a compromise between mechanical stability and free expansion of wire.

Thermistors

Thermistors are temperature sensitive semiconductors that their resistances vary significantly with temperatures. In another word, they exhibit a large change in resistance over a relatively small range of temperature change. We learn that there are two types of thermistors, one is positive temperature coefficient and one is negative temperature coefficient.

Thermistors' functional system is the same as resistance temperature detectors (RTDs). However, materials are used in thermistors are semiconductor materials like ceramic or polymer instead of pure metals in RTDs. Because thermistors use semiconductors, they are in solid-state devices catalog. They have larger sensitivity than do RTDs, so the temperature responses are also different. Thermistors are more precise in measuring temperature which has limited range from −90 °C to 130 °C. Thermistor has a non-linear temperature resistance characteristic instead of linear in RTDs. Therefore, they cannot be characterized by a single coefficient.

INFRARED RADIATION

The last and the most advantageous principle is infrared radiation. Infrared radiation is the electromagnetic waves which have longer wavelength than visible light wavelength, from 0.75 µm to 1000 µm. There are three different wavelength regions for the infrared radiation. The table 2.2.1 below is the list of regions and infrared wavelength range

Region (abbreviation)	Wavelength range (µm)
Near infrared (NIR)	.75 – 1
Short wavelength (SWIR)	1 – 3
Medium wavelength (MWIR)	3 – 6
Long wavelength (LWIR)	6 – 15
Very long wavelength (VLWIR)	15 – 1000

Table 2.2.1: Region and wavelength range of infrared radiation

There are some basic characteristics that infrared radiations have:

a. Invisible to human eyes – This is really helpful for any security applications; however it is a disadvantage for designing measurement and optical systems.
b. Small energy – in practice, molecules could be identified because the infrared radiation is equal to vibrational and rotational energy of molecules.
c. Long wavelength – this characteristic helps infrared radiation less scattered and makes infrared radiation transmitted better through various medium.
d. I could emit to all kinds of bodies.

For temperature measuring devices that use infrared temperature sensors, also known as pyrometers and non-contact temperature sensors are different from most temperature measuring equipment. These devices could measure the temperature of an object without contact. An infrared thermometer measures temperature by detecting the infrared energy emitted by all materials which are at temperatures above absolute zero, 0 Kelvin. This non-contact method of measure temperature is very useful when target is too hot for any contact devices like thermocouples could survive or target is out of touching range.

The principle of any object emits an amount of energy that is a function of its temperature is used in infrared temperature sensors. In another word, it indicates when the temperature of an object increases; the energy is emitted by the object increase as well. From there, an infrared temperature sensor could tell the temperature by calculating the intensity of energy given off by an object. Before going deeper to the infrared radiation measuring, we need to understand what blackbody radiation is, and how it relates to the temperature measuring.

Blackbody Radiation

Theoretically, a blackbody is a perfect absorber, which could absorb radiation of all wavelengths falling on it. Moreover, it reflects no visible light at Earth-ambient temperatures, so it appears black. In 1792, Prevost's theory states that the blackbody is the best radiation absorber so is the best radiation emitter. Therefore, the radiation emitted by the blackbody is call blackbody radiation or thermal radiation.

The temperature is the only factor that affects the intensities of the wavelengths that are emitted by blackbody radiation. The higher the temperature of a blackbody, the more energy is emitted into each band of wavelengths. As the temperature increase past a few hundred degrees Celsius, blackbody starts to emit visible wavelengths in order of red, orange, yellow, white and blue with increasing temperature. The **figure 2.2.2** below demonstrates the intensity of wavelength regard temperature change. As the temperature increase, the peak of the blackbody radiation curve moves to higher intensities and longer wavelengths.

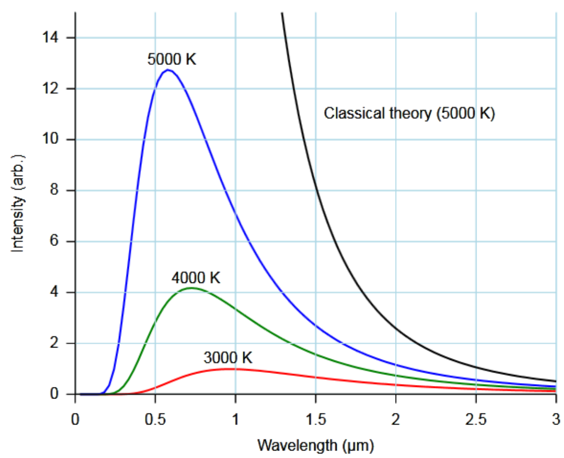

Figure 2.2.2: Intensity and wavelength
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Wien's displacement law formula,

$$\lambda_{\max} = \frac{b}{T}$$

- b is the constant, known as Wien's displacement constant, is equal to 2.8977685(51) ×10−3 mK.
- λ_{max} is the maximum wavelength at which the energy radiated
- T is the temperature in Kelvin.

From this formula we could see that the hotter blackbody emits the shorter the wavelengths would be. That explains why blackbodies are blue at high temperature, and they are red at lower temperature.

2.2.2 Principle of Infrared Radiation

Each body and materials has a different and unique behavior toward the infrared radiation. There are three principle behaviors of infrared radiations that are recorded by the thermal imager. They are included emitted radiation, reflected radiation, and transmitted radiation. Being understand and aware these three basic principle behaviors of infrared radiation would help reduce typical error, makes reliable results, and simplifies the reading

REFLECTANCE

Depending on the surface properties, type of the material, and the temperature, reflectance is a measure of the ability of a material to reflect infrared radiation.
Reflectivity, ρ, is the fraction between the reflected intensity, G_{refl}, and incident spectral intensity, G_{incid}.

$$\rho = \frac{Grefl}{Gincid}$$

Reflectivity is generally thought of the fraction of incident electromagnetic power that is reflected at an interface. In general, reflectivity should be treated as a directional property which is a function of the incident direction, incident wavelength, and reflected direction. In fact, reflectivity is value that applies to thick reflecting objects; therefore, reflectivity is distinguished from reflectance.
When the surface is getting thicker, reflectivity is the limit value of reflectance. The reflectance is a portion of radiation when it goes with the grey body. The small **figure 2.2.3** is the demonstration of reflectivity of the incident light to the object

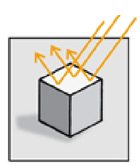

Figure 2.2.3: reflectivity of light to an object
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TRANSMISSION

Depending on the type and thickness of the material, transmittance is a measure of the ability of a material to transmit infrared radiation. It is also known as the fraction of incident light passes through a body at a specified wavelength.

$$T_\lambda = \frac{I}{I_o}$$

Where T is transmittance

I is the intensity of the incident light coming in
Io is the intensity of the incident light coming out

In this equation, the reflectivity is considered to be zero. The transmittance of a body is sometimes given in percentage. For long wave infrared radiation, most of materials don't have much transmittance. The small **figure 2.2.4** is the demonstration of transmission of the incident light to the object

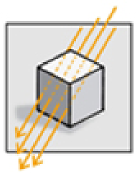

Figure 2.2.4: transmission of light to an object
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EMISSIVITY

We can see that measuring temperature of an object by calculating the intensity of emitted energy seems straightforward. However, the quantity of energy that an object emits is not a function of temperature only. Emissivity is another variable that effects emissions. Emissivity is an inherent surface characteristic that could vacillate with changes to texture, microstructure, surface oxidation, and composition. From practical standpoint, the emissivity of material is the relative ability of its surface to emit energy by radiation. Emissivity is the most important factor when it comes to non-contact temperature measurement. **Figure 2.2.5** is a demonstration of the emission of incident light to an object.

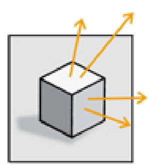

Figure 2.2.5: emission of light to an object
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With notation as ε or e, the emissivity is the ratio of energy radiated by a particular material to energy that radiated by a blackbody at the same temperature. It can have a value from 0 like shiny mirror to maximum of 1 which is blackbody. The ideal of emissivity = 1, which is blackbody, is a theoretical model. In practice, common applications define all sources of infrared radiations as a blackbody when the emissivity larger than .99. On another hand, any sources that are lower than .99 are referred as a graybody.

The mathematical statement behind the infrared temperature measurement

In fact, the amount of energy that a material surface emits is a function of temperature and its emissivity. Therefore, in order to have a correct temperature measurement of emitted energy, it is important to know the fundamentals of radiation and surface's emissivity.

Radiation is heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object. For normal temperatures, which are less than red hot, the radiation is in the infrared region of the electromagnetic spectrum. This relationship is proved by Stefan-Boltzmann Law

$$P = \varepsilon\sigma A(T^4 - T_c^4)$$

P = emissive power radiated per unit area   ε = emissivity
A = radiating area   T = temperature of radiator
δ = Stefan's constant T_c = Temperature of surroundings

$$\sigma = 5.6703X10^{-8} \times 10^{-8}\,\frac{watt}{m^2K^2}$$

T is the *absolute* temperature of the surface of the object in units of Kelvin.

Calibration of Emission

Quantifying emissivity of the infrared temperature sensors is the most challenge that all manufacturers and users have faced. There are some surfaces like alloys, aluminum, chromium, etc have a predictable emissivity; however, there are others have unpredictable pattern that change significantly. Throughout the years, manufacturers and high-end users have sorted out the surfaces from experience in order to know which one is easy to measure which one is hard to do. There are many different types of non-contact temperature sensors have been made that reduce and eliminate problems that caused by emissivity variations.

In the **figure 2.2.6**, a thermopile is usually used as the detector. The figure shows how a typical calibrator of infrared temperature measurement works. The temperature of a hot surface is inferred by an infrared pyrometer by calculating the temperature of the detector. Thermopile is used to measure the T_{det} which is the measurement of the detector inside the chamber (We will talk more about thermopile on section 2.2.4). The indicated temperature needs to calculate too, which is obtained by the known geometry and the radiation equations. In the calibrator, the indicated temperature is set up as a function of the voltage output.

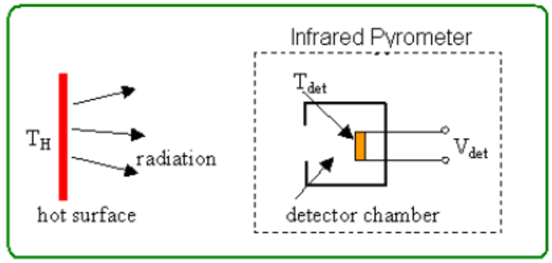

Figure 2.2.6: emission of light to an object

T_H is the temperature of the subject that need to measure. In this case, the Tind is the wrong estimate of TH, because the emissivity of the object is maybe different than the measurement by the infrared pyrometer. Therefore, in order to correct the actual emissivity of the object, manufacturers and high-end users use this formula

$$T_H := \left(\frac{\varepsilon_{assumed}}{\varepsilon_{actual}}\right)^{\left(\frac{1}{4}\right)} \cdot T_{ind}$$

The absolute temperatures are used in this formula.

2.2.3 Infrared Detection

In practice, infrared radiation is used in a wide variety of applications; moreover, new applications are constantly being developed every day. Even though there are tremendous applications out there, they are all based in this system to detecting infrared radiation. The **figure 2.2.7** below is the entire procedure of infrared detection

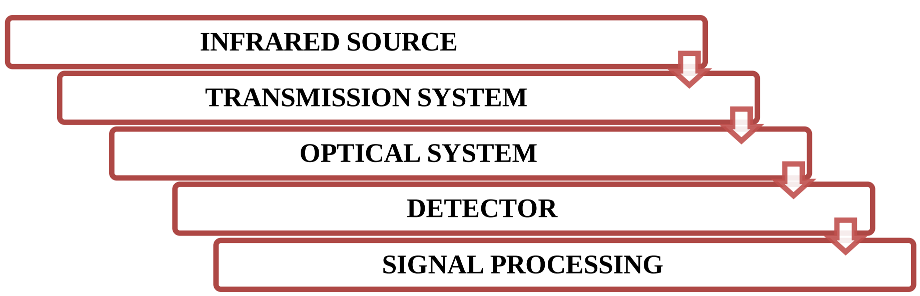

Figure 2.2.7: Infrared detection procedure

(Self-drawing)

In fact, every object that has an absolute temperature over 0 K will radiate infrared energy. Human body, for example, is an infrared energy radiator with a peak wavelength close to 10 µm. Electric heaters are made from Nichrome Kanthal would radiate from 2 to 5 µm. For longer wavelength from 1 to 50 µm are radiated from Nernst glower made of ceramic. From these radiant sources, infrared lasers that emit infrared energy of specific wavelength are made. In practice, there is a background radiation from the ground at a ambient temperature of 300 K. Therefore, if any wavelength region is over 3 µm, noise due to fluctuations in the background radiation will be considered. For most of the cases, cold shields and cold filters are used to reduce this type of noise. The **figure 2.2.8** below show us the different between wavelength with different type of laser like gas laser, solid state laser, and semiconductor laser.

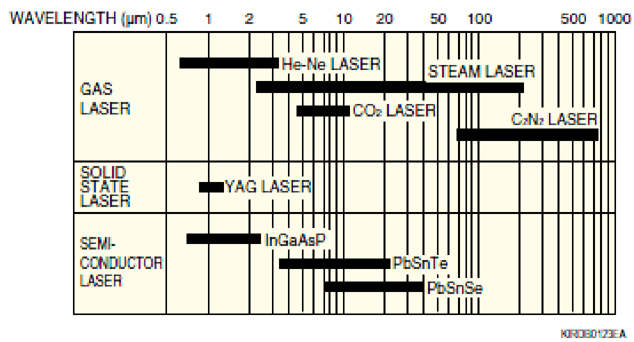

Figure 2.2.8: wavelength and type of laser
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As we could see in the **figure 2.2.9**, there are many different types of radiation sources with different methods and materials to use.

Type	Method	Material	Radiation source example	Wavelength (µm)	Remark
Thermal radiation	Resistor heating by current flow	Tungsten	Infrared bulb	1 to 2.5	Long wavelength region is cut off by external bulb (glass). Secondary radiation is emitted through the tube.
		Nichrome Kanthal	Electric heater	2 to 5	
		Silicon carbide (siliconate)	Globar	1 to 50	Constant voltage, large current
		Ceramic	Nernst glower	1 to 50	Pre-heating is needed.
	Secondary heating by other power source	Metal (stainless steel, etc.)	Sheath heater	4 to 10	
		Ceramic	IRS type lamp	4 to 25	
			Radiant burner	1 to 20	Heating by gas burning
	Heating by discharge	Carbon	Carbon arc lamp	2 to 25	Causes some environmental problems such as soot.
Cold radiation	Gas discharge	Mercury Cesium Xenon	Mercury lamp Xenon lamp	0.8 to 2.5	Long wavelength region is cut off by external bulb. Secondary radiation is emitted through the tube.
Stimulated emission	Laser reaction	Carbon dioxide Gallium arsenic compounds Lead compounds	CO_2 laser InGaAsP laser PbSnTe laser	9 to 11 1.1 to 1.5 6 to 7	

Figure 2.2.9: type, method, and material If radiation
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TRANSMISSION MEDIA

The medium or path in which the communication between transmitter and receiver take place is known as transmission media. The atmosphere, optical fibers, and vacuum are the typical examples of infrared transmission media. In earth atmosphere, H_2O, CO_2, and other elements absorb in specific wavelengths. When the rate of absorption is low, from 3 µm to 5 µm and from 8 µm to 12 µm, the bandwidths are called atmospheric windows. Atmospheric windows are used for remote sensing applications. There is not a media that could meet the theoretical value that has been developed; optical fibers made of quartz are close. Optical fiber is a thin strand of highly transparent glass or sometimes plastic that guide light. It is one of the best medium that is used to carry information from one point to another point in the form of light.

OPTICAL MATERIALS

In order to focus or to converge infrared radiation, optical lenses are used to do the job. Most of optical lenses are made of CaF_2, quartz, Al, Au or similar materials according to the wavelengths. There are applications where band-pass filters are needed to create a specific wavelength, or are to chop off any passing or interrupting a beam of infrared radiation. Center wavelength, half width, and a 5% transmittance width are necessary to be considered when designing a band-pass filter. Moreover, the side bands must also be taken care off; they are secondary transmission wavelengths which are called blocking. Optical materials are also varying with the temperature and angle of incident light that are used.

INFRARED DETECTOR SYSTEM

An infrared detector, which is known as *the eye of the digital battlefield*, reacts to infrared radiation. It is a transducer of radiant energy, which converts radiant energy in the infrared radiation into a measurable form. There two main types of infrared detectors which are thermal types and photonic (quantum) types. Classification of detectors is places in **figure 2.2.10** below.

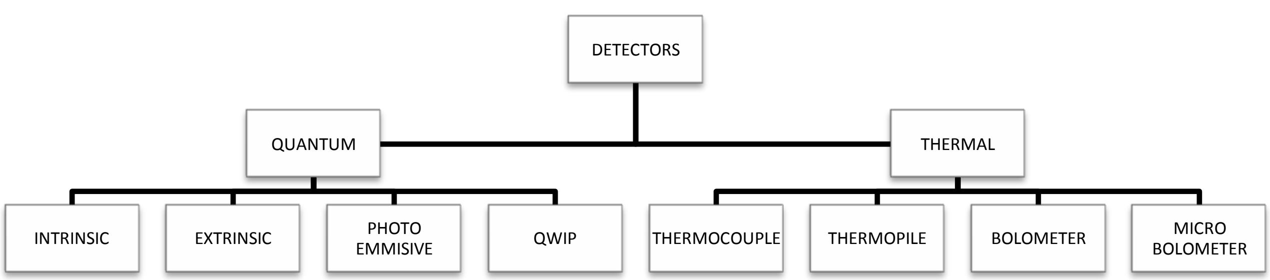

Figure 2.2.10: Detector type diagram
(Self-drawing)

Four main types of quantum infrared detectors are intrinsic, extrinsic, photo-emissive, and new quantum well infrared photo-detector (QWIP). Thermal detectors are classified in 4 different types which are thermocouple, thermopile, bolometer, and micro-bolometer.

Choosing the right detectors

Before choosing which detector to use for our project, we follow this selection guide in order to choose the right one for us.

1. Wavelength and temperature

The table on **figure 2.2.11** is the spectral response characteristics and the temperature limit table that we use to select the appropriate infrared detectors for our thermal detector.

Type			Detector	Spectral response (μm)	Operating temperature (K)	D^*(cm · Hz$^{1/2}$ / W)
Thermal type	Thermocouple · Thermopile			Depends on window material	300	D^* (λ,10,1) = 6×10^8
	Bolometer				300	D^* (λ,10,1) = 1×10^8
	Pneumatic cell		Golay cell, condenser-microphone		300	D^* (λ,10,1) = 1×10^9
	Pyroelectric detector		PZT, TGS, $LiTaO^3$		300	D^* (λ,10,1) = 2×10^8
Quantum type	Intrinsic type	Photoconductive type	PbS	1 to 3.6	300	D^* (500,600,1) = 1×10^9
			PbSe	1.5 to 5.8	300	D^* (500,600,1) = 1×10^8
			InSb	2 to 6	213	D^* (500,1200,1) = 2×10^9
			HgCdTe	2 to 16	77	D^* (500,1000,1) = 2×10^{10}
		Photovoltaic type	Ge	0.8 to 1.8	300	D^* (λp) = 1×10^{11}
			InGaAs	0.7 to 1.7	300	D^* (λp) = 5×10^{12}
			Ex. InGaAs	1.2 to 2.55	253	D^* (λp) = 2×10^{11}
			InAs	1 to 3.1	77	D^* (500,1200,1) = 1×10^{10}
			InSb	1 to 5.5	77	D^* (500,1200,1) = 2×10^{10}
			HgCdTe	2 to 16	77	D^* (500,1000,1) = 1×10^{10}
	Extrinsic type		Ge : Au	1 to 10	77	D^* (500,900,1) = 1×10^{11}
			Ge : Hg	2 to 14	4.2	D^* (500,900,1) = 8×10^9
			Ge : Cu	2 to 30	4.2	D^* (500,900,1) = 5×10^9
			Ge : Zn	2 to 40	4.2	D^* (500,900,1) = 5×10^9
			Si : Ga	1 to 17	4.2	D^* (500,900,1) = 5×10^9
			Si : As	1 to 23	4.2	D^* (500,900,1) = 5×10^9

Figure 2.2.11: spectral response characteristics and the temperature limit table
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2. Photo sensitivity and signal to noise (S/N)

The photo sensitivity and signal to noise required for infrared detectors are different depend on the intensity of light signals and the type of information to be obtained. Like all other detectors, to improve the signal to noise, cooling the infrared detector is necessary. There are many cooling methods like cryogenic cooling, thermoelectric cooling like dry ice and liquid nitrogen, and Stirling coolers in mechanical cooling. One thing we could note from the table is that cooling changes the spectral response. In fact, the spectral response can be evaluated in terms of these three characteristics.

a. Photo sensitivity

The photo sensitivity represents the magnitude of photo sensitivity on voltage or current. They stand for the magnitude of photo sensitivity per watt of incident light. In practice, V/W is the expression of photo sensitivity of photo-conductive detectors. On the other hand, A/W is the expression of photo sensitivity of photovoltaic detectors.

b. Noise Equivalent Power (NEP)

The noise equivalent power represents the detection ability of a detector. Moreover, it indicates the quantity of incident light equal to the quantity of noise. Moreover, the noise equivalent power also represents the quality of the incident light where its signal to noise becomes unity.

c. Delectability (D*)

We find out that detectability is the measure of signal to noise of a detector when the infrared radiation of 1 watt is given through an optical chopper. In fact, it is convenient in comparison between characteristics of the detector element materials because D* is known for independent from the active area and shape of the detector element. In practice, the detector active areas are normalized to 1 cm^2 and the amplifier bandwidth is set to 1 Hz when measuring the delectability. Moreover, measurement condition of delectability is expressed like this

$$D^* (A, B, C)$$

Where A represent the temperature of wavelength - µm, or source of light (K), where B represent the chopping frequency (Hz), and C represent the noise bandwidth (Hz). The unit of D* is $cmHz^{1/2}/W$. The higher the value of delectability can go, the better the detection capability could reach.

3. **Response speed and chopping frequency**

Depending on the applications, the response speeds that are required from infrared detectors go faster or lower. Optical communications, for example, require a respond speed of 1 GHz, where intrusion detection alarms require much faster speed of 0.1 Hz. Therefore, for our project purpose or any other application, selecting an appropriate infrared detector with respond speed and chopping frequency need to be suited.

4. **Active area size and number of elements.**

Just like response speed and chopping frequency, active area and number of elements are depending on optical systems in applications. Therefore, determine the size and geometry of active area, whether using a single detector, linear array, or 2-D array. In practice, InGaAs photodiodes detectors, InSb photovoltaic detectors, MCT photoconductive detectors, and PbS and PbSe photoconductive detectors are really flexible in terms of size, geometry, and moreover the number of elements.

5. **Package**

Last but not least that we need to consider when choosing infrared detectors is package. There are many different types of packages, whether it is a metal can package, a ceramic package, a DIP type package, or Dewar type package.
Moreover, depending on the application, the linearity, stability, temperature characteristics, so prince and other elements become important factor for selection.
The **figure 2.2.12** is an example of the package type:

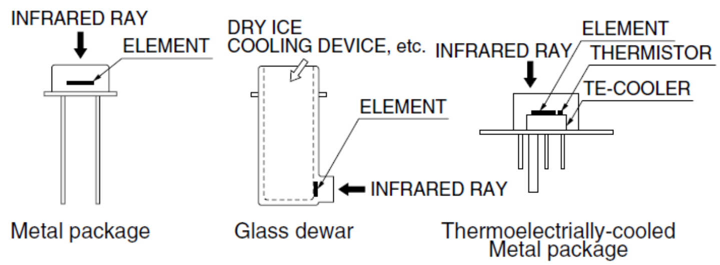

Figure 2.2.12: package
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2.2.4 Types of Infrared Detectors

Quantum detectors

Quantum infrared detectors, which are referred as photon detectors, generate an output which has signal proportional to number of photons that device material absorbed, not the total energy. Therefore, the energy of each single photon must be high to cause a delocalized effect to carriers across the device structure. That delocalization of carriers increase the device conductivity like in photoconductive detectors, or generate the potential difference across a junction like in photovoltaic detectors.

Quantum detectors' main advantages compare to others detectors are in improved performance. They convert photons directly into free current carriers. They do that by photo-exciting electrons across the energy band-gap of the semiconductor to the conduction band. That results a voltage, current, or resistance different of the detectors. In thermal detectors, the photo-exciting processing that is created by radiation interacts directly with the lattice sites. This interaction increases the thermal noise, number of carriers which thermally excited across the band-gap, and change the physical or electrical property of the detectors. Therefore, a cooling system is required to achieve the full potential of quantum detector. Cryogenic cooling system, the most used one, prevents thermal generation of free carriers that could compete with optically-generated carriers. Even though a cooling system would get a job done, it increases the cost highly.

In general, the spectral absorption and photo-excitation would vary the sensitivity of the quantum detectors. In fact, the spectral respond of quantum detectors depends on the energy. Here are some examples of quantum detectors.

1. **Photovoltaic intrinsic detectors**

We learn that photovoltaic intrinsic detectors use P-N junction devices as their bases. Moreover, the potential barrier of the P-N junction creates the photovoltaic effect under IR radiation. Electron-hole pairs is generated and photocurrent is excited when the incident phone with the energy greater than the energy band gap of the junction. The curve of the photovoltaic intrinsic detectors is similar to the normal P-N junction device; however it shifts downward like **figure 2.2.13** below.

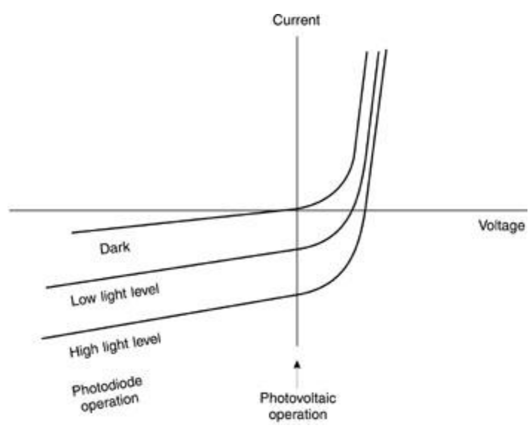

Figure 2.2.13: Light curves
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InAs and InSb photovoltaic detectors are the most two popular. They have faster respond speeds and better signal to noise (S/N), they are used in different applications that require faster speeds.

2. **Photoconductive intrinsic detectors**

As its given name, photoconductive in intrinsic detectors are created to produce the conductance change under the infrared radiation. The increasing of the conductance of photoconductive material is caused by the free carriers generated by the photon. Moreover, in photoconductive detectors, an electric potential is applied across the absorbing region. Therefore a current is created to flow in proportion to the irradiance if the photon energy exceeds the energy gap between the valence and the conduction band. The **figure 2.2.14** below is show the processing of photoconductive intrinsic detector

In practice, depend on their spectral responsibility function; photoconductive detectors are placed into different catalogues. There are photoconductive detectors for the visible wavelength range, photoconductive detectors for the near infrared wavelength range. Cadmium sulfide or CdS are two most popular for photoconductive detectors for visible wavelength. Lead sulfide or PbS photoconductive detectors are infrared detectors which use the photoconductive effect that the resistance value of the detector element decreases when exposed to light. Moreover, we learn that the photoconductive detectors can be either an intrinsic or an extrinsic semiconductor. Moreover, the spectral response of a semiconductor material could be controlled; doping the intrinsic semiconductor to make photoconductive detectors applicable in long-wave length infrared radiation (LWIR) detection.

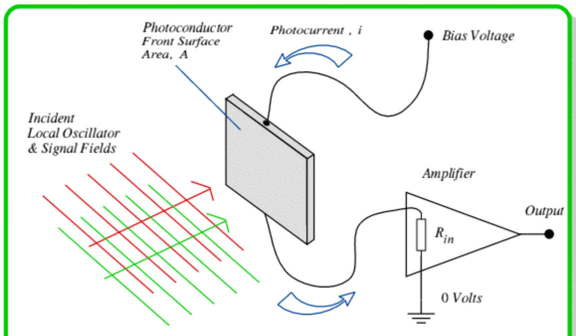

Figure 1.3 Bulk Mixer (Photoconductor) Arrangement.

Figure 2.2.14: procedure of photoconductive intrinsic detecting
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For intrinsic semiconductor itself, the incident IR radiation is absorbed to generate holes and electrons. On another hand, in case of extrinsic semiconductors, the photon energy is absorbed by the impurity; only the majority carriers are excited. The current level resulted from applied constant bias is proportional to the incident photon flux. In photoconductive detectors, the ratio of carrier lifetime to detector transit time is the photoconductive gain. Usually, the gain is about .5 to a bit larger than 1. However, if the carrier time was longer than transit time, the free carriers could transit through the detectors without recombination. Furthermore, the current gain is larger than unity. Even though, photoconductive detectors are used widely, they have bit issue. For example, if the current flows under a constant electric field, the photoconductive detectors would consume more power and so they generate heat. Therefore, this makes them unsuitable for larger infrared radiation array application. In addition, an extra noise source which is called the generation recombination noise exists in photoconductive detectors besides the thermal and the noise sources.

There are some advantages of photovoltaic detectors over the photoconductive detectors. The first easy recognize advantage is that photovoltaic is much better signal to noise ratio, simpler biasing, and better responsivity. However, photovoltaic detectors are more fragile, susceptible to electrostatic discharge and to physical damage due to handling. In practically photovoltaic detectors are made of Si, InSb, and HgCdTe. On the other hand, photoconductive detectors are made of Ge and Si combine with HgCdTe and PbSnTe. In table 2.2.2 are the properties of different detectors.

Parameter	PV Detectors	PC Detectors
Response time	Fast	Slow
Spectral responsively	Narrow and selective	Wide and Flat
Sensitivity	High	Low
Operating temperature	Cryogenic	Room
Cost	Expensive	Economical
System requirement	Cooling System	Optical Chopper

Table 2.2.2: comparison of PC and PV detectors
(Self-Drawing)

3. **Extrinsic Detectors**

Extrinsic detectors are based on Si and Ge doped with popular impurities like Boron, Arsenic, and Gallium. In fact, extrinsic detectors are almost like intrinsic detectors; however, in extrinsic detectors carriers are excited from the impurity levels and they are not over the band-gap of the basic materials. In practice, there are both photovoltaic and photoconductive types exist in extrinsic detectors. Extrinsic detectors have more advantage on being able to operate with much lower wavelength than MCT and intrinsic silicon. However, extrinsic have issue when there some positive holes left behind in valence band. The solution for it is higher doping density is used.

4. **Photo-emissive Detectors**

Photo-emissive detectors are the solution for avoiding extreme demands of extrinsic semiconductor detectors, for reaching even longer wavelengths. Photo-emissive detectors are also know at free-carrier or Schottky-barrier detectors. The metallic compounds, like platinum silicide – PtSi, in photo-emissive detectors are covered with one doped silicon layer. The advantage of photo-emissive detectors is that response doesn't depend on the characteristic of semiconductor materials. However, photo-emissive detectors depend on the metal materials which are extremely uniform. Therefore, the high uniformity of response is easier to finish.

However, the wavelengths of a few microns, sensitivity, and efficiency are much smaller than extrinsic detectors. That happens because the absorption is proportional to the square of the wavelength. Therefore, for any extreme long wavelengths like above 100µm, photo-emissive detectors are very useful. The **figure 2.2.15** below is example for a hole out of the conductor band into the silicon.

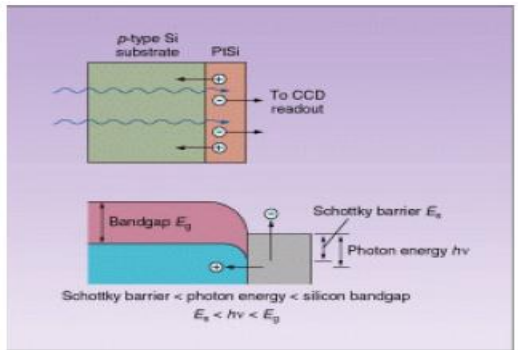

Figure 2.2.15: Hole out of conductor band into the silicon
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5. **Quantum Well Infrared Photo Detectors**

The last but important quantum infrared radiation detectors are the quantum-well infrared photoconductors which has acronym of QWIP. In fact, the quantum-well infrared photoconductors have the same principle of operation with the extrinsic detectors; they are altered the band structured using the dopants. However, in quantum-well infrared photo detectors, the dopants are more concentrated into microscopic regions. That incident creates quantum well where the band structure has shifted. In practice, the quantum well infrared photo detectors start to operate when photons knock holes or electrons out of the quantum well into the next bands. Quantum-well infrared photo detectors could be changed to reduce the energy a photon needs for detection as with extrinsic semiconductor detector. However, we learn that the quantum well infrared photo detectors are much more sensitive when compared to the extrinsic detectors. That happens because the entire quantum well acts like an absorber not just as an individual dopant atom. Moreover, we learn that the quantum wells are about 10 to 100 atoms across, so there effective absorption area is much higher. The **figure 2.2.16** below shows how the photon knocks an electron or hole out of the quantum well into neighborhood band to start the detection.

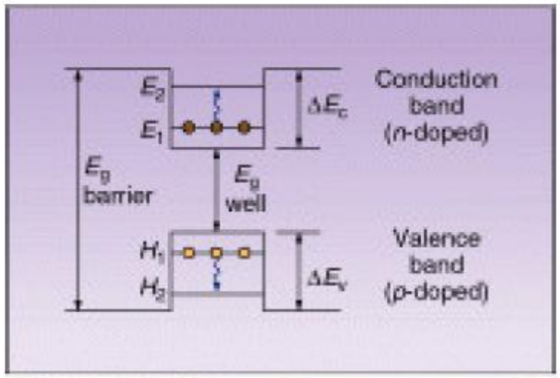

Figure 2.2.16: quantum well detecting procedure
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For all that advantages, however, quantum-well infrared photo detectors are not used widely. They are still under the development, relatively unproven, and still immature to stability in long term usage.

THERMAL DETECTORS

The more interested detector for our project purpose is thermal detector, most of all because of the cost. In practice, thermal detectors could operate at room temperature. Moreover, they have a wide range of spectral response. Because the operation of thermal detectors is based on the change in temperature, they have a slow response and a little bit low sensitivity compared to photon detectors. And this is the reason why they have economical price compared to photon detectors. In practice, the response time and sensitivity of thermal detectors are affected by the heat capacity of the detectors structure. Moreover, they are influenced by the optical radiation wavelength. Nonetheless, in some application, we find out that the thermal detectors also need an optical chopper. Because we intend to use thermal detectors for our project, we would go deep to detail of some popular thermal detectors. The following list is examples of thermal detectors.

1. **Pyro-electric thermal infrared detectors**

We learn that pyro-electric mean the ability of some materials to generate a temporary voltage when they are heated or cooled. Moreover, when the temperature changes, that modifies the position of the atoms slightly within the crystal structure. Therefore, the polarization of the material changes, which increases the voltage across the crystal. Like their names the pyro-electric detectors functions based on pyro-electric. We learn that they consist of a polarized material changes polarization when the object changes in temperature. Pyro-electric detectors operate in a chopped system. The **figure 2.2.17** below is show the principle set up of a pyro-electric infrared detector.

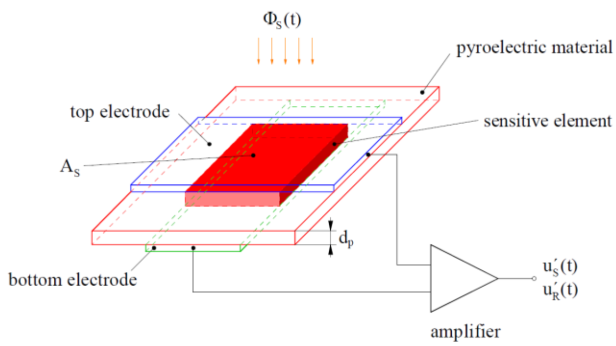


Figure 2.2.17: Pyro-electric
((Reprinted with permission from Hamamatsu)

As we could see that component of pyro-electric included responsive element and the preamplifier. These two components are essential elements that are integrated into the detector. Moreover the sensitive element of the pyro-electric detector is thin and is covered with electrode in two sides, top and bottom. Moreover, for some applications the absorption layer is applied to the front of the responsive elements in order to improve the pyro-electric detector behavior.
From the figure 2.2.18 we could see that the incident radiation flux hits the sensitive elements cover on the area of A_S and absorption coefficient α. Therefore, when the temperature changes, it will change the absorption of radiation flux accordingly. After that, the pyro-electric effect will generate charges on the electrodes. Those charges later are transformed into a signal voltage to calculate the temperature. The most advantage that pyro-electric infrared detectors have that we consider is that they have a large dynamic range covering power from 10 nW to 10 W. They are useful for exact and long term stability in measuring IR radiations. Pyro-electric detectors have a wide range of spectral response from 100 nm to over 1000 µm without the help of any cooling system like any other semiconductor detectors. Pyro-electric detector is one considerable candidate for being our thermal detector in the project.

2. **Thermistor thermal infrared detectors**

The second thermal detector what we consider is the thermistor. Like the section 2.2.1 principles of thermal measuring – thermal resistive was stated that the resistance of the elements varies with the temperature change in thermistor detectors. In fact, thermistor detectors could provide a high degree of precision in measuring. Therefore, they are widely used. Bolometer is one popular example of thermistors infrared detectors. Bolometers functions in either one of these two ways: monitor voltage with constant current or it would monitor current with constant voltage. As today technology, we could reach to Nano technology buy using micromachining of silicon. Therefore, the micro-bolometers are invented. Now we could reach to measurable changes of .1 centigrade from power input of 10 nW. The **figure 2.2.18** is the example how an metallic package of micro-bolometer look like and the procedure how micro-bolometer process infrared flux to signal

Figure 2.2.18: metallic package
(Reprinted from Wikipedia under the GNU Free Documentation License

Micro-bolometers have advantages in every aspect of our project requirement. They could reach the thermal insulation factor greater than 3 in every generation. They reduce noise level extra to 60%, keep usable time constant close to 12 ms for a 35 µm pixel pitch, and reduce pitch size from 45 µm to 25 µm. However, for the cost aspect of our project, micro-bolometer infrared detectors are way over our budget's range. Therefore, we don't consider them for our project.

3. Micro-cantilevers thermal infrared detectors

The third thermal detector that we consider is micro-cantilevers. The fact, micro-cantilevers are the most simplified Micro-electro Mechanical System (MEMS) based devices. They are commonly found in atomic force microscopy; they have excellent potential as detectors for many notable advantages like ultra-sensitivity, ease of mass production, and low cost. Different from pyro-electric and thermistors, micro-cantilevers are using bimetal effect to measure infrared radiation. The bimetal is known for its utilizing effect the difference in thermal expansion coefficients of two different bimetals. This effect would cause a displacement in a micro-cantilever. We learn that in combination with a reference plate, the micro-cantilevers form a capacitance. Therefore, when incident infrared light is absorbed by the micro-cantilevers, the micro-cantilevers deflect and generate the capacitance of the structure. We could measure the incident infrared radiation light using the change in capacitance that micro-cantilevers alter.

4. Thermopiles thermal infrared detectors

The last but the most considerable thermal infrared detector for our team's project is thermopile detectors. Therefore, we will into very deep detail of these detectors. Thermopile infrared detectors generate output that is proportional to the incident infrared radiation. In fact, they are serially-interconnected array of thermocouples. In order to understand how thermopile detectors work, we need to understand how thermocouple works first. In fact, any junction that is connected from different metals will produce a potential related to temperature. Therefore, thermocouples use that basic theory to generate thermal related voltage. The **figure 2.2.19** below shows us the basic thermocouple measuring circuit.

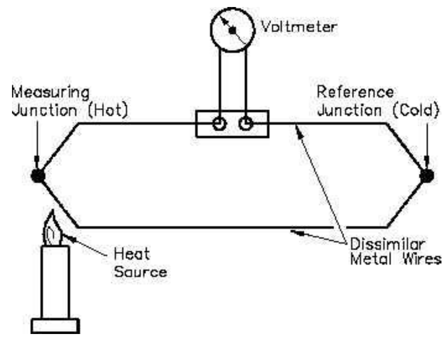


Figure 2.2.19: measuring temperature using thermocouple
(Reprinted from Wikipedia under the GNU Free Documentation License)

Thermocouples are junctions which consist of two different metals; they produce voltage when one side of the junction has different temperature to other. In another word, thermocouples are temperature sensors that measure and control, and convert heat into electricity.

In thermopile detectors, the thermocouples are placed across the hot and cold regions of a structure. Moreover, the hot junctions are thermally isolated from the cold junctions. We learn that the cold junctions are typically placed on the silicon substrate to provide effective heat sink. Looking at the **figure 2.2.20** below, we could understand the whole concept easier. In hot regions, we could see that there is a black body applied for absorbing the infrared. That would raise the temperature according to the intensity of the incident infrared light. In fact thermopile detectors use two different thermoelectric materials which are deposited on a thin diaphragm. This diaphragm has a low thermal conductance and capacitance. When the incident infrared radiations occur, this would generate a large temperature different between the hot and the cold regions. This structure of thermopile would enable its detecting function. When compared to other detectors, we learn that the thermopiles have some unique characteristics that other don't. For example, they have inherently stable response to DC infrared radiation, they are not sensitive to ambient temperature variations, and they respond to a broad infrared spectrum where they don't require a source of bias voltage or current from outside. In fact, these three properties are the reason we chose thermopile being our thermal infrared detectors.

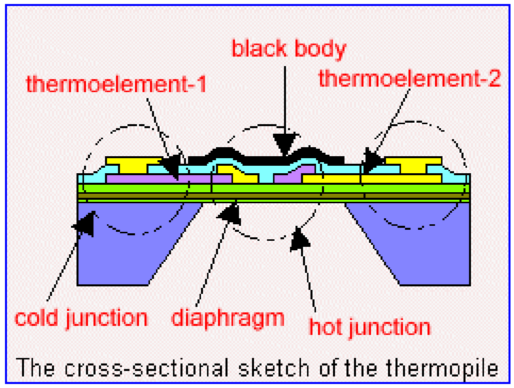


Figure 2.2.20: cross section sketch of the thermopile
(Reprinted from Wikipedia under the GNU Free Documentation License)

2.2.5 TYPE OF WAVELENGTHS

Depend on the material and applications, infrared temperature sensors fall into one of three categories: single wavelength, dual wavelength, and multi-wavelength.

SINGLE WAVELENGTHS

Single wavelength infrared thermal sensors are referred to as single color infrared thermal sensors. They are used in thermometers that measure all of the energy emitted from an object at one wavelength then calculate the average temperature of the measure object. Moreover, the single wavelength infrared temperature sensors assume that the optical path is unimpeded, and the object fills the measured area. In another word, they require that the object's emissivity to be relatively constant and known, otherwise change in emissivity will create errors. The error's size would vary with the percent change in emissivity, and with wavelength and temperature. It means that the size of error would be larger for longer wavelengths and higher temperature.

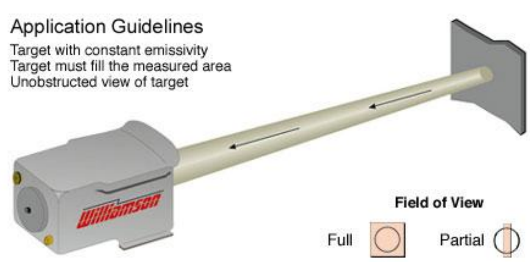


Figure 2.2.21: single wavelength sensor
(Reprinted from Williamson's Free Specification Document)

Single-wavelength temperature infrared sensors offered in a diversity of configurations with a wide selection of temperature range, spectral response options, and optics. They are available in short-wavelength, long-wavelength, and specific-purpose-wavelength versions.

a. **Short single-wavelength infrared sensors:** when measuring low temperatures and low emissivity materials, in order to have more effective result, short single wavelength infrared sensors are used. They are used to reduce errors resulting from a change in emissivity or when lens become soiled. They provide a more robust temperature reading from the varied change in emissivity or optical obstruction. Moreover, short single-wavelength sensors are able to view through any common infrared windows material like glass or quartz, and they are available in fiber-optic configuration.

b. **Long single-wavelength infrared sensors:** On the other hand, long single wavelength infrared sensors are used to measure high emissivity materials that absorbing and re-radiating thermal energy like zirconium, chromium, and cerium. Moreover, they are required to measure temperature when close by infrared heaters, or to measure near-ambient temperatures. They offer broader temperature spans, but are greatly more sensitive to varied emissivity change. Even though long single-wavelength infrared sensors are generally low cost, they are greatly more sensitive to emissivity changes.

c. **Specific purpose single-wavelength infrared sensors:** For the most parts, specific purpose single wavelength infrared sensors are used to view any targets which are transparent like glass, flames, thin plastics, crystalline materials, and gasses at the general purpose wavelengths.

DUAL WAVELENGTH

Dual wavelength infrared temperature sensors are referred as two-color sensors. They operate with assumption that the ratio of emissivity values of two measured wavelength A & B (or any other names) is known and reasonably constant. Dual wavelength infrared temperature sensors provide temperature values that are heavily weighted averaged towards the hottest temperature viewed. Dual wavelength sensors are usually used to measure bodies that above 150 C when there is an immoderate change in emissivity, when sensor lens are really dirty, when there are great temperature gradients, or alignment is difficult to achieve in order to the measured objects. In another word, they tolerate emissivity variation, dirty optic, obstruction, misalignment, nor even scale. Therefore, if there was any variation effects, both wavelengths, A and B, are measured the same.

Dual wavelength sensors have a diversity of wavelength pairs. It is necessary choosing a wavelength pair that equally affected in both wavelengths when dealing with translucent or transparent sources like water pray and steam.

MULTI WAVELENGTH

Multi wavelength infrared temperature sensors are needed when dealing with materials or applications that both single and dual wavelength sensor are unable because the existing of non-grey emissivity variation. Some of those common materials are measurement of aluminum, copper, stainless steel, chrome, tin, cold rolled steel, and electrical steel.

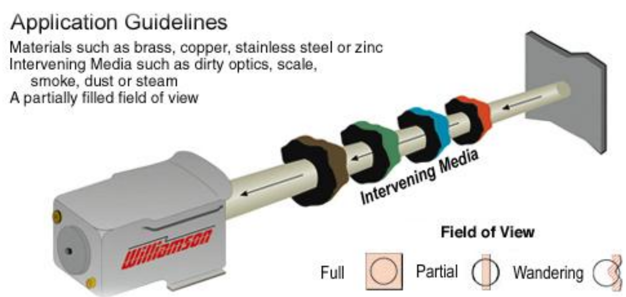


Figure 2.2.22: Multi wavelengths sensor
(Reprinted from Williamson's Free Specification Document)

These materials have emissivity changes over time or from part to part which is not emissivity stable constant for single wavelength sensors to work. Moreover, they have different emissivity in different wavelengths that make dual wavelength sensors useless. In addition, there are some materials will be coasted with a material that has different emissivity; these material need multi wavelength sensors to detect their temperatures.

2.2.6 PROJECT'S CONSIDERED DETECTOR

After consider the entire possible detectors that we could use for our project design from quantum to thermal in general, and from pyro-electric to thermopile for specific, we decided to use the thermopile detector. Like the reason we stated on section 2.2.4, the thermopile is affordable, it has an inherently stable response to DC radiation, not too sensitive to ambient temperature variations, and it responds to a broad infrared spectrum which doesn't require a source of bias voltage or current.

Due to the lack of support on the analog sensors which require look-up tables and precise values to calculate and calibrate, we decided to go with the digital sensor. The Melexis branded sensor, MLX90614, is used for our non-contact infrared temperature module. It is built from 2 chips which are developed and manufactured by Melexis:

1) The infrared thermopile detector MLX81101

2) The signal conditioning ASSP MLX90302, specially designed to process the output of IR sensor.

Both the IR sensitive thermopile detector chip and the signal conditioning ASSP are integrated in the same industrial standard TO-39 package can. The MLX90614 is factory calibrated in wide temperature ranges from -40 to 125ºC for the ambient temperature and -70 to 382.19ºC for object temperature. The field of view (FOV) of 35º offers an accuracy of ±0.2ºC; however, this accuracy is only rated for a range of 2 feet. Therefore, we extend the range of detection by using a Fresnel lens and changing the EEPROM from the SMBus.

MAIN FEATURES AND BENEFIT

1. MLX81101

- Solid state thermopile sensor
- On-chip thermistor for ambient temperature compensation in silicon edge of the sensor: closest possible sensing of sensor temperature
- High reliability and long-term stability
- Low cost, small size
- Fully CMOS compatible process
- Suitable for automotive applications

There are some other application that this thermopile could do out of automotive contactless temperature sensing like gas analysis equipment and occupancy detection. The **figure 2.2.23** shows us the basic function diagram of the MLX90614.

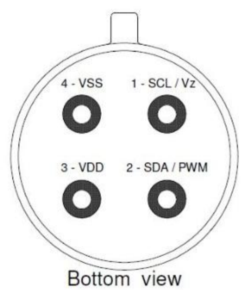


Figure 2.2.23: Pin definition and description
(Reprinted from the Specification of MLX90614)

The **table 2.2.3** is a table that shows us the pin definition and description of the MXL90614 from the top view down

Pin	Symbol	Description
1	SCL/Vz	Serial clock input for 2 wire communications protocol. 5.7V zener is available at this pin for connection of external bipolar transistor to

		MLX90614A to supply the device from external 8 to 16V source.
2	SDA/PWM	Digital input/output in normal mode the measure object temperature is available at this pin Pulse Width Modulated. In SMBus compatible mode automatically configured as open drain NMOS.
3	VDD	External supply voltage.
4	VSS	Ground. The metal can is also connected to this pin.

table 2.2.3: Pin definition and description
(Reprinted from MLX90614 datasheet)

2. **MLX90302**

The signal conditioning ASSP MLX90302 combines a low noise programmable amplifier, a high resolution 17-bit ADC, and a powerful DSP unit. Therefore, the MLX90614 can be used in applications as a high accuracy and high resolution thermometer. The principle operation of the signal conditioning MLX90302 is controlled by an internal state machine which controls the measurements and calculations of the object and ambient temperatures. The output of the MLX81101 sensor is amplified by a low noise, low offset, and programmable gain amplifier. Then it will be converted by a high resolution 17-bit ADC to a single stream and fed to a powerful DSP for further processing. In order to achieve the desired noise performance and refresh rate, the signal later is treated by programmable Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) low pass filters for further reduction of unwanted bandwidth of the input signal. The measurement result from the IIR filter is then available in the internal RAM. There are 2 different cells available, one of which is an on-board temperature sensor, and one for the MLX81101 sensor. The onboard temperature cell is the corresponding ambient temperature Ta, and the MLX81101 thermopile cell is the corresponding object temperature T_o. These both temperature measurements have a resolution of 0.02ºC. We could later read these two data either by reading RAM cells using the SMBus 2-wire interface, or we could read through the PWM digital output. For the purpose of design, power, and portable we use the first method which we read the values from SMBus compatible 2-wire interface that later will discuss in microcontroller section.

SPECIFICATIONS

We use some of the factor from the guide of section 2.2.3 to determine the advantages and disadvantages of the MLX90614

Specific Directivity

1. Noise equivalent power

When we look at a detector spec the first thing we should look is noise equivalent power NEP. It is a convenient information that help us predict the maximum power of given system can detect. However there is more information noise equivalent power could provide than that. At we look out the figure 2.2.24 which is listing the spec of MLX90614 we could see that the NEP that MLX90614 has is 2.6 nW/ Hz. This number is consider small so ti mean that MLX90614 is a good thermopile detector, However, it is theory kind of way to define which one is good. In practice, thermopile detectors which have different sizes would have different NEPs. Therefore, we could not say what a good noise equivalent power should be unless we specify the size of thermopile detector.

Parameter	Typical	Units	Condition
Sensitive Area	1.2 x 1.2	mm^2	
Wavelength range	5.5 … 15	µm	
DC membrane responsitivity	12	V / W	Ta = 25˚C Tbb = 60˚C
Sensitivity (Alpha)	$4.28^{\pm 25\%} \times 10^{-13}$	V/K^4	Full FOV
Thermopile output voltage	$46^{\pm 25\%}$	µV	Ta = 26˚C Tbb = 27˚C, Full FOV
Window aperture size	3.5	mm	
Field of view	88	Deg	50% thermopile signal
Spectral sensitivity	> 70 < 1	% %	7.5µm < λ < 13.5µm 0 < λ < 5µm
Thermopile Resistance	60	kΩ	Ta = 25˚C
Noise	32	nV / √Hz	RMS, Ta = 25˚C
NEP	2.6	nW / √Hz	RMS, Ta = 25˚C
Time constant	30	ms	
Thermopile resistance tempco	0.1	% / ˚C	
PTC value R(25°C)	$24^{\pm 30\%}$	kΩ	Ta = 25˚C
PTC TC_1	$6500^{\pm 20\%}$	ppm/˚C	
PTC TC_2	16	ppm/˚C^2	
Withstand ESD voltage	+ 800 - 7000	V V	

Figure 2.2.24: Pin definition and description
(Reprinted from the Specification of MLX90614)

2. Noise

Another important factor when come to pick a detector is noise; noise is determine the detector performance. There are many noise sources in a thermopile detector. In general, a fundamental noise is created by actual temperature fluctuation. Therefore, when the noise is at its minimum, a theoretical limit of thermopile sensitivity will be determined. When we look at the specification of the MLX90614, we got the level noise of 32 nV/ Hz. This is use usually indicated the Johnson noise. Since the device is mainly for thermopile detector there for it mainly for resistive. Even the specification already gave the number. This is a formula to find Johnson noise

$$V_J = \sqrt{(4kTRB)}$$

From the formula, we find out that B is the noise bandwidth. Generally, Johnson noise is the most important of electrical noise of any detector's noise sources for thermopile.

3. Wavelength Range

The MLX90614 covers any wavelength from 5.5 µm to 15 µm. That meant that it would cover some of the mid-wavelength infrared to all of the long-wavelength infrared. If we use the information on 2.2.5 type of wavelength infrared we could see that the long-wavelength infrared is the thermal imaging region. That means that we could completely capture the passive picture of anything in this world which has thermal emission. Moreover this function of wavelength range requires no external light or thermal sources from outside like moon, sun, or any other infrared illuminator. Therefore, the MLX90614 provides us a perfect specification on wavelength range for our thermometer function. We could measure temperature of anything, anytime, and anywhere.

4. Other factors

Even though, the specification table doesn't give some of important factors like detectability, response speed, chopping frequency, etc, for our project purpose, those factors are not that much important. However, there are some of the important specifications that we could find out. For example, we could see that the sensitive area (active area) of MLX90614 is 1.2 by 1.2 mm^2 which is pretty good for a detector with low cost. It is the area of the detector where an incident radiant power results in measurable output. The specification table lists that the sensitivity area of MLX90249 is around $4.28^{\pm 25\%} \times 10^{-13}$ V/K
The specification table doesn't give out thermistor resistance. However, we could use the provided formula to calculate it

$$R(T) = R(25°C)[1 + TC1(T - 25°C) + TC2(T - 25°C)^2]$$

Thermopile output voltage is: Vir = Alpha.[$(T_o^4) - (T_a^4)$]
Where T_o is the measured object temperature, both T_o and T_a are in Kelvins

This formula later will be used to calculate the thermopile voltage and resistor for our thermometer.
Moreover, the MLX90614 is the infrared sensor that is sealed to withstand a fine and gross leak test according to MIL883 Method 1014.

5. Package

Depend on the purpose of the applications; there are different kinds of packaging. Our MLX90614 is packaged with gold Au filter and thermistor. Moreover, the cap is welded with metal. MLX90614 is supplied with industry standard TO-39 package which meant it is a through-hole device. The package out is showed in figure 2.2.25

One of the most important factors that we chose MLX90614 is that it is packaged with thermistor. As chapter 2.2.1 Thermal-Junctive states, thermistor is there for the compensation of an environment temperature. According to the variation of an environment temperature, the output of the thermopile detector is also varying with the environment temperature. Therefore, it is important for us to choose one with the thermistor to compensate the environment temperature.

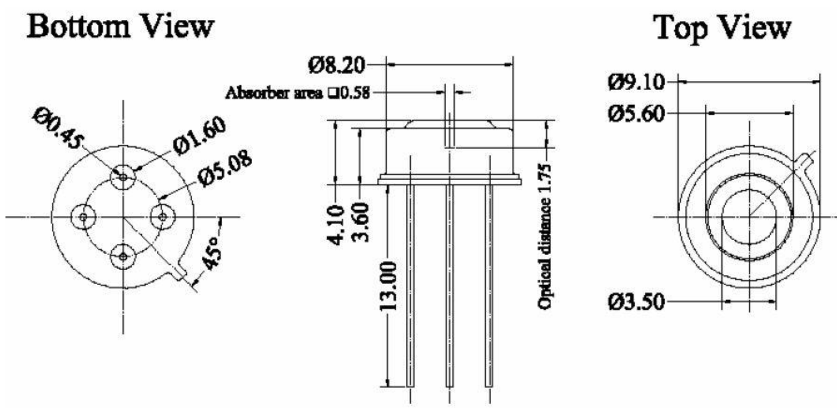


Figure 2.2.25: Cross section and internal of MLX902147
(Reprinted from the Specification of MLX90614)

From theory, in order to improve the thermopile detector performance, we should consider a very important factor is to select suitable filter for given application. The MLX90614 is basically using the broadband – gold Au filter which has the transmittance from 5.5 µm to 15 µm. That range of temperature is perfect for our project; the Au filter is doing the job.

2.2.7 MICROCONTROLLER

The microcontroller is used to display temperature of object, adjust emissivity, and adjust filter for Fresnel lens. The MLX90614 has two SMBus compatible communication pins, Serial Data (SDA) and Serial Clock (SCL). SDA pin is a digital input and output which used for both the external PWM module output of the measured object temperature and the digital input and output for the SMBus. On the other hand, the SCL is only a digital input which is used as the clock for SMBus compatible communications. Moreover, this pin has an auxiliary function for building an external voltage regulator. The connection between the MLX90614 sensor and ATmega328 is really straight forward; both the SCL and SDA are connected to any two of the five analog pins, and a calculated resistor needs to be connected between 3.3V and the SDA.

While the wiring is straight forward, the software interface the wiring between the MLX90614 and microcontroller is not. The standard wiring library doesn't work for the MLX90614 because it involve with SMBus compatible 2-wire interface, so we implemented the i2cmaster library. To complicate things even more, the i2cmaster library doesn't work out of the box with our ATmega328 microcontroller. We needed to rename, change, and add some files to get it working.

In coding part, we basically read the data from internal RAM where ambient temperature Ta is stored at 0x006 and object temperature stored at 0x007. With the resolution of 0.02ºC per LSB we use these formulas below as part of the code to calculate the temperature:

tempData = (double)(((**data_high** & 0x007F) << 8) + **data_low**)

Where tempData is data of at RAM address 0x007 of the object temperature To

tempData = (**tempData** * **tempFactor**)-0.01

Where tempFactor is resolution of MLX90614, 0.02 ºC

Celsius = **tempData** - 273.15
Fahrenheit = (**Celsius***1.8) + 32

Where Celsius is the object temperature in C, and Fahrenheit is the object temperature in F.

2.2.8 Optical Lens System

We learn that in order to have an excellent infrared transmitting from the infrared radiation to the detector, MLX90614, we need good material lenses like the germanium lenses. Germanium lenses could transmit perfectly infrared radiation in the 8 to 14 µm region. However, those germanium lenses are relatively expense, especially for the project like ours. We learn those germanium lenses are made by grinding and polishing techniques. There are some plastic materials out there could do the job. However, they are low in absorption in portions of the infrared spectrum. Moreover, they are limited to thickness of 1 mm which is preferably less. This limit of thickness makes those plastic lenses low in high f-number (the small aperture relative to the focus length). Through research, we learn that the perfect lenses for our thermopile infrared detectors are the Fresnel lenses. It is relatively cheap average around $2 to $4 each, and they do the job right.

Fresnel lenses can be made extremely thin; some of the Fresnel lenses are as thin as 0.13 mm. The **figure 2.2.28** below is a real life example of Fresnel lenses. We learn that Fresnel lenses are made of infrared transmitting plastics that have an infrared transmission range from 8 µm to 14 µm. This type of wavelength range is most sensitive for thermal detection, and it is perfect for our MLX9024, which has wavelength range from 5.5 µm to 15 µm. Moreover, the Fresnel lens is designed to have the rough surface faces the IR sensing element, and the smooth side face the subject.

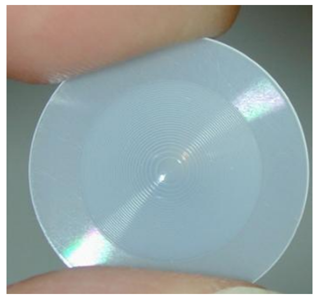


Figure 2.2.26: Fresnel lens
(Reprinted from Wikipedia under the GNU Free Documentation License)

2.2.9 CALIBRATION

The result from the MLX90614 is accurate compared to commercial thermometers. However, the accuracy is limited only 2 feet of range due to the large field of view of 35º. Therefore, we decided to implement a Fresnel lens in order to increase range of detecting. The task itself involves with precise temperature measurements and emissivity calibration. First we heat up an object which has assumed emissivity of 1 to a temperature of 66ºC (as long it is larger than 60 ºC). After that we implemented a Fresnel sensor in front of the MLX90614 which we isolate in a black tube, then calculate the new object temperature with the Fresnel lens in front of it. We got a new temperature measurement of 53ºC. We then measured an ambient temperature around 25ºC for both with and without the Fresnel lens. Finally, we use the equation below to find out the new emissivity

$$E = \frac{T^4_{O\_NEW} - T^4_{A\_NEW}}{T^4_{O\_REAL} - T^4_{A\_REAL}}$$

From this equation we found the new emissivity to be 0.64062. Using this value, we then calculated the new EEPROM values for the MLX90614. The corresponding 0.64062 value is calculated to be A3FF. After calculating the value in hex of new emissivity for the EEPROM address 0x04, we do the same with 0x0F where the new value is calculated to be 0EFD.

These two values of the new emissivity constants are addressed at 0x04 and 0x0F, and replace the old ones by using the microcontroller and SMBus interface. First we access the address, then erase them by writing them with zero, and finally write the new values to the address 0x04 and 0x0F with the right corresponding PEC.

2.2.10 Color Preference

In order to create more functionality for the infrared thermometer, we implemented the color preference to it. We are using triple output RGB LED which is connected to the ATmega328 microcontroller. The green color of RGB is set to the ambient temperature, the red color is set to anything larger than ambient temperature 10ºC, and the blue color is set to anything smaller than ambient temperature 10ºC. Moreover, in order to have the RGB LED brighter and more focus, we use the biconvex lens.

2.2.11 Similar project

When we were search information for our project, we came across some of the project that similar, some more or less advanced than ours. For example, the digital thermometer from IKALOGIC uses the AT89S52 micro-controller. This digital thermometer has schematic and structure that are more advanced than ours. However, this project is all about Analog to Digital conversion. All the components on the project are already built, from the temperature sensor, ADC, Micro Controller, to display. Moreover, this is a close distance sensor thermometer, while ours is far distance infrared thermometer. The **figure 2.2.29** is the picture of IKALOGIC's digital thermometer.

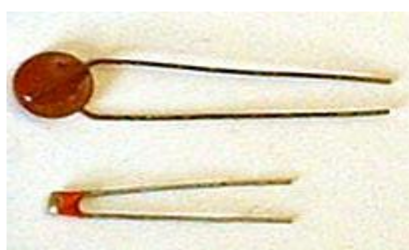


Figure 2.2.29: temperature sensor
(Reprint from free open source project from IKALOGIC)

2.3 Microprocessor

2.3.1 ACAM Time to Digital Converter (TDC)-GP21

One of the main limitations to the laser ranging function of our measuring device is its range capability. The reason we chose to do a time of flight (TOF) measurement is so that we could greatly increase the range of the device. Using triangulation, or any other method, would have limited our range to possibly 10m or less. However there are some very imposing obstacles to maneuver around when trying to implement the TOF method. For one, to measure any type of long distance, you need an extremely powerful, and therefore expensive, laser module to avoid losing power over those long distances. Perhaps the most daunting obstacle is the sheer speed of light, which makes measuring close to midrange distances next to impossible using a simple microcontroller. The time it takes for light to travel to a target distance of 3 meters, and back to the sensor is given below.

$$time = 2\frac{distance}{c} = \frac{3m}{300000000m/s} = 20ns$$

The average microcontroller uses a clock frequency in the range of 10-20 MHz; using an average of 15 MHZ, a typical clock cycle time is given below:

$$time = \frac{1}{f} = \frac{1}{15000000Hz} = 66ns/cyle$$

This shows that the time it takes for light to reach a target 3 meters away, and then return to the sensor is much shorter than the time it takes for the clock on the microcontroller to travel through one complete cycle, making it physically impossible to measure the time interval directly. Perhaps using a much faster microprocessor would yield the ability to measure those ranges; however, purchasing a full-fledged microprocessor greatly complicates the design of the system and takes a hefty toll on the budget. To solve this problem we started looking for previously completed projects for laser ranging; and though we didn't find much material on the subject, we did find that using a TDC is one of the only ways to make TOF ranging possible. This led us to research into the German company ACAM.

ACAM occupies a niche market and one of its specialties is the design and manufacturing of "time to digital converters," or TDCs. Essentially, a TDC is a very high precision tool that can receive 2 analog inputs and accurately measure the time difference between when the 2 signals arrived, and then convert that to a digital value for the microcontroller to use. The device itself is almost like another microcontroller, with and ALU on board and a set of registers that it uses to function correctly. ACAM offers several different options, ranging from very high-end to budget priced TDCs, and we considered each of them for our project.

Device	Package	Measurement Range	Max Channels	Interface Communication	Core Voltage	Price
GP1	TQFP44	2ns-200ms	2	Non-SPI		$48.22
GP2	QFN32	3.5ns-4ms	2	SPI	1.8-3.6V	$32.85

GP21	QFN32	3.5ns-4ms	2	SPI	2.5-3.6V	$32.85
GPX	TQFP100 TFBGA120	0ns - 10µs	8	Non-SPI		

Table 2.3.1

Figure 2.3.1

Considering all of these devices individually, we found that the device best suited for our needs would be the GP21 module. The measurement range of 3.5ns to 4ms theoretically gives us the capability of measuring anywhere from 1.05m to 1200km, though it will be next to impossible to get such long ranges using our elementary optics systems and relatively low-powered laser. However, these specifications show that it will be completely reasonable to expect to get ranges of around 100 meters or so. The GP21 also comes in a small QFN32 package, making it ideal to use on our PCB as it won't take up hardly any of the valuable space available. Though it has one of the higher operating voltages listed, the current draw of the device is significantly lower than the other models and it shares the lowest price point, making it the ideal choice for our application.

Device Operation

The TDC GP21 is the newest TDC produced by ACAM. It builds off of the previous generation of TDC, the GP2, but simplifies the overall design to limit the size of the external circuit of the chip. The device itself is capable of operating in multiple measuring modes, with several different configurations in each mode, and all of these options are controlled through a series of onboard registers, much like a generic microcontroller. These registers can be altered by a master microcontroller through the SPI communication. For our purposes, the GP21 needs to be configured into measurement mode 1, which allows the part to achieve the highest accuracy possible. Once the GP21 has been configured in the desired measuring mode, the device is ready to receive signals for measuring. The circuit inside of the GP21 waits for a signal to be applied to the START channel and then waits for another signal to be applied to a STOP channel. The signals travel through a large array of internal propagation delays to accurately measure the time difference between them. The raw data is collected from the delays and sent to the ALU for post processing and converting into a digital value that we can use to represent the distance. **Figure 2.3.2** shows the process of the propagation delay used by the TDC to measure the time difference.

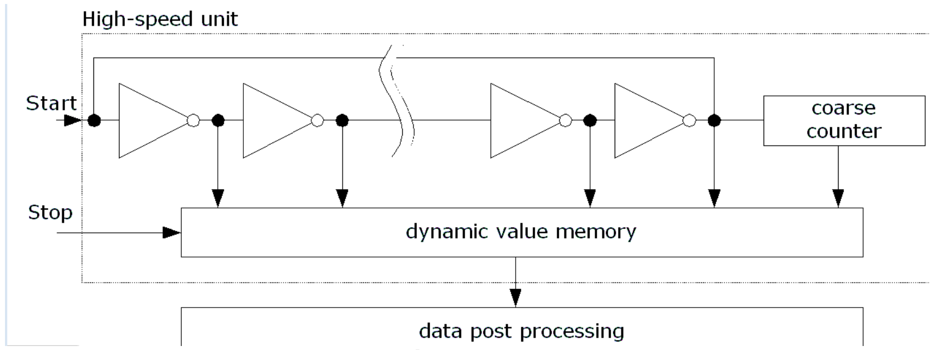


Figure 2.3.2

Block Diagram and Explanation

The GP21 is capable of multiple functions and can be applied to numerous types of projects. It's most common applications of that of laser ranging and ultrasonic flow and heat meters. For our applications the temperature sensing circuitry can be completely ignored, as they are inapplicable to IR ranged heat sensing, but rather for stationary temperature sensing.

The GP21 comes in a QFN32 package and is completely backwards compatible with the previous generation of TDC's, the ACAM GP2's. Calibration of the device relies on the 4 pins for the external oscillators rated at 32.768 kHz and 4 MHz. The high accuracy, 32.768 kHz oscillator is always on as long as the GP21 is powered, and is used to calibrate all components in the device, including the higher speed 4 MHz oscillator which is turned on and off throughout the measurement and calculation process to conserve current and power draw. The 32.768 kHz oscillator takes approximately 3 seconds to settle at its peak value upon starting up. The GP21 uses the 4 SPI pins to communicate with the master microcontroller to modify the configuration registers to select the appropriate mode and settings for measurement. The onboard pulse generator uses the registers to know how many pulses must be sent through to the laser, and at what frequency. The same signal that activates the pulse of the laser is sent to the START channel to allow the TDC to begin measuring time. This can be thought of as a dummy start, meaning the TDC will start measuring time before the laser pulse is actually sent, creating a delay, and therefore inaccuracy in the measurement process. This error will be discussed further in the design section of the GP21's circuit. When the laser's light returns and is collected by the APD, the STOP channel is activated and the TDC section can then calculate the time difference between the START and STOP signals. The time data is held in the Raw Data Register until it is fetched by the ALU which converts the raw data into a digital value that can be used to calculate the distance traveled. The master microcontroller can then use SPI commands to fetch the information from the Read register, which will contain a 32-bit 2's complement number representing the distance traveled, and do final calculations to export to the LCD screen. The completed block diagram is shown in **figure 2.3.3.**

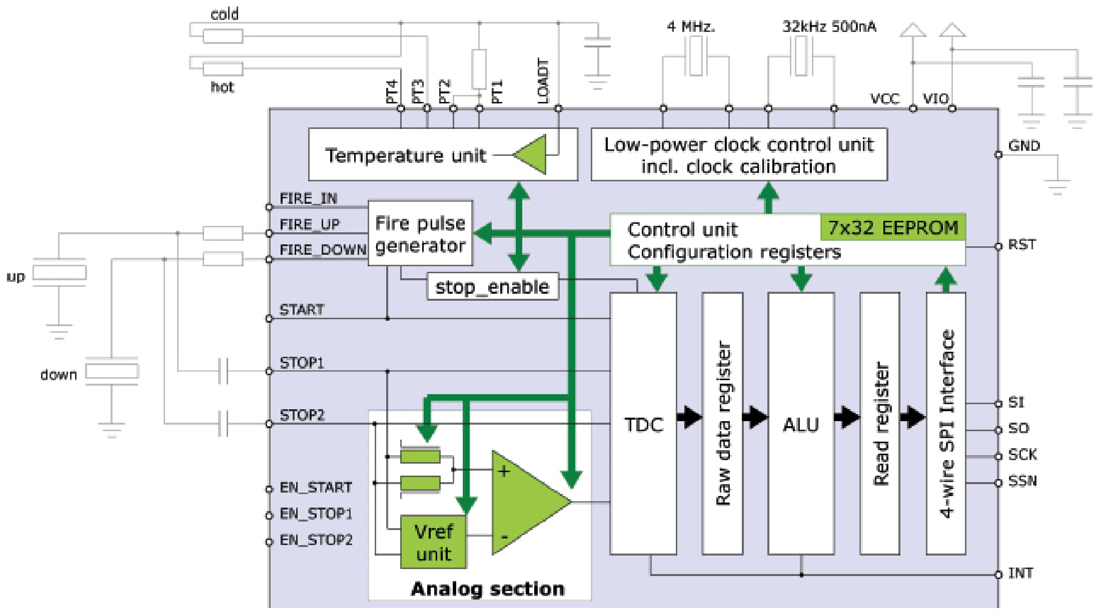


Figure 2.3.3

Device Communication

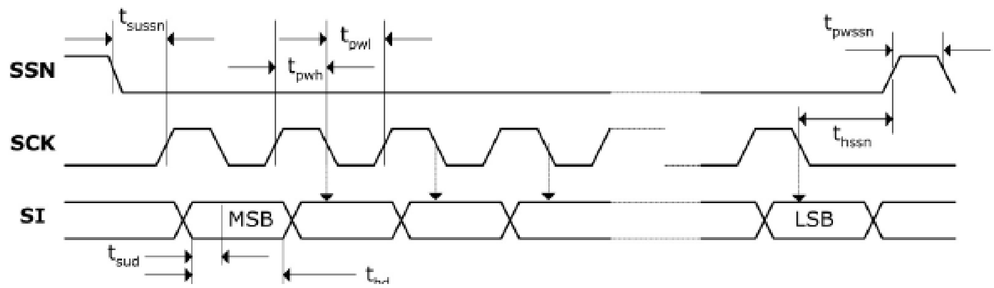
The GP21 communicates with other devices, specifically a master microcontroller, via SPI communication interface. Unlike some devices, the GP21 requires all 4 wires of the standard SPI pin to communicate correctly, otherwise the data will never be able to be collected from the GP21. The pins on the GP21 with their names and corresponding SPI standards are given below:

GP21 Pin Number	GP21 Name	SPI Pin
9	Slave Select Not (SSN)	Slave Select
10	SCK	SPI Clock
11	SI	SPI Data In
12	SO	SPI Data Out

Table 2.3.2

The second requirement to enable SPI communication for the GP21 is to set the Clock Phase Bit = 1, and also to set the Clock Polarity Bit = 0 in the configuration registers. **Figure 2.3.4** below shows how the SPI communication works through read and write cycles:

SPI Write



SPI Read

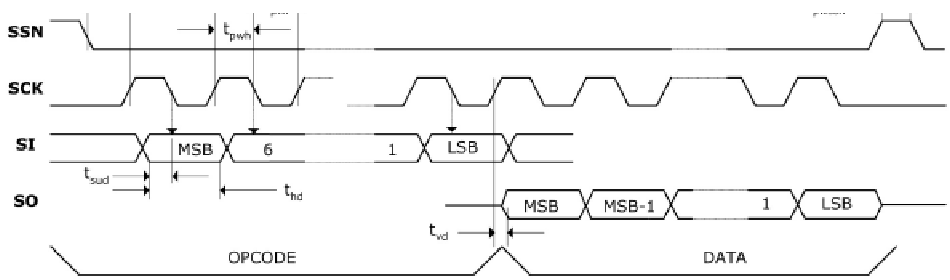


Figure 2.3.4

Device Calibration

The GP21 is an extremely sensitive device used to make very precise measurements. Because of the nature of the device, its functionality is affected by the temperature it operates at, and even a few degrees of temperature change can yield significantly different results from reading to reading. To compensate for this, the GP21 is able to be calibrated after every measurement made. Calibration can be done manually, but requires extensive analysis and reprogramming for each use, or automatically through software. One of the control registers contains the bit field that is responsible for setting manual or auto calibration functions. For our purposes, we are able to use the automatic calibration feature which continually compensates for changes in temperature after each reading, providing us with more stable measurements. The actual automatic calibration is possible because of the use of a high-accuracy 32,768 kHz oscillator as a reference to the propagation delays. The automatic calibration capability is controlled by a single bit in the control registers of the GP21. To activate auto calibration, a value of 0 must be written to the NO_CAL_AUTO bit of Reg0. This is done through SPI communication via a microcontroller.

Our application call for the GP21 to be configured into measurement mode 1, which allows for measurement ranges from 3.5ns to 2.5µs which corresponds to measuring distances from 0.5m up to 375m. Measurement mode 2 allows for measurement ranges from 500ns up to 4ms, corresponding to distances of 75m up to 60km. These ranges were calculated using the following formula:

$$d = \frac{c * t}{2}$$

Clearly measurement mode 2 is capable of ranging at farther distances, though it is unrealistic to think that our elementary optics systems and relatively low-powered laser could attain such distances. However the distances capable of being measured in mode 1 are well within the specifications of our design, and actually allow us to exceed our initial expectations. To configure the GP21 into the correct mode, we must use a microcontroller to write to the MESSB2 bit of Reg0 on the GP21. The default value in MESSB2 is 1, which is measurement mode 2, so it must be changed to 0.

2.3.2 Microcontroller

Choosing the correct microcontroller for our design is one of the most fundamental decisions in realizing our final product. Though there are countless microcontrollers on the market, and it is very reasonable to believe that this project could be realized with almost any of them, we still had a somewhat difficult time narrowing down the parts to our final decision. We knew that it must support SPI communication in order to communicate with our TDC and that it needed a relatively high clock speed for speedy functioning. We also needed to choose a microcontroller that had a sufficient support community for when we ran into trouble while programming the device. For that reason, we decided that we needed not only a right microcontroller, but the right development board as well. Our top considerations were immediately the Arduino boards and their Atmel chips, as well as the Texas Instruments boards and their MSP series of microcontrollers. Both of these boards, along with their corresponding processors, have a large community base with plenty of support available on the internet.

Micro-Controller	Clock Speed	Core Size	I/O Pins	Package Size	RAM	SPI Interface	Operating Voltage	Price
ATmega 328	20 MHz	8 bit	23	Dip-28	2kB	Yes	1.8-5.5V	$6.27
MSP430 G series	16 MHz	16 bit	10	Dip-14	128 Byte	Yes	1.8-3.6V	$1.87

Table 2.3.3

Development Board	Micro-Controller	Operating Voltage	PC Connection
Arduino Uno	ATmega328	5V	USB ab
Arduino Nano	ATmega328	5V	Mini USB
TI Launchpad	MSP430G	3.3-3.5V	Mini USB

Table 2.3.4

As it stands now, the microcontroller that we are planning on using is the ATMEL chip, the ATmega328, because it is compatible with the Arduino development kits. The deciding factor wound up being the extensive support community and availability of open source coding for the Arduino boards, as the one thing our design group lacked is experience in programming. The Arduino's wide support base made learning how to program with it extremely easy; and we were able to begin completing their example code immediately to apply what we learned to our project. We decided upon the Arduino Uno model because of the ease with which it could be manipulated to best suit our project goals. The Arduino Nano has almost as much functionality, but is a little more difficult to work with due to its size. The Arduino Uno board has the output and input pins of the ATmega328 configured like a breadboard for easy manipulation during prototyping and circuit building.

2.4 Power System

When designing the power system for our device, there are many factors to consider when it comes to choosing the type of system needed. First, we must consider the nature of our device. We have chosen to create a portable device that will be able to determine the distance from a target and the temperature of said target, thus, we must look at powering our device with batteries. Also, because the device must be mobile, the battery(s) that we choose must not weigh too much for the device to be comfortable to handle. Anything past a couple of pounds will become uncomfortable to hold after more than a few minutes of use. Next we must consider price. We must choose a technology of battery that will not cost a large percentage of our overall budget. Our power system, lastly, must power our device for an appropriate amount of time. Once we have figured out our load current, we will be able to consider what each battery technology can run (voltage, milliamp hours, discharge rate, etc.).

2.4.1 Batteries

A battery is a device that converts chemical energy directly into electrical energy. It consists of a number of voltaic cells, each voltaic cell containing two half cells connected in series. One of the half cells includes electrolyte and the electrode to which anions migrate, also known as the anode. The other half cell includes electrolyte and the electrode to which cations migrate, also known as the cathode. The half cells are split up within the battery by a thin barrier that keeps the electrolyte from mixing but allows the anions and cations to flow.

There are two types of batteries. There are primary batteries, which are designed to be used once and then be disposed of. The other types are secondary batteries, which are designed to be recharged and available for multiple future uses. Batteries come from in many sizes, from miniature cells that power hearing aids to banks of batteries the size of rooms that provide standby power for computer data centers. Below is a table of the two main battery types, primary batteries, and secondary batteries.

Cell Type	Cell Voltage(V)	Anode Material	Cathode Material	Main Electrolyte Material
		Primary Batteries		
Zinc Carbon	1.5	Zinc	Manganese dioxide	Ammonium/Zinc chloride
Zinc Chloride	1.5	Zinc	Manganese Dioxide	Zinc Chloride
Alkaline	1.5	Zinc	Manganese dioxide	Potassium hydroxide
Oxy Nickel Hydroxide	1.7	Zinc	Manganese dioxide/ nickel oxyhydroxide	Potassium hydroxide
Lithium	1.0-3.6	Lithium	Iron sulfide	Lithium salts in ether
Mercuric Oxide	1.35	Zinc	Mercuric oxide	Potassium hydroxide
Silver Oxide	1.55	Zinc	Silver oxide	Potassium hydroxide
		Secondary Batteries		
Nickel Cadmium	1.25	Cadmium	Nickel hydroxide	Potassium hydroxide
Lead Acid	2.0	Lead	Lead dioxide	Sulfuric Acid
Nickel Metal Hydride	1.5	Hydrogen storage metal	Nickel oxide	Potassium hydroxide
Nickel Zinc	1.65			
Lithium Ion	3.6	Lithium	Iron sulfide	Lithium salts in ether

Table 2.4.1

Zinc-carbon cells, also known as Leclanché cells, were invented by Georges Leclanché in 1866. They have been widely used because of their relatively low cost. Zinc-carbon batteries were also the first batteries widely available for household use. The battery has a low cell energy density and the voltage drops over the use due to a drop in electrolyte concentration around the cathode. The battery can provide a current large enough to power most portable devices. It also has a short shelf life because of the chemical makeup of the battery itself. The Zinc is attacked by the ammonium chloride and can corrode the battery and the device it’s in.

When an **alkaline** electrolyte instead of a mildly acidic electrolyte, is used in a normal zinc-carbon battery, it is called an “alkaline” battery. Alkaline batteries are able to produce a lifetime of five to six times longer than its zinc-carbon predecessor. Alkalines made up for a large percentage of batteries purchased in the home before rechargeable batteries became more prevalent.

Nickel-cadmium cells are the most commonly used rechargeable batteries to be found in a household. They are used for power small appliances like garden tools, remote controls, and other small electronics. Nickel cadmium cells offer high currents at relatively constant voltages and are very rugged batteries. Nickel-cadmium batteries also tolerant to inefficient usage cycles, that is to say, a few cycles of discharge and recharge can often return one of these batteries back to nearly full memory. On the down side, Nickel-cadmium batteries are pretty expensive. Cadmium is an expensive metal and is also toxic, making the price high.

Nickel-metal hydride cells are the fruits of scientists researching an alternative to cadmium made cells. The nickel-metal hydride cell can last 40% longer than the same sized nickel-cadmium battery and have a life span of up to 600 recharge cycles. These characteristics make it useful for high energy devices like laptops, cellular phones, video cameras, digital cameras, etc. These batteries' downside is their high self-discharging rate and their cost.

Nickel-zinc cells are another alternative to using cadmium electrodes. Though nickel-zinc batteries offer a promising yield of output energy, the cell has some unfortunate performance limitations that prevent the cell from having a lifetime of over 200 charges. When a nickel-zinc cell is charging, the zinc redeposit's in random, causing the electrode to become misshapen and eventually leads to the failure of the cell.

Mercuric oxide cells have high energy density and a completely flat voltage profile, closely resembling silver oxide cells. These mercuric cells are also ideal for specialty batteries. Unfortunately, the main component, mercury, is relatively expensive and is dangerous to humans when exposed, and is also toxic to the environment.

Silver oxide cells have a relatively high energy density and an almost completely flat voltage profile. Because of the cost, silver oxide technology is limited to use in specialty batteries. However, silver oxide batteries can provide higher currents for longer periods of time than other specialty batteries, which is a good benefit that also sends silver oxide into the realm of use in specialty batteries.

Lithium and Lithium Ion battery technology is promising due to its high electro-positivity. The cells usually have a nominal voltage rating of 3 volts. These battery technologies boast batteries that are light in weight, have a low per-use cost, and have higher and more stable voltages. Unfortunately, the same chemicals that make the batter so great make the battery a danger. Many of the inorganic components in the battery are destroyed by the lithium ions and, on contact with water, create hydrogen, which can ignite or cause excess pressure in the cell, causing it to blow up. Lithium primary batteries are generally seen as the button shaped silver batteries usually found in watches, computers, calculators, and some other electronics. These batteries can last three times longer than their alkaline counterparts, but unfortunately also can cost almost three times as much. In general, secondary lithium ion batteries have a good high power performance, excellent shelf life, and better lifetime than nickel-cadmium. Unfortunately, they have a higher initial cost, and the total energy available per usage cycle is somewhat less.

Lithium titante cells are essentially lithium ion cells that have been modified to be able to handle a faster recharge time. A lithium titante cell is a modified lithium ion battery that uses lithium titante nanocrystals on the anode instead of carbon. This gives the surface area of the anode about 100 square meters per gram, compared to 3 square meters per gram of its carbon counterpart. This allows electrons to leave and enter the anode more quickly, allowing recharging to be much faster and provides higher current when need be. The disadvantage is that lithium titante cells have a lower nominal voltage and energy capacity than conventional lithium ion battieries. Experts believe that this technology, after it has had time to be matured and researched, will be the battery of choice to power future electric cars, because of its ability to be charged quickly.

Perhaps the largest place batteries are needed is in the household. In a given household, there are many, many, extremely important devices running in the house that are running off a battery. Every day, in our houses, we can come in contact with up to 50 devices that use batteries daily. Devices like alarm clocks and fire alarms are necessary items we use in day to day life and take for granted the fact that they use batteries and must be maintained to keep us safe and responsible waking up. There are also luxury items in the house that run off battery. Our laptops, remote controls, and mp3 players must all run off battery also. Household batteries most often come in five forms. There is your most common, everyday use, cylindrical cells; they come in four sizes, from smallest to largest, AAA, AA, C, D. There is also a 9v, rectangular in shape battery. These batteries are often used in higher drain devices and larger devices. Below is a table that illustrates the different sizes of household battery, their nominal voltage output, and their dimensions. As previously discussed, the most common primary household battery is the alkaline battery, and the most used secondary battery in households is nickel-metal hydride.

Household Batteries		
Size	Voltage (V)	Shape and Dimensions
AAA	1.5	Cylindrical, 44.5 mm tall, 10.5 mm diameter.
AA	1.5	Cylindrical, 50.5 mm tall, 14.5 mm diameter.
C	1.5	Cylindrical, 50.0 mm tall, 26.2 mm diameter.
D	1.5	Cylindrical, 61.5 mm tall, 34.2 mm diameter.
9 Volt	9	Rectangular, 48.5 mm tall, 26.5 mm wide, 17.5 mm deep.

Table 2.4.2

When you buy batteries, you are generally leaving the house to find a quick change of batteries for your remote control or maybe your mp3 player and the batteries above are what you are looking for. Of course there are other types of battery found in households. There are also cylindrical cells that you may find in some portable devices, but mainly watches.

2.4.2 Charging

Charging of a battery occurs when a voltage or current is fed into the battery terminals in reverse. Instead of draining the battery like would normally happen when hooked up correctly, the current or voltage feeds backwards into the battery, forcing upon it a charge that holds as long as the battery technology is a secondary type and is not damaged. On a chemical level, the electrons are able to re-seat themselves back within the anode.

The ability to charge the power source is an important decision for groups to look into while creating their prototypes. The decision to build a charging circuit into your prototype extends beyond saving money on batteries. It is a great way to ensure your project is always going to be powered so there’s no down time scrambling to find new batteries. Creating a charging circuit for your power supply also demonstrates your knowledge in the subject of power systems.

Types of Charging

There are many battery charging methods, leading to many different types of battery charger. Because there are so many batteries that fit so many different needs and applications, there are several methods of charging created to maintain all these different batteries for their chosen application. Below I will discuss a few of the most common battery chargers out there. Choosing a correct battery charger for the battery type and application it is used for is very important, as can be seen from the following.

A **simple** battery charger works by supplying a constant DC or pulsed DC power source. A simple charger does not alter its output based on time or current charge on the battery. Because of their simplicity, simple chargers are very inexpensive, but there is a tradeoff for it being inexpensive. Typically, it takes a long time for a simple charger to fully charge a battery. Also, if a battery is left in a simple charger too long after reaching full capacity, it will weaken or even destroy the battery.

A **trickle** battery charger is typically a low current battery charger (500-1500mA). A trickle charger is generally used to charge batteries with small capacities (2-30 amp hours). This type of battery charger is also used to maintain larger capacity batteries, such as those found in cars, boats, RV's, and other vehicles. In these larger applications, the small current provided is only enough to provide maintenance to the battery. Depending on how the charger is built, often times trickle chargers can be left connected to the battery without ever needing to disconnect it. These chargers that never need to be disconnected are referred to as smart or intelligent chargers.

Inductive battery chargers use electromagnetic induction to charge batteries. The charger sends electromagnetic energy through inductive coupling to an electrical device which then stores that energy in the battery. This is done without the need for metal contacts between the charger and battery. This technology is often seen in electric toothbrushes and the new "charge mats" that energizer and some other companies have released to allow you to set your device on the pad and it charge. Because there is no electrical contact on the battery, there is no risk of electrocution.

Fast chargers make use of the control circuitry in the batteries that are being charged so that the battery can be rapidly charged without damaging the cells' elements. Most of these chargers have a fan on board to keep the temperature of the cells from reaching dangerous levels. Most fast chargers are capable of being used overnight, even if the battery does not have control circuitry built in to manage the charging. Some fast chargers can fast charge any NiMH battery even if it does not have the control circuit built in.

Pulse chargers use pulse technology, which is where a series of voltage or current pulses are fed directly into the battery. The DC pulses have a strictly controlled rise time, pulse width, pulse repetition rate, and amplitude. With pulse charging, high instantaneous voltages can be applied without overheating the battery. This type of charging has been said to work for any size, voltage, and chemistry of battery.

Solar energy chargers convert light energy into DC current. They are generally portable, but for larger applications, can be fixed mount. Fixed mount solar chargers are known as solar panels, which are the same solar panels you may see on school campuses, people's houses, and many other places. Fixed mount solar chargers are usually connected to electrical grids whereas portable solar chargers are used off the grid in cars, boats, RV's, etc. Portable solar chargers can be used in applications where there is little solar energy because of their applications. They are generally used in trickle charging, so they are more used to maintain a power system, although some ARE made with high enough wattage to be able to charge a battery from dead.

USB-based chargers are able to exist because the universal serial bus (USB) provides a five volt power supply. With USB 2.0, the still current standard for computers, five unit loads can be drawn. A unit load is defined as a maximum of 100mA on USB 2.0. This means with 5 total loads, USB 2.0 can deliver 500 mA from the port. USB charging is mainly used for portable devices such as cellular phones and mp3 players. Because of the convenience and the amount of USB 2.0 devices out there, USB was at one point the standard for charging cellular phones.

Universal battery charger-analyzers are the most sophisticated type of charger. They are used in critical applications such as military or aviation batteries. These heavy duty automatic "intelligent" chargers can be programmed to perform complex charging cycles specified by the battery provider. The best are universal, that is to say can charge all battery types, and include automatic testing and analyzing functions too.

Charge Rate

Each battery is able to charge at different rates, however all these rates are related the same way. Charge rate is often denoted as "C" or "C-rate" and signifies a charge or discharge rate equal to the capacity of any one battery technology in one hour. For example, for a 1.5 amp hour battery, C=1.5A. That is to say, there must be a flow of current rated at 1.5 amps fed into the battery for an hour to return such a battery to a full charge. For a charge rate of C/2 (1.5/2 = .75A), .75 amps must be applied for two hours to completely charge the battery. If the charge rate were 2C (2*1.5 = 3.0), then a current of 3 amps must be applied and the battery will charge in thirty minutes. These charge rate equations are assuming the battery would be able to accept such a charge rate, and also assumes that the batter is 100% efficient in storing the charge.

Charging Ni-Cd/Ni-MH

Slow Charge:
Slow charging is defined as being the ability to keep a charging current on the batter indefinitely without damaging the cells, sometimes referred to as trickle charging. The maximum rate of trickle charging is dependent upon both the battery chemistry and cell construction. Thus, the maximum rate of trickle charging changes for each battery technology.

Most nickel cadmium batteries will easily tolerate a sustained charging current of C/10 (1/10 the cell's amp/hour rating) indefinitely without doing damage to the cell. At this rate, C/10, the typical recharge time would be around twelve hours. There are also high-rate Ni-Cd's (optimized for higher charging rates) that can tolerate a continuous trickle charge current as high as C/3, bringing the time for a full charge to around 4 hours. Slow charging is beneficial in that it does not require any end of charge circuitry to let the user know that the battery is done charging. This is of course attributed to the fact that no matter how long you leave the battery on the charger, there will be no damage to the cells.

Fast Charge:
Fast charge for the two batteries mentioned is defined as having a one hour recharge time, which corresponds to a charge rate of 1.2*C. Fast charging can only be done safely between 10 degrees and 40 degrees Celsius, with the optimal charging temperature being 25 degrees Celsius. There are also some high-rate Ni-Cd cells that are optimized to tolerate a charge rate of 5*C, allowing for a fifteen minute charge time.

Both batteries present hazards if they are fast charged for excessive lengths of charge. The constant current being applied to the battery quits causing a reaction in the battery and only begins to produce heat and pressure in the cell. If the pressure reaches too high a vent should open, releasing some of the gas, but if there are any problems and the vent does not open, the battery will explode and leak chemicals.

The Ultimate Charger:
Sometimes the most important issue is the lifetime of the batteries or the total lifetime cost of the power system. The following specs will ensure that both needs are met.

1. Soft start. If the temperature is above 40 degrees Celsius or below zero degrees Celsius, start with a charge of C/10. If the discharged battery is

voltage is above 1.0 volts per cell, start with a charge of C/10. If the discharged battery has a voltage that is above 1.29 volts per cell, also use a C/10 charge.

2. Optional: If the voltage of the discharged battery is above 1.0 volts per cell, discharge it until it is below 1.0 volts per cell and then proceed to submit it to a rapid charge.
3. Rapid charge at 1C until the temperature reaches 45 degrees Celsius, or dT/dt indicates a full charge on the battery.
4. After terminating the fast charge, slow charge the battery at C/10 for four hours to ensure that there is a full charge on the battery.
5. If the voltage climbs to 1.78 volts per cell without terminating the charge itself, then the user must terminate the charge.
6. If the time on fast charge exceeds an hour and a half, then the user must terminate the charging cycle themselves.
7. If the battery never reaches a condition where the fast charge time starts, then time out the slow charge after fifteen hours.

Charging Lithium ion

Constant Voltage Charging:
A constant voltage charger sources current into the battery in an attempt to force the voltage to a certain value. Once this voltage is reached, the charger will source only enough current to keep the voltage of the battery at this constant desired voltage. Major manufacturers of lithium ion batteries recommend 4.2V +- 50 mV as the ideal set voltage.
The charging cycle of lithium ion batteries is split into two phases. The first phase is the current limit phase. This is the phase where the maximum charging current is surging into the battery because it is below the set voltage level. About 65% of the overall charging is done during the current limit phase. Assuming a 1C charging current, this portion of the charging would have a maximum time of forty minutes. The second stage, the constant voltage stage, is where the batter has achieved its set voltage and is working to maintain it. This means the charger is doing its job of lowering and raising the current just enough to maintain the voltage. This phase of the charging, 35% takes about twice as much time as the first stage, 65%.

2.4.3 Voltage Regulation

There are two types of voltage regulators. The first type is called a linear regulator. A **linear regulator** is a voltage regulator based on an active device operating in its “linear region” or passive devices like zener diodes operating in their breakdown region. The device imitates a dynamic resistor continuously adjusting a voltage divider circuit to maintain a constant output voltage. Linear regulators exist in two forms, series and shunt regulators.

The **series regulator** provides a path from the supply voltage to the load through a variable resistance. The power dissipated by the regulator is equal to the power supply's output current multiplied by the voltage drop in the regulating device.

The **shunt regulator** provides a path from the supply voltage to the ground through a variable resistance. The current through the shunt regulator is diverted away from the load and flows uselessly to the ground, making shunt regulators even more inefficient than the series regulator.

A **switching regulator** rapidly switches a series device between off and on. The duty cycle of the switch determines how much charge is transferred to the load. This is controlled by a similar feedback mechanism found in linear regulators. Because the switching regulator is either off or fully conducting, there is little to no power dissipated and therefore little to no heat, making switching regulators efficient. Switching regulators are also able to output a higher voltage than is input to the regulator and also can put out both a negative and positive signal, something that linear regulators cannot do.

Now that I have discussed both types of regulators, I will compare the two in an effort to further breakdown the usefulness of each type.

- Linear regulators are best used when low output noise and low radiated noise is required.
- Linear regulators are best used when a fast response to input and output disturbances is required.
- At lower power levels, a linear regulator will be cheaper in parts to create and the design will occupy less printed circuit board space than a switching regulator.
- Switching regulators are best when power supply efficiency is important, like in computer power supplies. However, linear regulators ARE more efficient in certain cases. Cases which require the use of, say, a constant 5v input, then a simple linear regulator will work. The complexity and expense of a switching regulator in such a case will be a complete waste and take up more space and money than is worth.
- Switching regulators are required hen the only power supply is a DC voltage and a higher output voltage is required.
- At levels of power above a few watts, switching regulators are cheaper. This is due to the extra power and the fact that the switching regulator doesn't have to worry about dealing with heat dissipation, the cost of removing heat is not there.

Since batteries do not supply a constant voltage over the life of their charge, we must ensure that our devices that need a constant voltage get that needed voltage. To do this, we will use two linear voltage regulators. We are using a chip that requires a constant +-5v, so we must find a chip that will allow us to supply that constant voltage. Below are two chips that we have considered will fit our needs. The use of both regulators should supply our +-5v supply.

Figure 2.4.1 is an image of a LM7805 voltage regulator, which is one of the regulators that we will be employing in our design. At the top of the chip rests the heatsink, where the excess heat from stepping the voltage down/up will dissipate to.

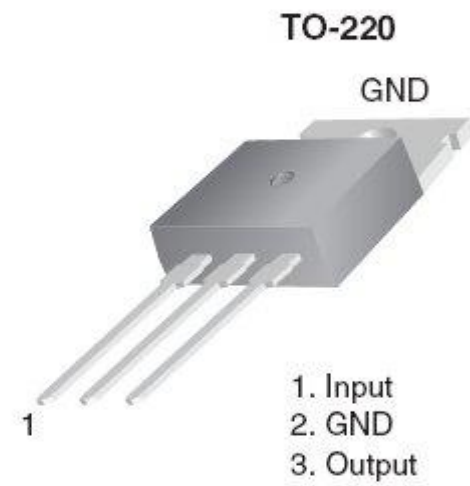


Figure 2.4.1

As we can see, these are simple three pin regulators. Pin 1 is hooked to our battery, pin 2 is grounded, and pin 3 will hook to our devices where we need the regulated voltage to become and input. Each pin layout is different, however, so the above image and pin layout cannot be used for every regulator, and the datasheet should be referenced for the correct pin layout.

LM7805

The chip, made by Fairchild Semiconductor, is one in a series of three terminal positive regulators available in a range of fixed output voltages. The LM7805 is the chip in the series that is capable of outputting +5v constantly, fulfilling our need in a positive voltage regulator. The chip uses internal current limiting and thermal shutdown to ensure the chip safely shuts off if it is pushed outside of nominal operating conditions. If properly heat sinked, the chip is capable of delivering over 1A of output current. Since this specific chip seems to be of a solid build quality and fits our needs perfectly on the voltage regulation, we believe it to be perfect for our power system. In table 2.4.3 is a list of the LM7805's electrical specifications.

Electrical Characteristics (LM7805) Condition unless otherwise specified: -40°C<Tj<125°C Io=500mA, Vi=10v, Ci=0.1uF							
Symbol	Parameter	Conditions		Minimum	Typical	Maximum	Unit
Vo	Output Voltage	Tj = +25°C		4.8	5.0	5.2	V
		5mA<=Io<=1A, Po<=15w, Vi=7v to 20v		4.75	5.0	5.25	
Regline	Line Regulation	Tj = +25 °C	Vo = 7v to 25v	-	4.0	100	mV
			Vi = 8v to 12v	-	1.6	50.0	
Regload	Load Regulation	Tj = +25 °C	Io = 5mA to 1.5A	-	9.0	100	mV
			Io=250mA to 750mA	-	4.0	50.0	
Iq	Quiescent Current	Tj=+25°C		-	5.0	8.0	mA
ΔIq	Quiescent Current Change	Io=5mA to 1.5A		-	0.03	0.5	mA
		Vi=7v to 25v		-	0.3	1.3	
ΔVo/ΔT	Output Voltage Drift	Io=5mA		-	-0.8	-	mV/°C
Vn	Output Noise Voltage	f=10Hz to 100kHz, Ta=+25°C		-	42.0	-	uV/Vo
RR	Riple Rejection	f=120Hz, Vo=8v to 18v		62.0	73.0	-	dB
Vdrop	Dropout Voltage	Io=1A, Tj=+25°C		-	2.0	-	V
Ro	Output Resistance	f=1kHz		-	15.0	-	mΩ
Isc	Short Circuit Current	Vi=35v, Ta=+25°C		-	230	-	mA
Ipk	Peak Current	Tj=+25°C		-	2.2	-	A

Table 2.4.3

The LM7805 is one of the most commonly used voltage regulators, and for our application, it fits and makes perfect sense to use. Our 9V battery will drive the proper input voltage. The approximate 1 amp capable of being delivered is also more than enough current for driving the parts connected.

LM7905

The chip, made by Fairchild Semiconductor, is one in a series of three terminal negative regulators available in a range of fixed output voltages. The LM7905 is the chip in the series that is capable of outputting -5v constantly, fulfilling our need in a negative voltage regulator. The chip uses internal current limiting and thermal shutdown to ensure the chip safely shuts off if it is pushed outside of nominal operating conditions. If properly cooled, the chip is capable of delivering in excess of 1A of output current. Since this specific chip seems to be of a solid build quality and fits our needs perfectly on the voltage regulation, we believe it to be perfect for our power system. Below is a list of the LM7905's electrical specifications.

Electrical Characteristics (LM7905) Conditions unless otherwise stated: Vi=-10v, Io=500mA 0°C<=Tj<=+125°C, Ci=2.2uF						
Symbol	**Parameter**	**Conditions**	**Minimum**	**Typical**	**Maximum**	**Units**
Vo	Output Voltage	Tj=+25°C	-4.8	-5.0	-5.2	V
		Io=5Ma to 1A, Po<=15w, Vi=-7v to -20v	-4.75	-5.0	-5.25	
ΔVo	Line Regulation	Tj=+25°C, Vi=-7v to -20v	-	5	50	mV
		Tj=+25°C, Vi=-8v to -12v Io=1A	-	2	25	
		Vi=-7.5v to -25v	-	7	50	
		Vi=-8v to -12v Io=250mA to 750mA	-	7	50	
Δvo	Load Regulation	Tj=+25°C Io=5mA to 1.5A	-	10	100	mV
		Tj=+25°C Io=250mA to 750mA	-	3	50	
Iq	Quiescent Current	Tj=+25°C	-	3	6	mA
Δiq	Quiescent	Io=5mA to 1A	-	0.05	0.5	

	Current Change	Vi=-8v to -25v	-	0.1	0.8	mV
Δvo/ΔT	Temperature Coefficient of Vd	Io=5mA	-	-0.4	-	mV/°C
Vn	Output Noise Voltage	f=10Hz to 100kHz Ta=+25°C	-	40	-	uV
RR	Ripple Rejection	F=120Hz Δvi=10v	54	60	-	dB
Vd	Dropout Voltage	Tj=+25°C Io=1A	-	2	-	V
Isc	Short Circuit Current	Tj=+25°C Vi=-35v	-	300	-	mA
Ipk	Peak Current	Tj=+25°C	-	2.2	-	A

Table 2.4.4

Since the input voltage is required to be negative, we had to employ the second 9V battery since there are only two terminals, and for us to use a positive and negative voltage from one battery, we would need a third terminal, which isn't the case.

LD1117V33

The LD1117 is a series of low drop voltage regulators able to provide up to 800 mA of output current. The V33 is the 3.3V output regulator of the series. The chip contains internal current and thermal limiting to prevent the chip from failing. Below is a table of the electrical characteristics of the LD1117V33 voltage regulator.

Electrical Characteristics (LD1117V33) Conditions unless otherwise specified: Tj = 0 to 125°C, Co = 10uF						
Symbol	Parameter	Test Condition	Min.	Typical	Max.	Units
Vo	Output Voltage	Vin=5.3V Io=10mA Tj=25°C	3.267	3.3	3.333	V
Vo	Output Voltage	Io=0-800mA Vin=4.75-10V	3.235	-	3.365	V
ΔVo	Line	Vin=4.75-15V	-	1	6	mV

	Regulation	Io=0mA				
Δvo	Load Regulation	Vin=4.75 Io=0-800mA	-	1	10	mV
Δvo	Temperature Stability	-	-	0.5	-	%
Δvo	Long Term Stability	1000 hrs Tj=125°C	-	0.3	-	%
Vin	Operating Input Voltage	Io=100mA	-		15	V
Id	Quiescent Current	Vin<=15V	-	5	10	mA
Io	Output Current	Vin=8.3V Tj=25°C	800	950	1200	mA
eN	Output Noise Voltage	B=10Hz-10Khz Tj=25°C	-	100	-	uV
SVR	Supply Voltage Regulation	Io=40mA F=120Hz Tj=25°C Vin=6.3V Vripple=1Vpp	60	75	-	dB
Vd	Dropout Voltage	Io=100mA Io=500mA Io=800mA	-	1 1.05 1.1	1.1 1.15 1.2	V V V
-	Thermal Regulation	Ta=25°C 30ms pulse	-	0.01	0.1	%/W

Table 2.4.5

The LD1117V33 will share a 9V battery with the LM7805. Unfortunately, the load on this battery will be higher, but it won't matter much since we can hot-swap batteries at any time we need. This regulator will be used to power the single raid of the TDC-GP21.

DE-SW050

The DE-SW050 is a switch mode voltage regulator designed to be the easiest possible way to add the benefits of switch-mode power to our project. The DE-SW050 will allow us to take a higher input voltage (I.E. our 9V battery) and step it down to a 5V output in an efficient manner, that is to say that with any excess power dissipated by the chip, it will not all be transferred into heat. The DE-SW050 is pin-compatible with the common 78XX family made by Fairchild Semi. They have integrated decoupling capacitors, so external capacitors are generally not necessary. The DE-SW0xx family operates over a wide range of input voltages, from (Vout = 1.3 volts) all the way up to 30 volts. The chip is efficient up to 87% and the ripple is less than 2%. The DE-SW050 is considered a drop-in replacement for the LM7805 in applications where the LM7805 is dissipating too much heat or a larger heat sink cannot be used or is undesirable to be used in the application. Below is a table of the typical performance characteristics we can expect from the DE-SW050.

Performance Characteristics (DE-SW050)			
Characteristic	**Minimum**	**Typical**	**Maximum**
Input Voltage	Vout +1.3V	-	30V
Output Current (RMS)	0A	-	1A
Pulsed Output Current (5 sec)	-	-	1.5A
Output Ripple	30mV	70mV	100mV
Efficiency	65%	83%	87%
Transient Response in Load Regulation	-	4%	-
Power Dissipation	100mW	800mW	1.2W
Power Output in Still Air	0W	-	5W
Quiescent Current Draw (Vin=12v)	-	16mA	-
Switching Frequency	230kHz	270kHz	290kHz

Table 2.4.6

As can be seen from the table, this switching regulator could very well take the place of our LM7805 depending upon how much heat the chip will put off when our device is being built. Unfortunately, the DE-SW050 is a much more expensive regulator than the LM7805 we currently plan to employ. This is not to say that in general a switch-mode regulator costs more, it is just at these low power levels, the materials used in the linear regulators happen to be cheaper. As previously mentioned, if the heat dissipated by the 7805 looks like it may damage our internals, a switch to the much more efficient and much more expensive DE-SW050 will suffice.

2.5 LCD Output

Choosing an LCD for our project can be viewed in many different ways. Our individual goals for what each person may think we need for the LCD could be very different. Fortunately, there are guidelines for picking this sort of exciting technology out. Day to day, we see large use LCD technology deployed in our tv's, cellular phones, computers, pretty much everywhere. For our application though, we really should stay cost effective because of the real usage the LCD will see. All we need to do is print a few lines for the end user who is using the device to be able to read out the data that the device itself is measuring. All we technically need is four rows eight columns to stay safe. Since we will be printing to the screen temperature and distance, they are really the only things that will need to be on each line. There is also the possibility of having a battery indicator, so we want to make sure that the LCD can print enough rows/columns if it is needed. Below, we will discuss advantages and disadvantages to different kinds of LCD.

2.5.1 Types of LCDs

The two main LCD technologies that are used by hobbyists and engineers alike are passive matrix and active matrix. The passive matrix LCD works by arranging the screen into a pattern of columns and rows in which each dot, or pixel, can be individually addressed to change its brightness. Color passive LCDs exist by using three different layers behind each pixel so that the color filters can be varied to display a combined color to the user. While these devices are easy to use and considered simple in design, the do have distinct disadvantages. Since they have a very low contrast in just displaying the character, they require the use of a backlight so that the user can see the value. This generally causes them to consume more power than other technologies available. They also have a slow response time and are not usually used for displaying videos or similar applications. The active matrix LCD overcomes many of these problems, but is far more advanced. Thanks to the thin film transistor (TFT) the active matrix LCD offers a brighter screen, faster response time, and can display over 256 colors at of time. These devices, being must more advanced, usually are accompanied by dedicated logic boards or even microprocessors whose sole job is to regulate the display.

2.5.2 Project Display Requirements

The main goal of the portable sensing field device is to measure both distance and temperature of a target. With this being the case, we won't need an active display. Using such a device would be very complicated to interface with the rest of the hardware and would be defiantly be “overkill”. We will most likely use a simple passive matrix display.

Range: XX m
Temperature: XX C

Shown above is the extent of what we will need to display on the LCD. Since at the most, that is 17 characters, we’ll need an LCD that is at least 17 characters wide with at least 2 rows. The HD44780 LCD from spark fun offers a 16x2 matrix display with adjustable brightness. This is a very simple device and is also fairly straightforward to interface with a microcontroller. Shown in the below code window is how one might interface with this LCD. Since the textLCD.h library is included and freely available, displaying text is virtually done with a single line of code.

```
#include "mbed.h"
#include "TextLCD.h"

TextLCD lcd(p15, p16, p17, p18, p19, p20); // rs, e, d4-d7

int main() {
    lcd.printf("Hello World!\n");
}
```

It is also important to note that the backlight is included with this device. The operation will utilize about 11 general I/O lines on the MCU.

Chapter 3: Design

3.1 APD Module

The following section regards the APD module design process. The APD module refers to all APD related circuitry components for the entire design. It will be treated as a ‘black box’ device with an input/output unless otherwise stated. The design of the APD module will be discussed below. Shown in **figure 3.1.1** is the overall block diagram of the APD module.

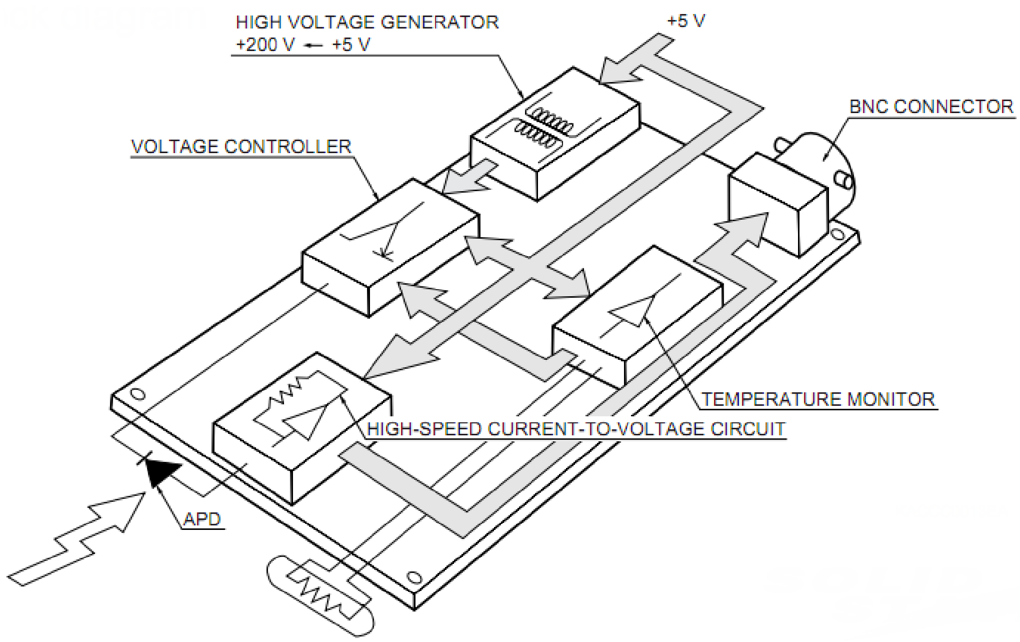


Figure 3.1.1: Reprinted with permission from Hamamatsu

The APD module is responsible for absorbing incident light of the proper wavelength and putting out an acceptable voltage with minimal distortion. One can see that the main components that must be designed are the HV supply, the temperature compensations circuit, the APD circuit, and the transimpedance amplifier.

Component Design

The APD module circuit will be one of the most important parts of the ranging system. Since this APD deals with such small signals, it is absolutely vital that the signal remain intact. The Hamamatsu S2381 APD has a peak wavelength pass-band at 800 nm. This is well within the range for our output laser which operates at 780 nm. The APD will be powered using its own independent DC-DC boost converter. This is required due to the high reverse biasing of the device to take advantage for the avalanche multiplication. If the DC-DC converter is set at 80 volts output, this will have a direct effect on the gain. This of course is heavily dependent on the ambient temperature of its surroundings. But given room temperature (25°C) this should yield a gain of 10. However, Hamamatsu's engineers recommended that for the best response for low light applications (laser range finders), the APD should be biased very close to its breakdown voltage; which for the S2381 is 150 volts. Shown in **figure 3.1.2** below is the bias voltage/gain characteristic of the S2381 device.

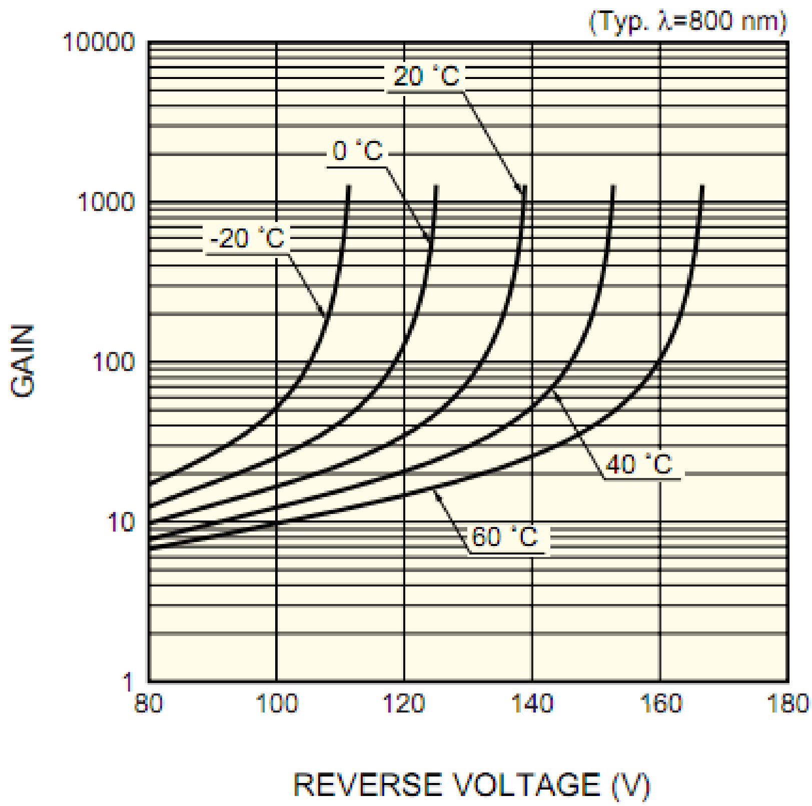


Figure 3.1.2: Reprinted with permission from Hamamatsu

Since the gain is temperature dependent, there are several different curves on the graph; where each represents the gain output for a change in +/- 20°C. Since this device is not being designed for extreme conditions, the main design will be focused around room temperature (20°C). The Hamamatsu avalanche photodiodes are limited to gains of below 200 due to the fact that increasing the bias too high will cause a series voltage drop across the substrate of the diode itself. For the scope and function of this APD module, we will be setting our gain (M) at 100. This is large enough to achieve a substantial current multiplication but at the same time, is far enough away from 200 that we do not need to worry about reaching the gain limitation of the diode.

Since the gain of the device is the parameter that determines the photocurrent; which directly affects the output voltage of the entire module, for function operation, it is absolutely essential that the gain remain as stable as possible. Like mentioned before, the APD gain is heavily dependent on its ambient temperature. So a small temperature change in the APD surroundings will cause the gain of the device to change. This is pictorially seen in the above image, where each curve is the gain characteristics at that constant temperature. So we want this device to be able to be operated in both, room temperature conditions (20°C), and say for instance, a very hot day in Florida (40°C), we must accommodate for these temperature changes in some way. The two most common solutions for gain variations due to changes in temperature is cooling the avalanche photodiode directly using a thermocouple and adjusting the APD bias voltage output due to changes in temperature. Cooling the APD directly would be an acceptable solution; however the thermocouple must be directly in contact with the silicon die. So this would require a completely different device to be purchased. These are available from Hamamatsu, but were all priced in the upper $800 range. This is well outside of our price margin; thus is not an option. So the only option that we have for gain variation control is using a high voltage bias supply that has the ability to change its HV output using some control reference voltage. This will allow us to design either an analog or digital solution that changes the reference voltage in response to temperature; consequently maintaining the gain at the most constant level. Since we are designing this APD module around room temperature conditions and for a regulated gain of M=100, we must first determine the bias voltage that should be output from the supply under room temperature conditions. Unfortunately, Hamamatsu does not have any kind of equation that governs the curves in figure 9; reverse voltage must be determined by approximation. For room temperature and a gain of 100, the APD requires a reverse biasing about of 134V. This biasing must change in accordance with temperature to achieve a stable gain output. This will require both an accurate and fast response control circuit. Shown in **figure 3.1.3** is how the bias voltage must change as the ambient temperature increases to keep gain stable at M=100.

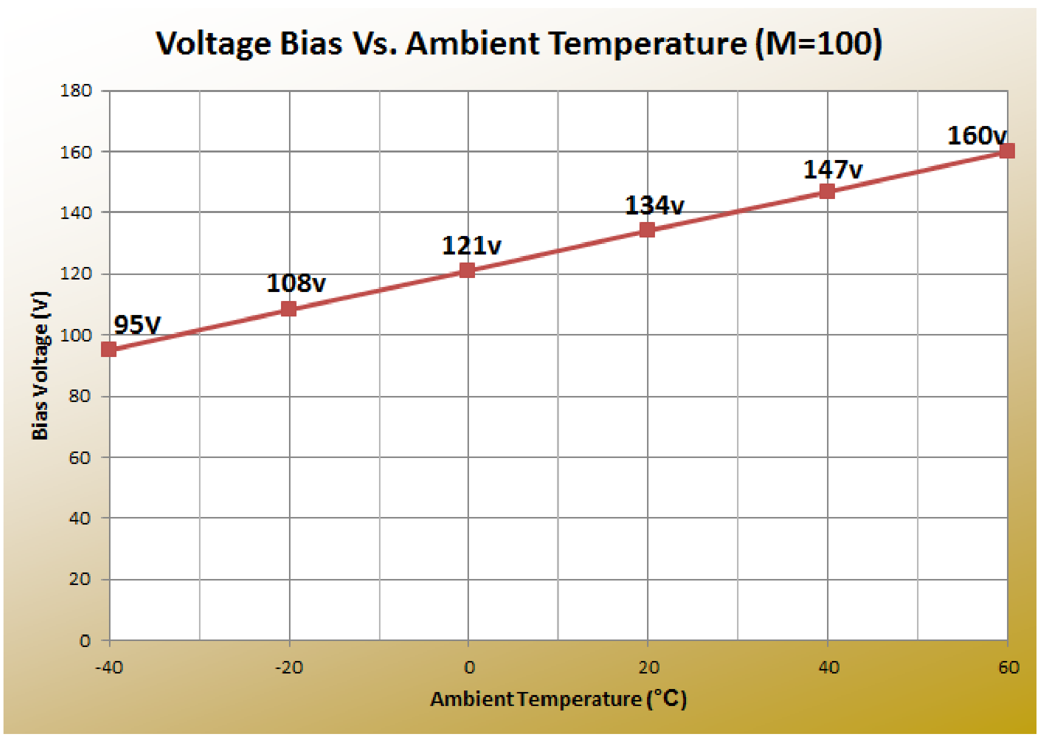


Figure 3.1.3

Each of the points on this linear curve is the voltage and temperature in which M=100, or the points in which the curves in figure 9 cross over the M=100 horizontal axis. This method can accurately predict what biasing values must be over a temperature range of -40°C to 60°C (-40°F to 140°F). This range is well within the operating conditions in which we intend to use this device.

So the next problem that we must ask ourselves is how does one go about automating the process of adjusting bias voltage of a high voltage supply without user input? Well the solution in a broad sense is rather simple, but a challenge to implement. What we need is a high voltage supply that has a control pin that allows the high voltage output to be adjusted given a DC reference voltage. This reference voltage is usually in the range of, or the same, as the input voltage to the HV supply. So this method allows for a voltage to change the output. This reference voltage can be either an analog solution or a digital method. A very simple solution would be to use a voltage divider connected to +Vcc where one of the resistors is a potentiometer. This however, would not be an automated process as it requires the user to adjust a knob to compensate for temperature changes. This method is also going to be must more inaccurate; the gain may be a bit more stable by manually adjusting it, but the user will not know exactly how much to turn the knob. The better and more difficult solution to this problem is to use a digital control interface. If we can take in a continuous, changing voltage using a thermistor that is actively transducing ambient temperature to a voltage signal, we can then turn it into a digital quantity and use that digital output to determine when, and by how much, the control voltage should change. This would effectively automate the process and stabilize the APD gain leading to more accurate and reliable range calculations.

APD Design

The next step in designing the output current of the device is finding out the responsivity of the S2381. From its datasheet it is found to be 0.5 A\W. This measurement is given at a gain of M=1. So for our particular biasing of 80 V, which yields an M of 10, makes the sensitivity equal to 5 A\W maximum at wavelengths of 800 nm light. The image shown in **figure 3.1.4** below is the APD peripheral interconnect circuit.

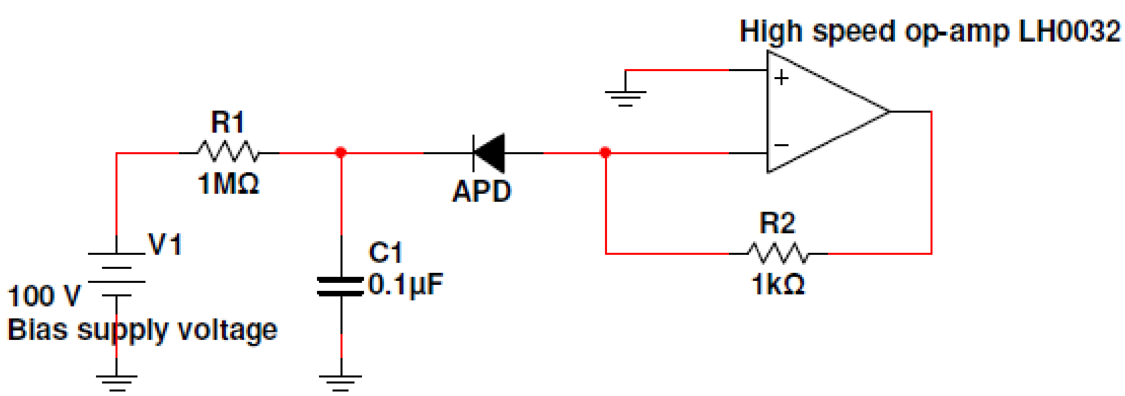


Figure 3.1.4

The bias supply voltage is the DC-DC boost converter. This has a high value resistor in series with it to limit the current going into the APD. The APD outputs a negative current that is somewhere on the order of 100nA-1mA. Since we can't use a photocurrent for comparative processing, it must be converted into a voltage. The op-amp is connected in as an inverting transimpedance amplifier.

$$Vo = -Id * R2$$

The output of the amplifier is described by the equation above. Since the current is already negative, we get a positive voltage that is directly proportional to our incident incoming light on Vo. Due to the feedback resistance R2; we get a much larger voltage in comparison to the output current from the APD. For example; a 1mA photocurrent passing through the transimpedance amplifier will translate to a 1V output. Due to the high operating speeds required by the nature of the speed of light, a high speed, low noise op-amp will be required for the transimpedance conversion. Picking the right op-amp will be a very careful process. Since we are dealing with such a dynamic signal, all must be considered. The most important parameters of the op amp for our application is the slew rate, the noise, and the bandwidth.

Bias Power Supply

The APD, being a photosensitive device, is not all that much different from a normal photodiode. The main difference and reason it is such a sensitive detector lies in the fact that it is reverse bias under such a high voltage. Typically in the range of anywhere from 100-300 V, there is a very large electric field present in the device when in operation. So that when an incident photon is absorbed and causes an electron-hole pair, it is quickly swept away at a very high drift velocity. This causes mechanical collisions with the lattice of the material; leading to impact ionization and thus creating a multiplication factor. With that being said, to properly design an APD circuit, the biasing is fundamental to its function operation.

There a several different options when it comes to creating a circuit that takes a lower voltage and ups it to a high voltage. The simplest method, that may come to mind for many, is using a step up transformer. This would normally be a very easy task to do, when working with alternating current. Since our main voltage source will be coming from a battery, we are dealing with DC. DC obviously is not able to be stepped up/down using a transformer; this doesn't mean that it can't be done however. One possible solution for using DC with a transformer is utilizing a sinusoidal oscillator. By taking the DC from the battery source and turning it into a sine wave oscillating at some frequency and feeding it into a transformer, a transformed voltage will be induced on the secondary winding of the device. This turn the peak to peak value of your sine wave at a higher magnitude; however the APD requires DC, so this AC must be retranslated back into DC using a rectifier and envelope detector. The circuit shown in **figure 3.1.5** is a Wein Bridge Oscillator.

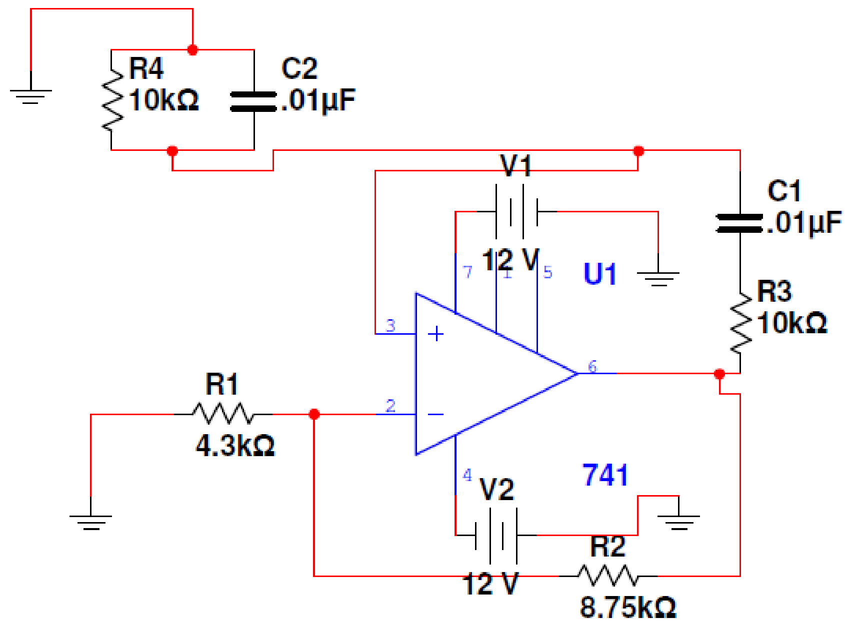


Figure 3.1.5

It is the simplest and best known circuit for generating a stable sinusoidal output. This particular circuit, using a NI-LM741 operation amplifier, simply takes +/-12V and turns it into a sine wave of about the same magnitude.

While building our own bias supply would be a great engineering experience, it would most certainly increase the size of our overall design. Since size and portability is one of our goals that we initially set for the project, we are better off using a prebuilt HV supply. The DC-DC HV supplies that are available for purchase do basically the same thing that was detailed above. They however, generally use surface mount parts and low profile transformers; allowing for the device packing to be very compact and efficient. Shown in **figure 3.1.6** is the generalized block diagram of the high voltage supply.

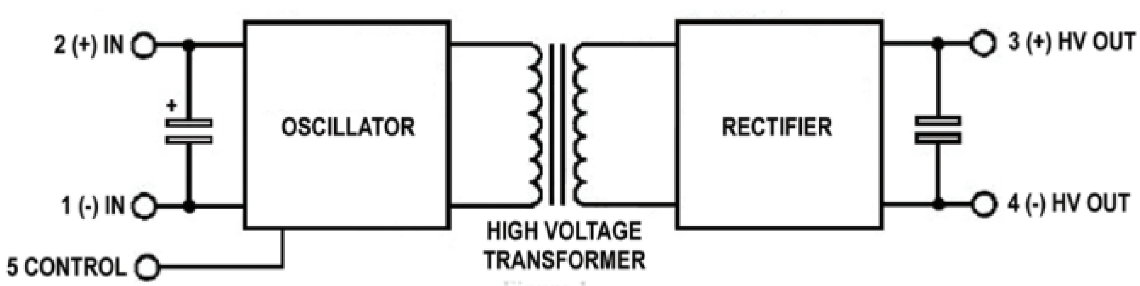


Figure 3.1.6: awaiting permission of use from EMCO HV

This particular image was taken from the A series low profile, high voltage model. The A series also has variable voltage control on pin 5 of its package. This pin takes in an analog voltage and changes its output accordingly. This is where the digital quantity from the thermistor will input to the bias supply. Shown in figure 3.1.7 is the package design and size comparison of the A series high voltage supply.

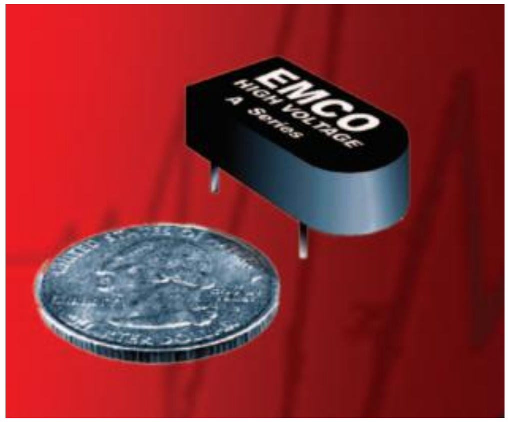


Figure 3.1.7: awaiting permission of EMCO

With physical dimensions of only 0.92L (23.37L) x 0.45W (11.43W) x 0.25H (6.35H) and a weight of 5.66g, the A series is ideal for compact portable applications.

There are several different design considerations that must be accounted for when picking out the right high voltage supply to use for biasing an APD. Since we want the ability to bias our APD with at least 150 volts, we need to make sure that the HV supply has a voltage output of at least that, or greater. The A series runs in intervals of 100v, so in using the A series supply, we would have to use the A02, which outputs 200v at maximum. Like mentioned before, since the A series device has a control pin, the 200v maximum is only going to be reached when the control voltage is at 100%. The A series model A has a rated output power of 1 watt. This is under full load conditions of maximum current draw of 5mA and maximum output voltage. The input current levels for the A02 are shown below:

	A Model – 1 Watt	
Vin	No-load	Full-Load
5 VDC	<100mA	<300mA
12 VDC	<50mA	<125mA
24 VDC	<25mA	<60mA

Table 3.1.1

The A series device comes in 3 different models all using a different input voltage. Since we will have a 5 volt rail local to the system, we obviously will want to use the 5 volt boost converter. Using this information and fundamental power calculations, the maximum power utilized by the HV supply is 1.5 watts.

BIAS SUPPLY AUTOMATED ADJUSTMENT - TEMPERATURE CONTROL

Since the APD needs to operate with a relatively constant gain, we must automate the bias voltage for the APD due to variations in the ambient temperature. In setting out to achieve such a task, we are obviously going to need a method in measuring the surrounding temperature in which the device is operating. From the research shown in chapter 2, the easiest and most cost effective technique is through the use of a thermistor. Pretty much all thermistors available can be purchased for less than a dollar or two and are exceptionally responsive to changes in its surrounding temperature by varying its resistance accordingly. Since this device changes its resistance as a function of temperature, the best way to generate a continuous voltage signal that is a function of temperature is to use a simple voltage divider. In using the local 5 volt rail as the supply voltage to the division, the thermistor effectively acts as the R_2 resistor and will generate a proportional, temperature varying voltage signal. It is also a good idea to use an output unity gain buffer on V_o. In doing this, the temperature dependent signal will be isolated from the 5V source on the voltage divider. Effectively allowing the voltage divider to operate undisturbed on matter what the current draw of where V_o goes to. Any additional current draw on that line will come from the +/- V_{cc} supply of the op-amp. At this point, we have a power supply independent, analog voltage that is changing with ambient temperature. We will need to add some digital control to this reading in order to be able to actively and logically change it so gain stays stable. To do this, we have two options:

- Send analog voltage to an ADC and isolated sub MCU within APD module
- Send analog voltage to main MCU (ATmega328); performing ADC and digital control within unit itself.

Since we are unsure of what method is the most efficient, we will detail both. For the method of the APD module using its own dedicated MCU, we will use the TI MSP430G2231. From TI's Launchpad wiki, the MSP430G2231 specs include:

"2kB Flash, 128B RAM, 10 GPIO, 1x 16-bit timer, WDT, BOR, USI (I2C, SPI), Internal Temp Sensor, 8ch 10-bit ADC"

The two most useful features that make this an ideal device is the fact that it has a 10-bit ADC built in to the chip and it has an internal temperature sensor. So using this method, we may not even need to use a thermistor voltage divider circuit. It also has 10 general input/output lines, so if we were to decide to add some other digital control in the future for this power supply, we would have that option. However, the main functionality of the MSP chip will be to control the voltage response of the temperature sensor so that the HV supply will change its output accordingly; such that it stabilizes the gain of the APD. The graph in **figure 3.1.8** shows how the high voltage output of the A02 changes as a function of the control input voltage.

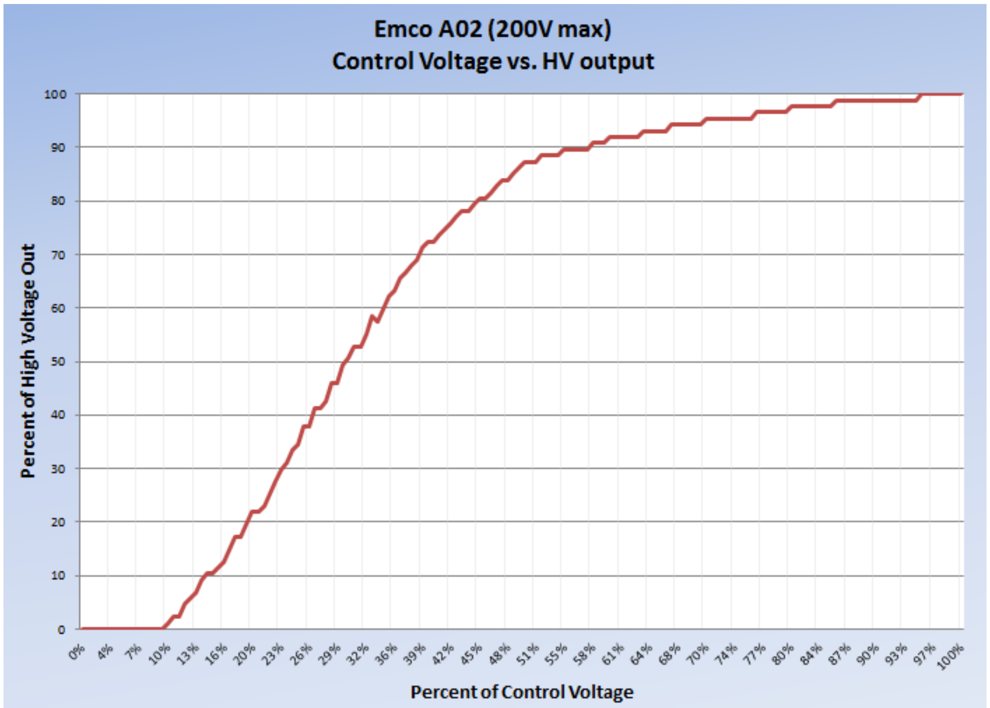


Figure 3.1.8

As of the data shown in figure 10, to maintain a gain of M=100 at 20 °C, we will need the HV supply to be biased at about 134 volts. The A02 has a maximum output of 200 volts; which means 134 volts is about 67 percent of the max output. As of the graph shown in figure xx, 67 percent is achieved by using a control input of about 38 percent. For the A02, the range of the control voltage varies from 0-V_{cc}; where in our case, V_{cc} is +5 volts. So a gain of 100 at 20 °C can be achieved by using a control voltage of about 1.9 volts (.38*5=1.9). Using this same logic and the above graphs, the total range of values that the control voltage will take, to cover the temperature variations of -40°C - +60°C and maintain a gain of 100 is as follows:

From figure 3.1.3,

V_{HVout}= 95 – 160v For, M=100, -40°C ≤ T_{range} ≤ +60°C

V_{CNTRL}=30%-45% V_{CNTRL}(max)=+V_{cc}=5V

$$\boldsymbol{1.5v \leq V_{CNTRL} \leq 2.25v}$$

So in order for the HV supply to maintain a voltage level that establishes gain stability in the APD over the operating conditions of the device, the control voltage must actively change its value from 1.5-2.25v in response to changes in ambient temperature. This range represents the extreme operating conditions of the device; in normal operating conditions (room temperature) the control will be somewhere around 1.9 volts. **Figure 3.1.9** summarizes the temperature compensation circuit.

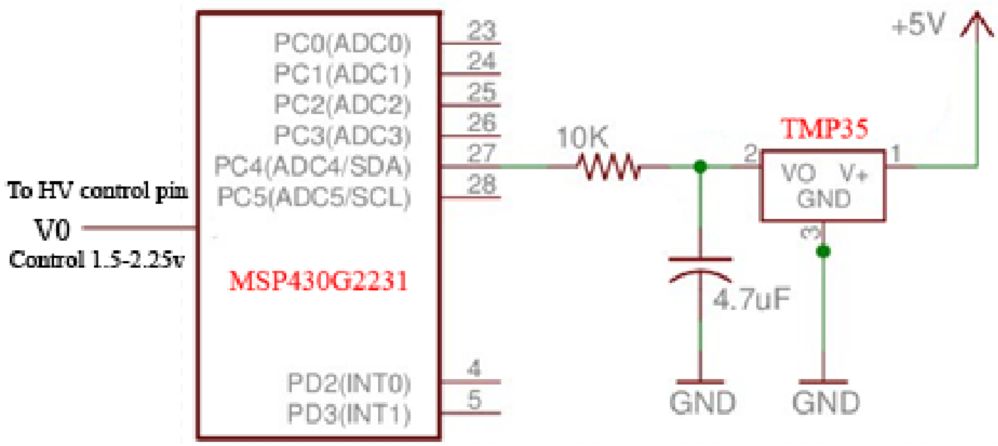


Figure 3.1.9

Although the MSP430 does have an internal temperature sensor, the overall temperature response may be more precise though the use of a TMP35 temperature sensor. This is a semiconductor solution for temperature sensing that outputs a voltage response much in the same way as the thermistor voltage divider circuit. The advantage in using aTMP35 is that we can physically position the sensor in closer proximity to the APD. This will allow for a more accurate measurement of the ambient temperature that the APD is currently experiencing; thus producing a more accurate bias voltage.

The TMP35 outputs a voltage from 0-5000mV with a change of 10mV representing 1 °C of change. The MSP430 chip has a 10-bit analog to digital converter on board; so its digital input can takes vary from 0-1024 increments. Therefor the ADC increments by 2 for every degree change in Celsius. The following code fragment displays a basic method of taking in an analog voltage from a temperature sensor and displaying that analog value to an LCD. Written in basic C, may need modifications for the MSP430 chip.

```
#include <mxapi.h>
#include <lcd.h>
#include <adc.h>

int main(void)
{
    int analog_value;
    adc_init();
    lcd_init();
    while(1==1)
    {
        analog_value=adc_read(4);           //Read value on Port C4
        analog_value=analog_value/2;             //Divide value by 2
        lcd_decimal(FIRST_LINE, analog_value, 3); //Display to LCD
        lcd_character(FIRST_LINE+4, 223);   //Display degree symbol
        lcd_text(FIRST_LINE+5, "C");        //Display the letter "C"
        delay_ms(100);                     //Wait 100 milliseconds
```

```
    }
}
```

However, this code does not do exactly what we want. We need the digital output to go to the control voltage of the Emco A02 power supply for HV adjustment. This may require the use of a precision voltage reference or a separate digital to analog converter.

In conclusion, the APD module represents both a technically and costly addition to the device. Although it is a lot of work, it is essential for us to be able to achieve our set distance goal of 50 meters. Its operation in summary is as follows. The high voltage power supply is temperature controlled to maintain a constant gain across the APD. The temperature control module consists of a semiconductor temperature sensor and a simple microcontroller for regulated adjustment to the HV supply. Incident photons on the APD provide a photocurrent that is relatively constant in magnitude due to the constant gain. The small signal current is turned into a voltage via a high speed operation transimpedance amplifier and sent to the TDC chip for further processing.

3.2 – Optics and Filtering

This section will focus purely on the optics involved with the transmission and receiving of the laser pulses generated by the TDC-GP21’s Fire Pulse Generator function. As of the publication date of this paper, our design is based on the use a 25mW laser with an average wavelength of 780 nm, or a frequency of 1,282,051.282 Hz. The reasons for this decision are given in the research section, however there is a possibility that the current laser may be switched out for a laser of a longer wavelength if the future of the design process. Just as important as laser choice, the chosen APD will severely affect the performance of the device, and the optics involved in receiving the laser. At this time, we have decided upon the S2381 APD produced by Hamamatsu, whose spectral response is given in **Figure 3.2.1**, which shows the photosensitivity for the S2381 APD as a function of the gain and wavelength of the incoming light.

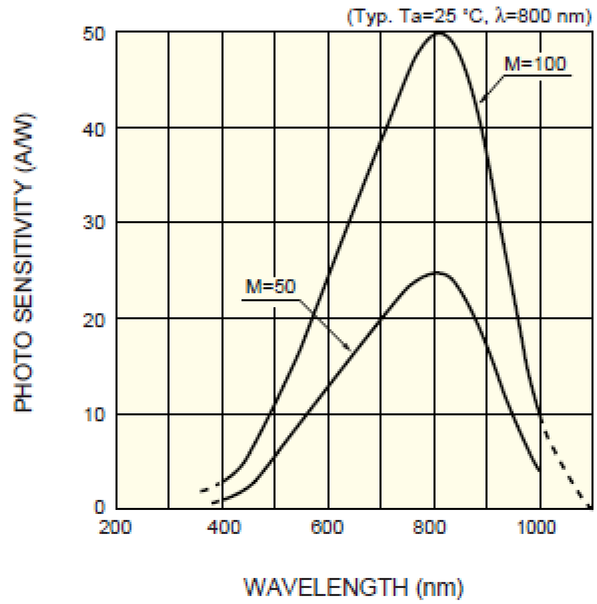


Figure 3.2.1: S2381 Spectral Response

As stated in the APD design portion, we will be attempting to operate the S2381 with a gain value of as close to 100 as possible. At this gain, the APD very sensitive to our target wavelength of 780nm, however the decrease in photosensitivity isn't sharp enough for ranges outside of our target wavelength, which could potentially cause the false triggering of the APD circuit, and therefore yield inaccurate results in our final design. Operating the S2381 at this gain would still produce sizable current due to incoming light anywhere in the range of 600nm up to almost 100 nm. To avoid this, we designed our optics system to be as discriminating as possible, using a 2-layered approach based upon a highly efficient filter, and a specially coated planar convex lens.

Our optics design begins initially with an optical filter, which is a relatively new concept for our design team, as the only filters we have any experience with are purely electrical, and much of what we learned is detailed in the research section. We decided to use *Edmund Optics* as the source for all of the optical components for our design. Just like our electrical filters we are familiar with, *Edmund Optics* had a multitude of low-pass, high-pass, and band-pass filters available to us, all specially designed for use in laser-based optical systems. Clearly we needed a band-pass filter for our design, and there were plenty available to choose from with a wide range in diameter choice and price point. Our design requires us to block out all wavelengths of light besides the light that our laser puts out, light in the 780nm range. To do this, the first element of the receiving optics to implement is our band-pass filter. We decided upon a part number **NT65-723**, which is a 780 nm band-pass filter. This part possessed all of the unique properties we needed for our design; the specifications of the part are given in **Table 3.2.1**.

780nm Band-Pass Filter Part no. NT65-723	
Bandwidth	10 nm
Diameter	25 mm
Thickness	7.5 mm
Center Wavelength (CWL)	780 nm
CWL Tolerance	+/- 2 nm
Minimum Transmission	>50%
Blocking WL Range	200-1200 nm
Optical Density	>3.0
Operating Temp	-50 to +75 °C
Mount	Anodized Ring
Price	$99.00

Table 3.2.1 780nm Filter Specifications

The center wavelength of the band-pass filter is the exact same wavelength of our laser, and with a tolerance level of +/- 2nm only, we were positive that the filter would allow maximum transmission of our laser pulse. The tolerance of our laser's wavelength is within the 10 nm bandwidth of this filter, which further ensures that only our desired wavelength would be passing through the filter at any significant magnitude. This filter will act as the primary optical filter; however there remains the possibility of other wavelengths of light still hitting the APD, and therefore false triggering. To circumvent this potential issue, further filtering optics will be implemented via the use of a specially coated focusing lens, the details will be explained further on in this section.

The only immediate issue with using this particular filter is that the maximum percentage of light that passes through the filter, even at the peak wavelength, is roughly 60%. This property will essentially cut the amount of power hitting our APD in half; whether or not this will be an issue will become clear in the prototyping stage of development, set to start early in May. **Figure 3.2.2** shows the transmission properties of the band-pass filter, where it can be seen that the expected percentage of transmission at our target wavelength is nowhere near 100% transmission.

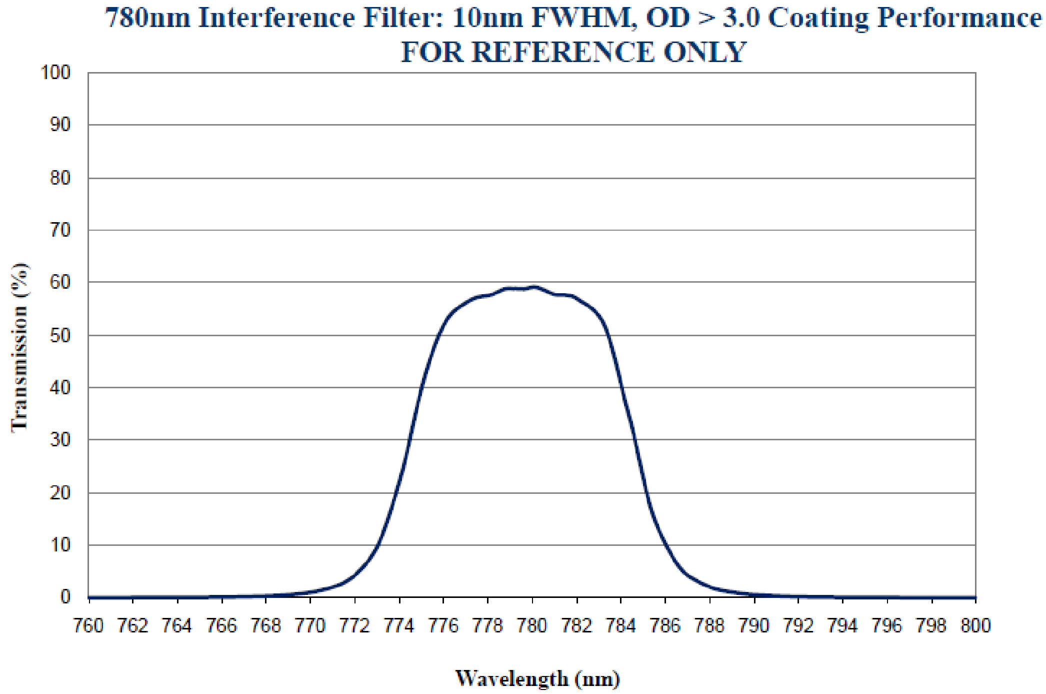


Figure 3.2.2

The second component in the reception optics is the actual lens that will take the incoming collimated light and focus it onto the APD. The lens that will be responsible for this vital task was again chosen from *Edmund Optics'* wide array laser-based optics, specifically part number **NT65-527**. This lens is a laser-grade, plano-convex lens with a special coating that has some filtering properties to help ensure that the only light that registers on the APD is the light returning from the object being ranged. *Edmund Optics* calls this coating their *V-Coating*, which ideally reflects all incoming light, except for the light at the target wavelength. Unfortunately, there are no lenses that specialize specifically in 780 nm light; the closest V-Coat lens available is 785 nm. Luckily for our design, the 785 nm lens will be sufficient, as reflectance properties of the lens will allow the incoming 780 nm light to pass through sufficiently with minimal reflection. The specific reflective properties of the lens are shown in **Figure 3.2.3**, and it can be seen that our target wavelength should be able to pass through the lens unaffected, and anything outside our target wavelength will be reflected by the lens if it has not already been blocked by our initial optical filter. Aside from the special V-Coating, this lens has an effective focal length of 100 mm, which will allow our optics to magnify a more specific area and increase the magnitude of our ranging capabilities. We are currently thinking of replacing this part with another lens with a slightly longer focal length, giving us even more magnification; however this may prove to be too long, and cause excessive size in our design.

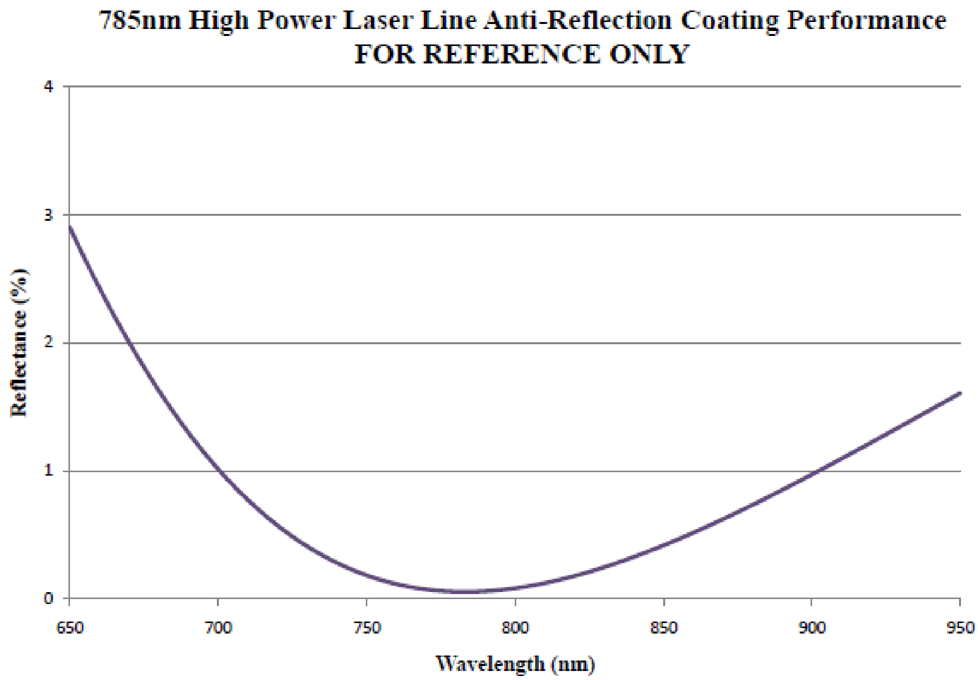


Figure 3.2.3

Our current design for our receiving optics calls for both the band-pass filter and the plano-convex lens to be mounted in anodized rings. These rings will be able to be attached to a secure mounting system that must be completely stable. Even the slightest error in the orientation will dramatically decrease the odds of a successful transmission and reception of our laser pulse. The filter will be the first component mounted inside of our enclosure, and the edges will be sealed tightly as to prevent any other form of light from entering the optics tube. The filter is 7.5 mm and we expect to place the plan-convex lens approximately 20 mm behind the filter inside of the optics enclosure. The lens has a thickness of 4.3 mm at the center; 2.77 mm of the thickness at the center is due to the cylindrical part of the lens, which cuts down the effective focal length of 100 mm down to a focal length of 97.17 mm from the back of the lens. This is where the active area of the APD will be placed and where the incoming light will be focused. The entire length of the receiving end of this device should be no longer than 160mm or just over 6 inches.

3.3 – Micro Controllers

TDC-GP21 Module

This section will detail the circuitry revolving around the ACAM TDC-GP21. This element of the design is very closely related to the APD module as the sole function of the TDC in this implementation is to measure the time differences between the triggered laser pulse, and the returning laser pulse registering on the APD. The electronics for this section are surprisingly simple, however the tolerances are quite tight, as any slight differentiation in any of the core or input/output supply voltage can cause misreading while the device is in use. The software aspect of the TDC-GP21 is much more complicated than the actual circuit appears to be.

Wiring the GP21 to the APD module

The TDC-GP21 is a very complex device internally and is capable of performing multiple functions. As can be seen in the GP-21 block diagram, the device is equipped with temperature sensing hardware, and many of the external pins of the GP21 are dedicated to that hardware (pins 17, 18, 19, 20, 23, 24), so in our design they can be ignored and set as "no connection." Vio and Vcc for the GP21 can both be set to 3.3V and therefore in the circuit Vio is simply connected to Vcc. Several of the pins on the GP21 are dedicated to a common GND and are therefore tied together as well. The circuit in **Figure 3.3.1** shows the TDC-GP21 in a standard DIP configuration, connected to a simplified version of the circuit for the avalanche photodiode.

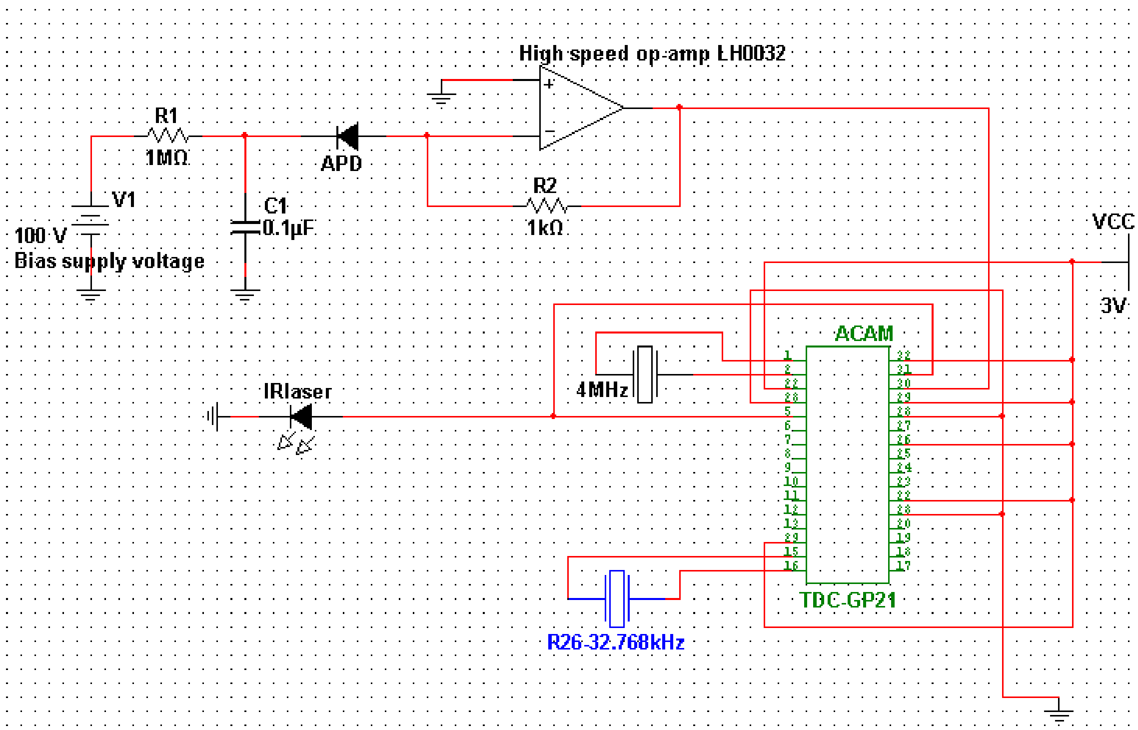


Figure 3.3.1 TDC and APD Module Configuration

With the GP21 set in measurement mode 1 (45ps resolution, 1 stop channel) the STOP2 channel on the TDC is disabled, along with the EN_STOP2, so both of those pins can also be set to "no connection." The output from the APD receiving module will be directly wired to the STOP1 channel (pin 30). The FIRE_UP (pin 5) is the output from the Fire Pulse Generator, which was programmed through software (via SPI interface) to send out our pulse to the laser module. The laser will be activated for the programmed amount of times set in the FIRE_UP register on the TDC.

The FIRE_UP pin is also directly wired to START channel, which will tell the TDC to start measuring the time difference from the first input from the Fire Pulse Generator to the time when the STOP channel 1 becomes high. This can essentially be thought of as using a "dummy start" because the TDC is meant to activate its measuring sequence when the first incoming light is registered on the START channel. Using the dummy method will cause inaccurate measurements because of the start–up time for the laser. Pulsed laser diodes can be quite expensive, so to minimize our design costs we are using a continuous wave laser module, which will have a significant delay time. This delay will cause the TDC to start measuring time before the actual laser pulse used for the measurement is even sent out from the module, and this will throw off our measurements if the delay is not accounted for in conversion. We do not know the precise delay of our laser at the moment, but prototyping will ensure we can compensate for the delay in the laser module activation.

TDC-GP21 Clock Requirements

The GP21 needs a total of 3 clock signals in order to operate at maximum potential, which are supplied by the 32.768 kHz high accuracy oscillator, 4 MHz high speed oscillator, and the clock signal from the master microcontroller (which will be discussed in the next section). The clock signal from the ATmega328 can also be used as the high speed oscillator signal; however the signal must be divided internally by the GP21 lower it down to a usable speed. We considered using this method, however we were informed by *Transducers Direct* that using the master clock signal as the high speed oscillator input would cause excessive noise, and to maintain as accurate measurements as possible, we should avoid doing this. The high speed oscillator can assume any value from 2-8 MHz; however ACAM and *Transducers Direct* both recommended using a 4 MHz oscillator for stability because of the lower signal noise and sufficient speed. The clock itself requires a relatively large amount of current to run continuously when compared to other components of the GP21, so it is actually off for majority of the process and only activated when needed; this is controlled by the START_CLKHS parameter in the control registers. A delay is also implemented in between the time the high speed clock activates and the time when the op-code is given to start the TDC measurement to ensure that the clock has had time to settle. The pins of the oscillator are connected to the Xin and Xout pins on the GP21 and we have implemented a filtering capacitor on each node of the oscillator to reduce the noise in the signal.

The TDC's most important clock signal is supplied by the 32.768 kHz oscillator; this clock is the reference for all the internal timings of the GP21 and therefore must be highly accurate and low noise. For this reason, the 32.768 kHz oscillator was chosen to be a crystal oscillator, specifically quartz oscillator. Unlike the 4 MHz oscillator, which draws roughly 200 µA of current when on, the quartz oscillator will be continuously on and only draws about 0.7µA of current when the GP21 is powered at 3.3V. This oscillator is used to keep the less accurate, 4 MHz ceramic oscillator properly calibrated to ensure correct measuring of times during TDC activation. This can be done manually using the master microcontroller, or automatically via control register. We decided to use the automatic calibration tool available by setting Register 0's Bit 12 (NO_CAL_AUTO) to "0."

Wiring the TDC-GP21 to the ATmega328 Arduino Board

Wiring the GP21 to the ATmega328 is quite simple; there are only four connections that need to be made in order for these two components to communicate correctly. The SPI pins on the Arduino Uno development board are located on D13 (SPI Clock), D12(Master In Slave Out), D11(Master Out Slave In), and D10(Slave Select). The SPI pins on the TDC-GP21 are pins 9(Slave Select Not), 10(SPI Clock), 11(Slave In), 12(Slave Out). The Arduino SPI library requires the Slave Select line at D10 to be high in order to have the ATmega328 act in Master Mode; so in our software we had to write D10 as HIGH, and then declare pin D9 as a new functional Slave Select line for the TDC-GP21. In order to add more slave device to our current setup, we can declare any one of the digital pins as another Slave Select line.. **Figure 3.3.2** shows the basic wiring needed to perform successful communication between the Arduino interface and the TDC-GP21.

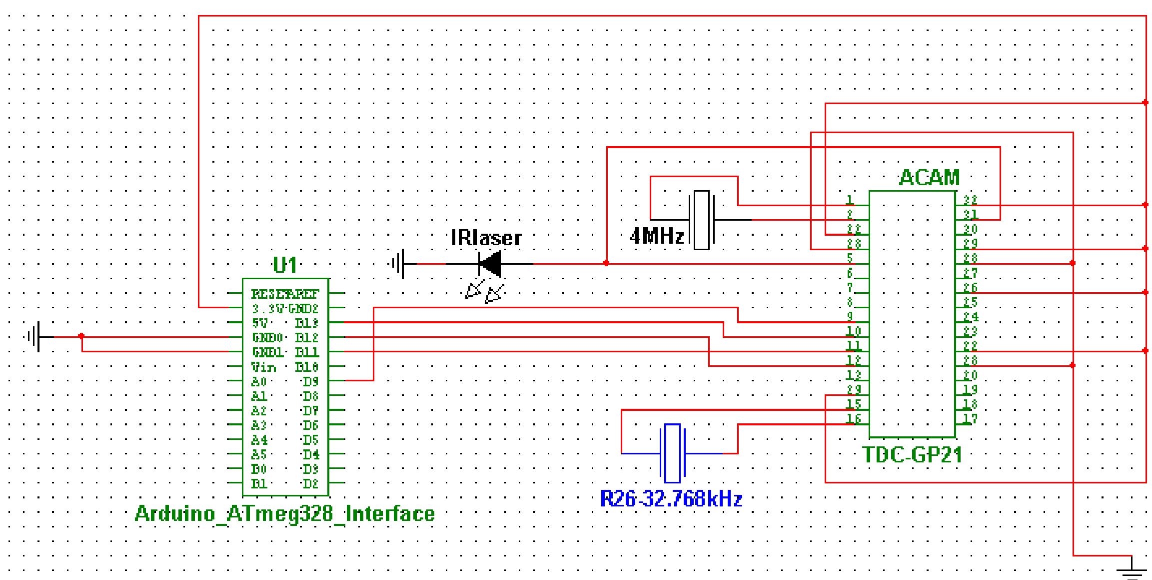


Figure 3.3.2 TDC-GP21 to Arduino Communication

Both the Arduino module and supports a 3.3V output source for our prototyping purposes, so the core voltage of the GP21 can be supplied directly from the Arduino board, though our end design may have some slight alterations. The maximum SPI clock speed that the GP21 can communicate at is actually a function of its core voltage. Even though the clock speed of the ATmega328 is 20 MHz the GP21 will not be able to communicate at those speeds without the proper core voltage. This is why it is vital for our power supply to be exactly 3.3V with as little sway as possible. The GP21 needs exactly 3.3V to be able to communicate at a 20 MHz rate with the ATmega328, which is our desired optimum speed. It is possible for the devices to communicate at lower clock speeds if the core voltage of the GP21 drops below 3.3V, however this can more than double the amount of time it takes to transfer data from one to the other, not to mention the error that will be caused in the measuring process by the voltage drop.

Wiring the Arduino Interface to the 16x2 LCD

Now that the Arduino's dedicated SPI pins are wired directly to the TDC-GP21, we need to wire up the LCD with the remaining available digital pins. For now we are planning on using pins D2-D7 to wire up the 16x2 LCD display. Our display we are using is compatible with the Hitachi HD 44780 driver, which is supported by the Arduino Liquid Crystal Library. This display can take over 5V on its Vcc line, so we simply wired the Vcc of the display to the 5V source of the Arduino and connected the GND of the display to the GND of the Arduino. To be able to adjust the brightness of the display, we placed a 10k potentiometer between the Vcc and the GND of the LCD and wired the wiper of the potentiometer to the Vo terminal of the LCD. **Figure 3.3.3** shows how we plan to wire the LCD to our Arduino Board with the some of the remaining digital pins. Pin D2 on the Arduino Interface will be wired to D7 on the LCD, D3 Arduino to D6 LCD, D4 Arduino to D5 LCD, and D5 Arduino to D4 LCD. The R/W line of the LCD will be wired to the ground to enable writing, and the E line and the RS line on the LCD will be wired to the D6 and D7 pins on the Arduino.

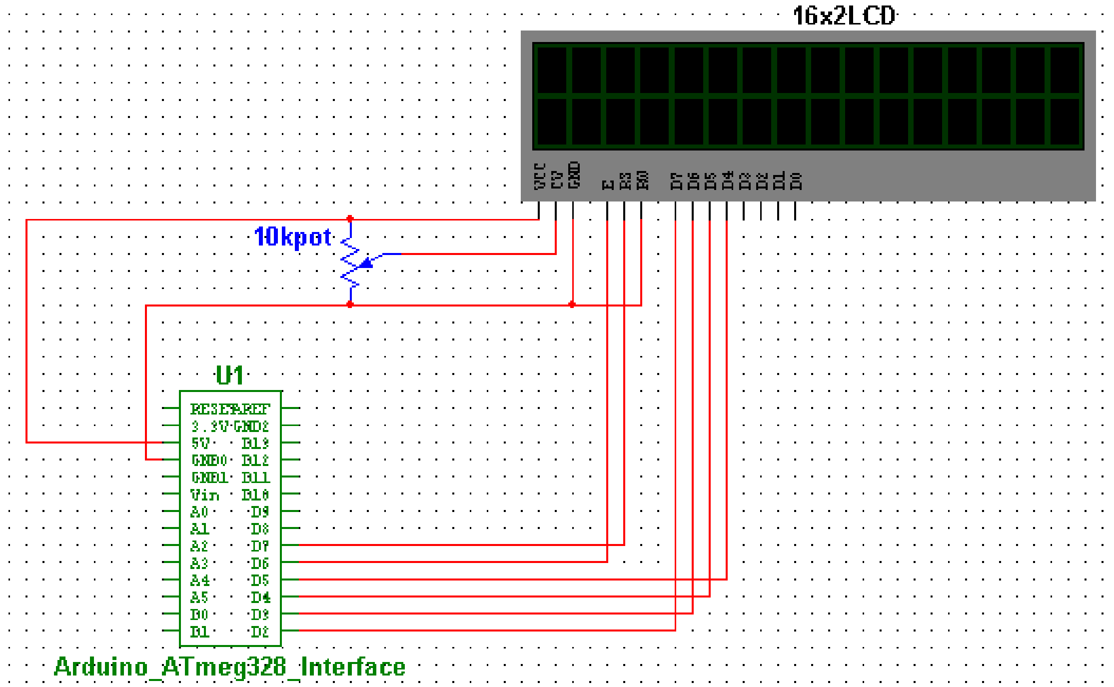


Figure 3.3.3 Arduino to LCD

3.4 IR Temperature Design

Like we mention in Section 2.2.7- Small Signal Amplifier, the MLX90614 is like any other thermopile infrared detector, needing an amplifier to generate a bigger signal. Moreover, the output voltage of the any thermopile detector will be positive whenever the measured objects have higher temperature than the detector. In the other hand, it would be negative whenever the measured objects have smaller temperature than the detector. Therefore, the detectors, MLX90614 included, need to be connected to a different amplifier that could accept both positive and negative input signals as the output voltage could become either positive or negative values. This is the planned schematic that we design in order to amplify the small signal from MLX90614 in purpose measuring the temperature.

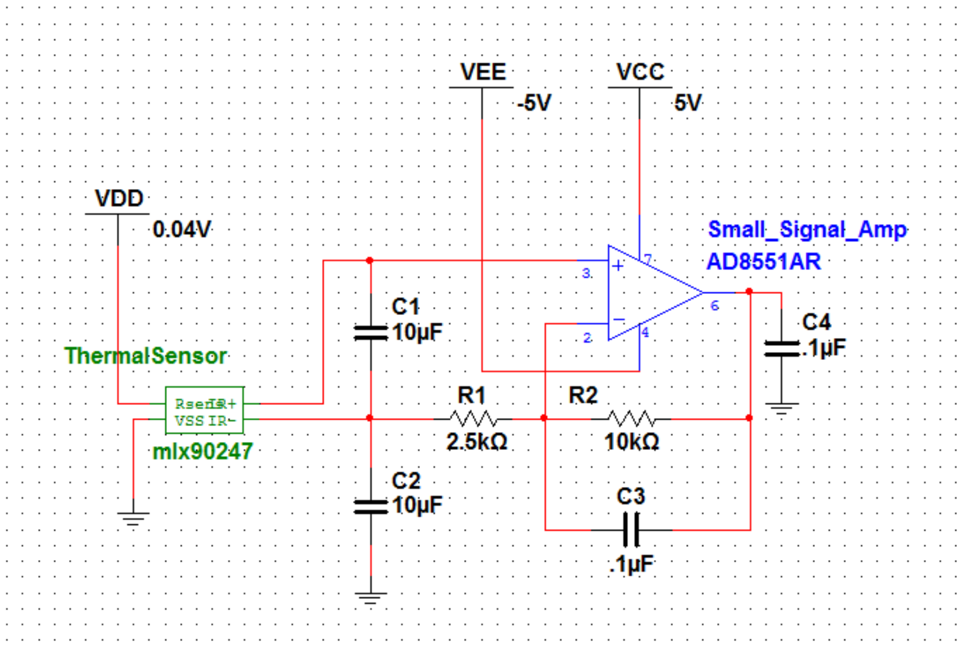


Figure 3.4.1

3.5 Power System

There were several factors that had to be evaluated when choosing what we would power the device with. Since we have silicon that requires both a positive and negative rail, we immediately knew we must employ two separate batteries to be able to achieve both the positive and negative regulated voltages. Since we have to use two separate batteries, we must choose batteries that are going to be as light as possible while still giving us an appropriate voltage with an appropriate capacity.

The batteries we chose and currently plan to implement into our design are two 9VDC alkaline batteries, either Duracell or Energizer. Both batteries have a milliamp hour rating of approximately 600mAh. They are small batteries and weigh in at about 45 grams, making them very light and also great for portability. They are also cheap, about 3-5 dollars dependent upon quantity purchased or store purchased from. Since we will be using the 9V batteries, there are no concerns with safe operation like with lithium or NiMH technologies.

3.5.1 Regulator Circuits

The power system must be designed so that our silicon chips are able to receive their constant operating voltages, something that be obtained from just a battery source. Thus, the power system design must be setup to run the appropriate voltage regulation modules that will help us to obtain a power supply that operates our device and does so without destroying any parts. Below is a mock circuit that should deliver a +5V signal.

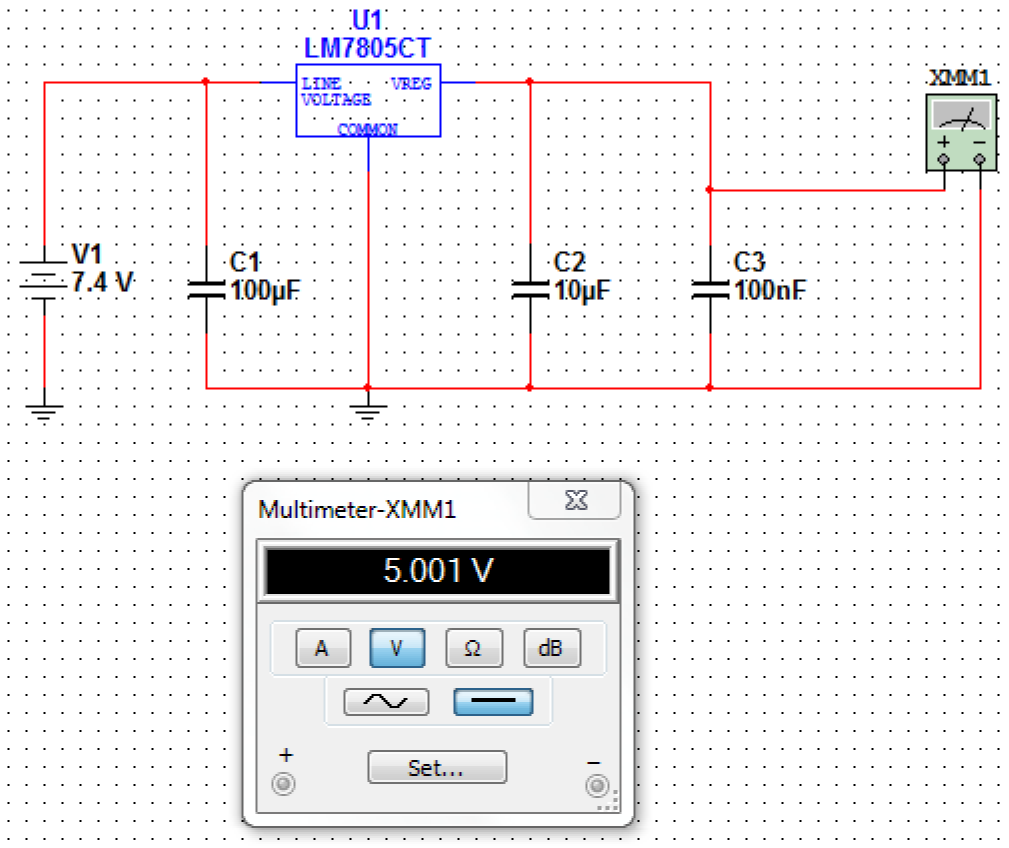


Figure 3.5.1

As seen above, these regulators provide a pretty rock solid voltage output, and the capacitors are there to provide filters of high frequency noises. The design for our -5V LM7905 and 3.3V LD1117V33 will similar: only changes to the filtering capacitors will be changed in accordance to the datasheet.

Because our APD module is a pretty sensitive device, we must regulate the voltage to the 3.3V it requires to operate. Unfortunately, Multisim does not have the LD1117V33 in its database, so creating the correct circuit is not possible. Figure 3.5.2 is an example from the datasheet for the circuit that will be used to correct the 9V input to its 3.3V output.

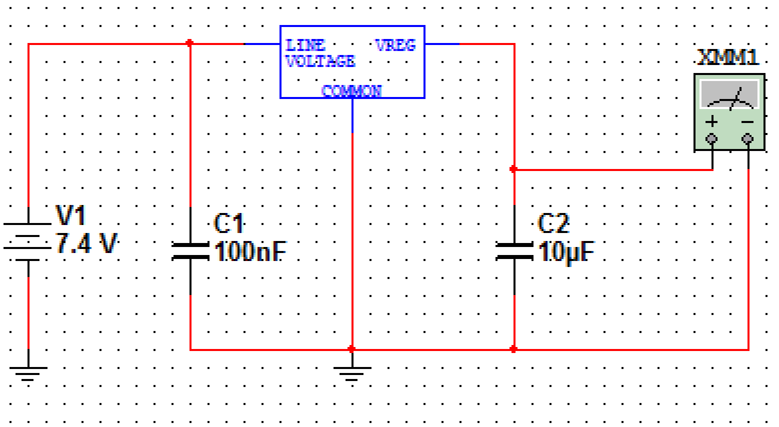


Figure 3.5.2

The LM7905 will be the long regulator on the second 9V battery source. Figure 3.5.3 is the circuit that will be employed to achieve the -5V output that we desire.

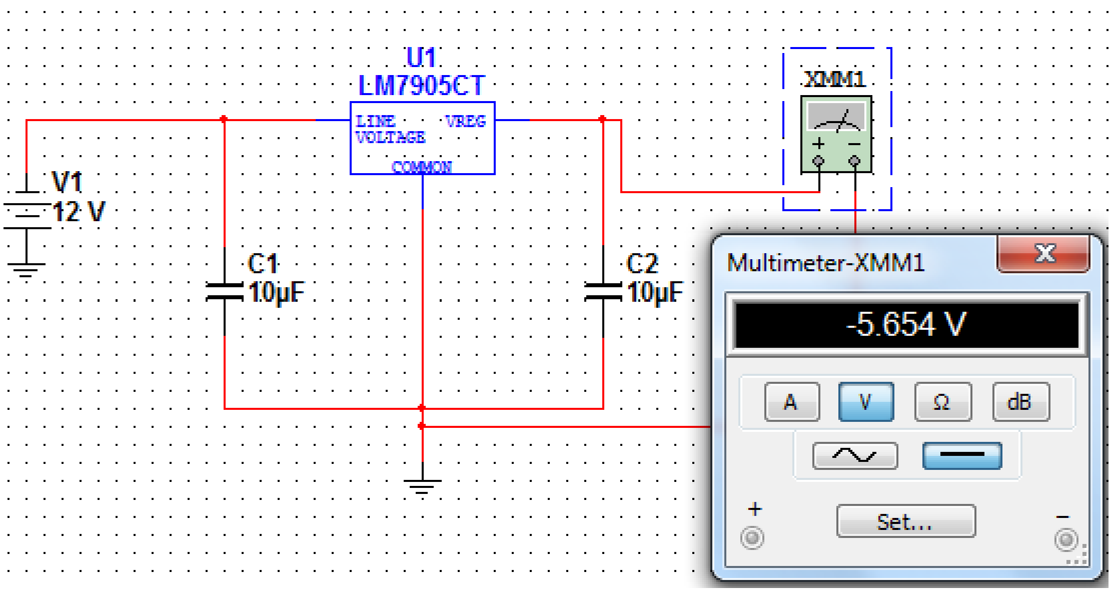


Figure 3.5.3

3.6 Project Enclosure

The project enclosure that we use must be carefully chosen. This is the device that will encase all of our sensitive electronics. It must be stable, large enough to hold everything as well as visually appealing. We have the option to either build a custom enclosure or use a casing from some other product. For the scope of this project, it will be easier to use the enclosure from another product; then we can put more emphasis on the functional design. Shown in **figure 3.6.1** is one possible type enclosure that we could use. This is the enclosure from a spotlight commercial flashlight. This would of course require use to modify the casing quite a bit, but still will be easier than building a completely custom case.

Figure 3.6.1

The front part where the light bulb usually is, we could place the 2 lenses for the APD and the IR temperature sensor. The large cylindrical design should be more than enough to accommodate for all of the parts for the sensing the device. The spotlight also already has a triggering mechanism on the handle. We could use this to turn the device on and start taking readings. As for the display, we will probably have to cut a large hole in the back on the spotlight and mount it there somehow. The large handle on the device could also be used to house the battery for the device, allowing us to separate it from the main sensitive circuits.

Chapter 4 Design Summary

4.1 APD Module

The design of the APD module consists mainly of the APD, the transimpedance amplifier, the high voltage supply, the microcontroller, and the temperature sensor. The APD module will have 3 different power rails that are utilized by the system. The +/- 5V rails will be used by the op-amp for its main power and the 3.3 will be used by the MSP430 chip. As the ambient temperature changes, the analog output from the TMP35 chip will range from 100-2000mV; with a voltage change of 10mV for every degree change in Celsius. This changing analog voltage is fed into the MSP430 MCU where it is immediately converted into a digital quantity using its built in analog to digital converter. Once we have a binary representation of the ambient temperature, that value will be compared using C-code to a set table to quantities of how the output voltage should change in response to ambient temperature. The analog output of the MSP that is fed into the A02 control pin, should be in the range of 1.5V-2.25V. In doing this, the high voltage output will change from 95v-160v in response to ambient temperature; at room temperature, the HV out will be 134v. When the APD is biased at 134V while in room temperature, its gain should be about 100. In using the temperature control circuit, the gain of the APD should stay at about 100 under the set operating conditions. The output of the HV supply has a resistor in series. This is the current limiting resistor that is needed to do the relatively high power consumption by the APD. There is a 0.1μF bypass capacitor to ground also attached. This is used to reduce the change in the power supply voltage due to high current draws. This capacitor should also be placed as close as possible to the APD for best results. There is also an excessive voltage diode branching off the main circuit. This is used to divert excessive voltage to the main power supply voltage line. From here the photocurrent is fed into the transimpedance amplifier, where it is converted into a voltage. By using a 10k resistor, the photocurrent, usually very small, is multiplied by a factor of 10,000 to obtain a proportional voltage. The op-amp that will be used will be an OP184ES; chosen for its very high slew rate and its low bias current. The output voltage is fed into the TCD module from there where it is compared to the original laser fire pulse and the time can be determined. **Figure 4.1.1** below is the schematic design summary and shows the overall operation of the APD module.

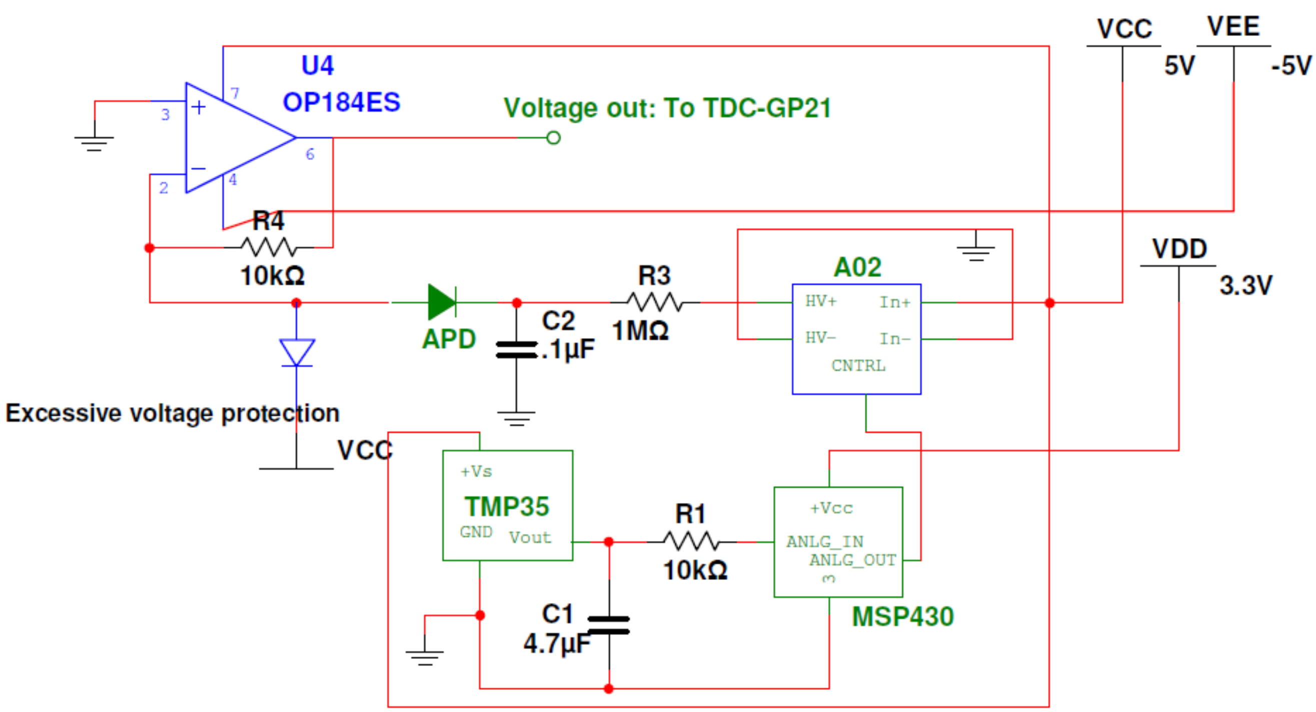


Figure 4.1.1

4.2 Temperature Circuit

Like we mention in Section 2.2.7- Small Signal Amplifier, the MLX90614 is like any other thermopile infrared detector, needing an amplifier to generate a bigger signal. Moreover, the output voltage of the any thermopile detector will be positive whenever the measured objects have higher temperature than the detector. In the other hand, it would be negative whenever the measured objects have smaller temperature than the detector. Therefore, the detectors, MLX90614 included, need to be connected to a different amplifier that could accept both positive and negative input signals as the output voltage could become either positive or negative values. This is the planned schematic that we design in order to amplify the small signal from MLX90614 in purpose measuring the temperature.

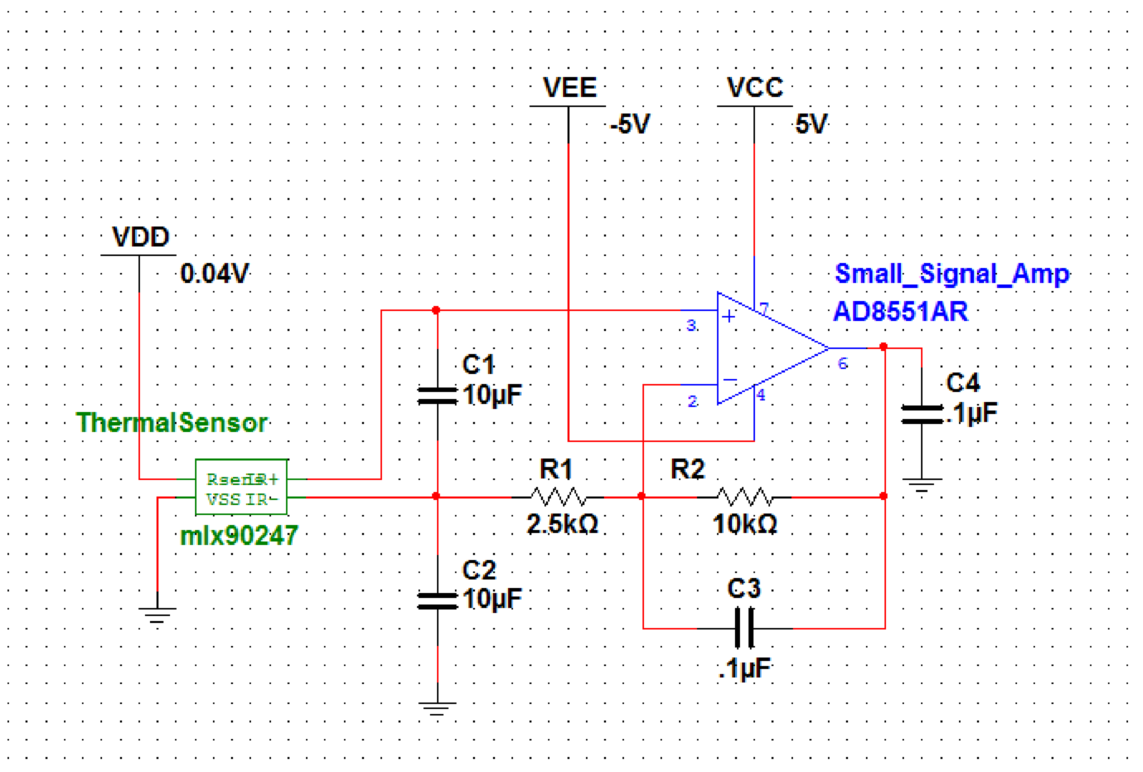


Figure 4.2.1

4.3 Microcontrollers

Arduino to TDC-GP21 Circuit

In order to be able to use the information gathered by the TDC-GP21, we need to use a master microcontroller to fetch the information. Our design is implemented using an Arduino Uno board, with an onboard ATmega328. The communication between the Arduino and the GP21 is done through the use of the 4 pin SPI communication. We are using the standard SPI Library that is available from the Arduino website though we had to make one slight alteration. The 4 SPI pins on the Arduino interface are pins D13(SCLK), D12(MISO), D11(MOSI), and D10(SS); however in order to have the ATmega328 actually act as the Master, you have to write pin 10 to be high at all times, and you must designate another external digital pin to act as your new Slave Select line. We chose to use pin D9 as our new Slave Select for communication with the GP21. The SPI pins on the

GP21 are pins 12(MISO), 11(MOSI), 10(SCLK), and 9(SSN). We simply had to wire the SPI pins on the Arduino to their respective pins on the GP21 to enable communication between the 2 devices. Now the GP21 can be configured in any way that we like through the Arduino software, which is a C-based programming language. For our purposes we need to make a few changes in the control register configurations to enable Measurement Mode 1, which has the capability of measuring our desired range with high accuracy. We also programmed the GP21's Fire Pulse Generator to send out a series of 10, very high speed pulses to ensure that we would be able to recover at least one of the pulses on the APD module. It would require less current consumption to send out only one pulse, however this would greatly reduce our chances of the recovering the reflected laser pulse, so we decided that 10 pulses would be sufficient to avoid any issues with losing our signal.

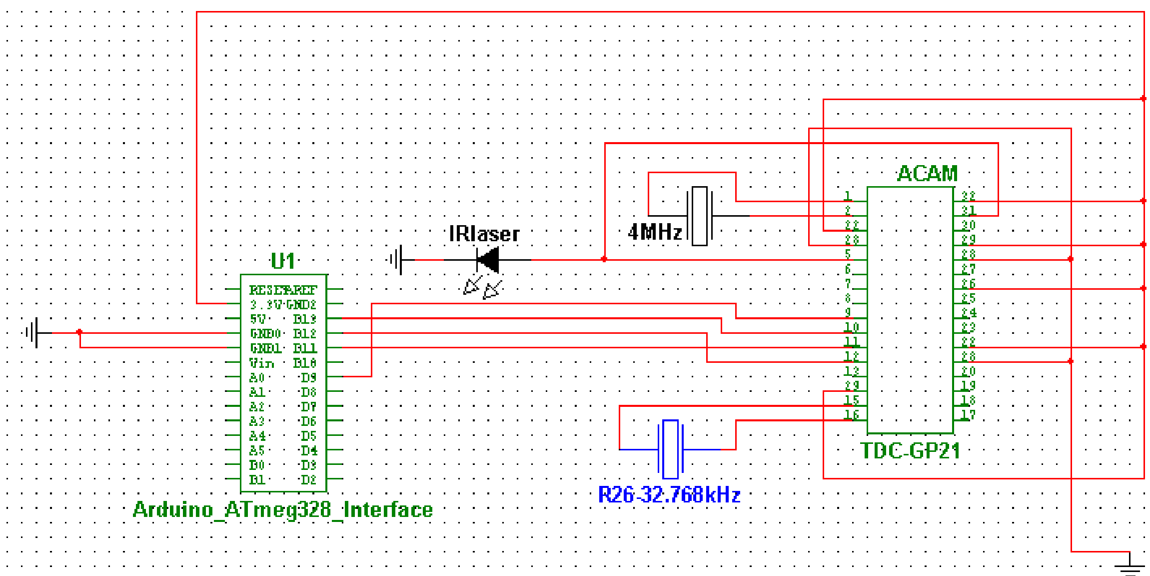


Figure 4.3.1

TDC-GP21 to APD Circuit

The TDC-GP21 is essentially the foundation for the laser ranging function of the device as it is in control of firing the laser, receiving the pulse voltage signal from the APD module, and performing the necessary calculations in order to return a usable value to our micro controller. The GP21 has 2 GND pins, as well as 2 VCC pins that must be wired to GND and 3.3V respectively. In Measurement Mode 1, only the STOP1 channel is used, so therefore the pin that controls STOP2 is also wired to GND. The GP21 also has 2 Vio pins that can share the same voltage source as the VCC pins, so they are also directly wired to the 3.3V source. The 2 external clock signals that the GP21 needs to function are supplied by a 4 MHz high speed ceramic oscillator and a 32.768 kHz high accuracy oscillator. The high accuracy oscillator is connected to pins 15 and 16 (CLK32OUT and CLK32IN respectively) and we may choose to implement additional filtering capacitors on the line to reduce any possibility of noise. The high speed oscillator is connected to pins 1(Xin) and 2(Xout) and will also likely have additional filter capacitors connected to it. The output of the Fire Pulse Generator will be coming from pin 5 (FIRE_UP) and will be wired directly to the leads of our laser module to active the laser pulses. The output from FIRE_UP will also be directly wired to the START channel to tell the TDC circuitry to begin measuring time. The output of the APD module will be wired directly to the STOP1 channel (pin 30) of the GP21 so that when the light from the laser pulse returns and is received by the APD, the TDC unit will stop measuring the time and begin doing its conversion calculations.

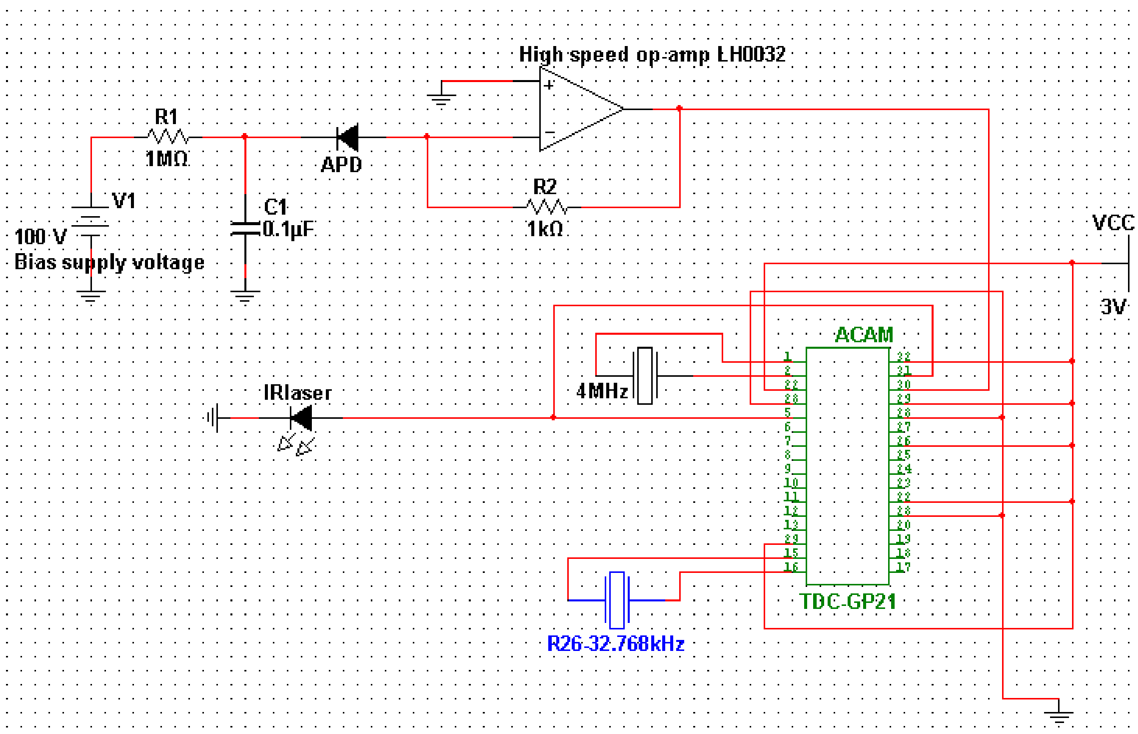


Figure 4.3.2

Arduino to LCD Circuit

In order to view the results of our TDC's measurement, we need to implement some sort of display, and a 16x2 LCD was chosen for its simplicity and compatibility with the Arduino interface. Our 16x2 LCD is compatible with the Hitachi HD 44780 driver, which is fully supported by the Arduino "LiquidCrystal" programming library. The LCD has a 16 pin interface, however we only need to wire 10 of the pins to the Arduino for full function. Pin D2 of the Arduino is wired to pin D7 of the LCD, D3 Arduino to D6 LCD, D4 Arduino to D5 LCD, and D5 Arduino to D4 LCD; these pins connections will be responsible for actually sending the data to be shown on the LCD. Pin D6 Arduino is wired to pin E on the LCD and pin D7 Arduino is wired to pin RS on the LCD and to actually enable the LCD to be written to, pin R/W on the LCD must be tied to GND. To actually power the LCD we need to power it with a 5V power supply, which is supplied directly from the Arduino interface and the GND of the LCD can also be connected directly to the GND of the Arduino. In order to be able to adjust the screen brightness, we used a 10k potentiometer that is connected in between the VCC and the GND terminals of the LCD, with the sweeper pin connected to VO of the LCD. Changing the resistance of the potentiometer will now change the brightness of the LCD.

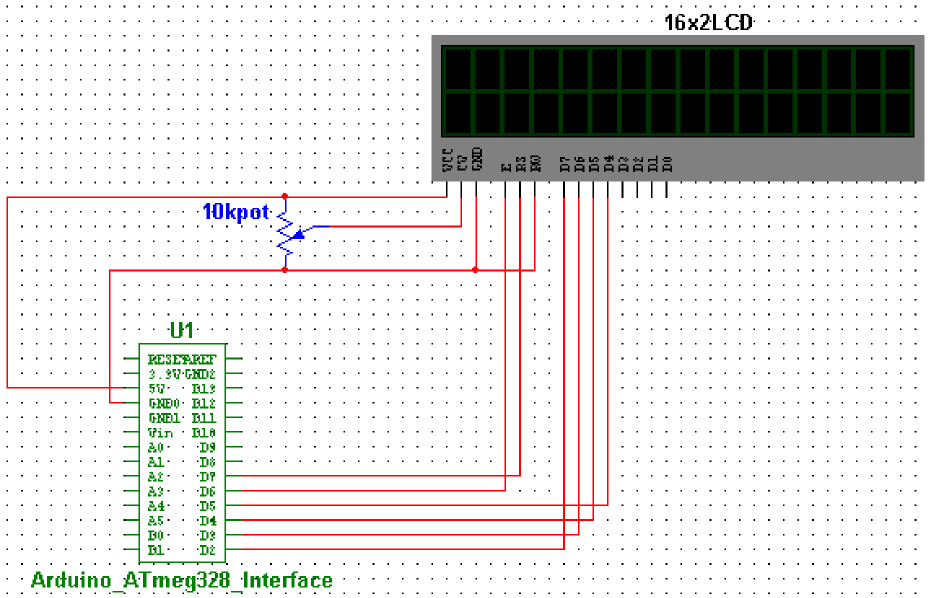


Figure 4.3.3

MLX90614 to Arduino

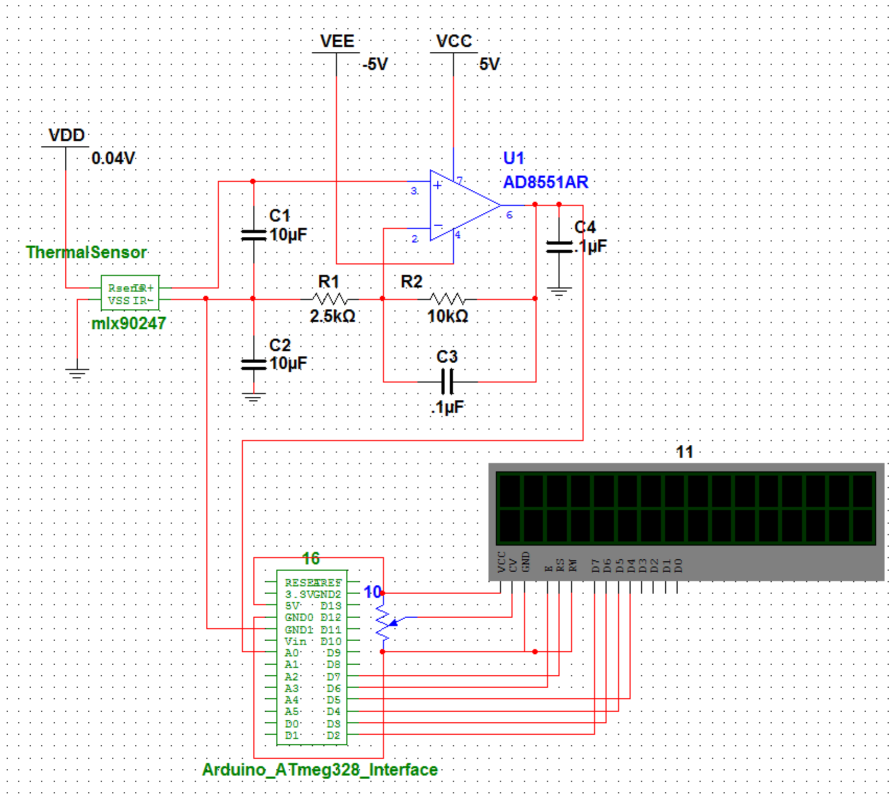
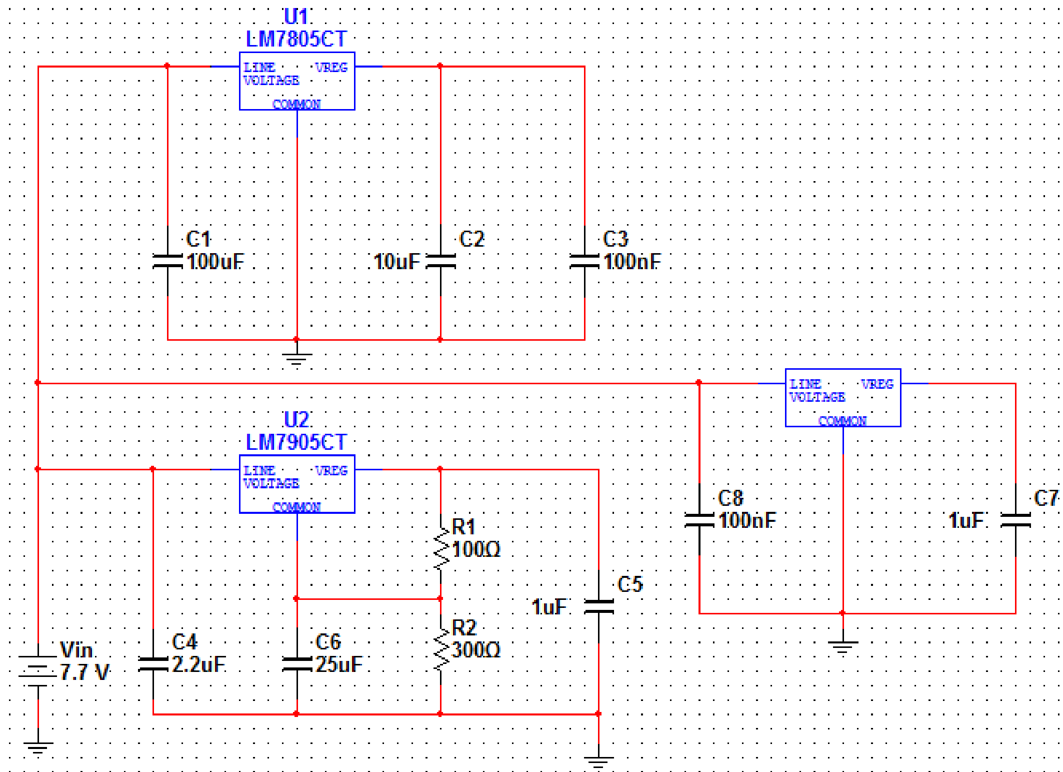


Figure 4.3.4

As mentioned in Section 2.2.7- Analog to digital converting, we use Arduino Uno to convert the analog signal that come out from the amplifier. The connection is simple as plug and play; we connect the output to one of the analog on the Arduino Uno, and the negative output to the ground. After everything is connected we connect the Arduino Uno to the LCD in order to embed code to it, so we could see the digital number of the measured temperature. The figure XX below will demonstrate what we going to do for our thermopile infrared detector. Keep in mind this is a subject to change, so the schematic in future might be changed.

4.4 Power System

In figure 4.4.1, we used a generic 3 pin device that will hold place for our LD1117V33 3.3v regulator. In figure 5.4.1 is the Multisim schematic of what we expect our power system design to look like. We will employ a single source, with three different voltage regulators running off of the source.



Chapter 5 Prototype and Testing

While building our functional prototype, we will exhaustively test each part of our design both for individual functionality, as well as when each module is working together. It is during this stage that we will have most, if not all, of our parts needed already and we should start but knows their specifications well and testing them to make sure that they perform as advertised. It is also very likely that during this stage we will both break components and have to redesign certain methods. It is for this reason that when we order parts, as long as they are decently inexpensive, we should order more than we need, just in case we burn out a component.

5.1 APD Module

Since the APD module will be one of the most sensitive parts of the entire design, it is likely to occupy most of the time when it comes to initial prototyping and testing of the device. Discussed in detail in the chapter 3 design portion, the APD module consists of the APD sensor, high voltage power supply, the temperature sensor, the MSP430 chip, and the current to voltage converter circuit.

Upon getting the APD sensor chip from Hamamatsu, we should first test the specifications to be sure that it performs as advertised. Verifying that it is working properly will allow us to remove it from the equation when troubleshooting the design when something goes wrong. The S2381 should have an optical pass band of 800nm at maximum and a photosensitivity of 0.5 A/W for M=1. Since we want to verify the operation of these two specifications, we will not worry about biasing the APD under a high voltage. Doing so will likely just add another parameter that could be malfunctioning and making it more difficult to determine if the part is working properly. To verify that these two parameters are working, we should bias the APD with the standard 5V; in doing so, the gain should be unity (0.5A/W). Next, while the APD output is hooked up to an oscilloscope, we should expose the sensor to radiation of different wavelengths and observe the photocurrent that comes out. As of the datasheet from Hamamatsu, the highest current response will be present using IR light of 800nm. So even while in a room that is lit by fluorescent lights, there current output should go way higher than the ambient response when exposed to 800nm. Doing this will verify that the pass band is accurate for the device; however we must also be sure that the gain of the device is working as it should. For a photosensitivity of 0.5A/W, at 800nm, a laser of 25mW, incident at a 90° angle to the sensor, should induce a current of -12.5 mA when measured from the anode of the sensor. These results can be further verified by increasing the amount of bias voltage and making sure the current output increases in proportion. Another factor of the APD that we should consider and test before constructing anything, is the temperature coefficient and the dark current within the device under zero incident photon absorption. The recap, the temperature coefficient is the measure of the voltage change in the device for every degree change in temperature Celsius. The temperature coefficient directly affects the gain of the device; so a 20°C increase in ambient temperature will require a bias adjustment of current bias+0.65*20 to maintain the same gain output. So for testing this constraint we should find/calculate the gain at room temperature, then heat up the APD by some amount and see how much the gain goes down. Finding out the actual response of the APD is very important because this number is going to be what is used when designing the temperature adjustment system for the high voltage power supply. If this number is off, then the gain may be changing which may lead to false measurements. To measure the dark current of the device we must bias the device to achieve our target gain (M=100). So under room temperature conditions, this will be about 134 degrees Celsius. Next and most importantly, we have to cover the viewing window of the APD with something so that no light is able to get into the sensor. This is required because the dark current is defined as the amount of residual current that is present under normal biasing and no incident photonic energy. In hooking up the anode of the device to an oscilloscope, we should be able to measure the small amount of current moving in the device which we will either verify with the datasheet or record for use later in the design process.

The Emco high voltage supply will also need to be exhaustively tested for stability and constant voltage output. This is especially important because this is the device that is going to determine how constant the gain output of the APD is. The main parameters that will need to be tested with this device prior to using is the high voltage output at maximum, the effect of changing the control voltage, and the total current draw of the device under maximum conditions. Testing the high voltage maximum of the device should be fairly easy. By wiring the control voltage to $+V_{cc}$ (5V), the high voltage should be at maximum. The rated max of the A02 is 200 volts. So we should see 200v at the output. Any differences or discrepancies will be noted and considered in further design and testing. Testing the control voltage's effect on the output will be best achieved by using an adjustable voltage source and changing it to observe the change it has on the HV out. Witnessed results should obviously match those of the datasheet.

The testing of the temperature control module is also a fundamental portion to the stable operation of the entire APD module. The first and most essential part of this stage of testing is verifying that the temperature sensor of the module is both accurate to the highest degree and changing in the smallest time interval. The TMP35 temperature sensor circuit is pretty simple, consisting of a resistor to limit current and a capacitor for noise reduction; with its temperature varying output going into the analog input of the MSP430. Once wired and we can verify that the digital output is properly representing the changing temperature we will need to convert that back into an analog voltage that can be fed into the control input of the HV supply. We will need to output of the DAC to be varying from 1.5V-2.25V, as shown in section 3.1.

The next part of the testing process for the APD module is testing the current to voltage converter. The transimpedance amplifier is going to be one of the most sensitive parts of the design, as well as provide many limiting factors on its response. Since we are going to be dealing with pulsed light, the amplifier must be able to jump from one voltage level to another, in a very fast period of time; so a high slew rate will be required. Since many op-amps tend to come in small packages, we will either need to obtain a workable DIP chip so we can prototype with it, or use a surface mount chip and obtain a breakout board for it. It would be best to get a DIP chip so then we can avoid having to solder surface mount parts and risk damaging the chip.

5.2 Optical Testing

Since we are going to be dealing with at least 3 different optical/filtering lenses, we need to be sure that they are properly working before we integrate them into our design and depend on their functionality. For the ranging device, we will be using an optical filter that only lets light pass with a wavelength of about 780nm (+/- 20nm). To test this, we should use a simple photodiode with the filter in front. While having the output of the photo-detector to an oscilloscope and the filter in front, the largest response should occur only when using light of about 780nm. For instance, when doing this, the ambient light from the room should only cause a very small response in comparison to the light from the IR laser. We also must test the functionality of the focusing lenses. The main parameter to test with the lenses is their advertised focal length. This is pretty much the most important parameter and we must be sure that they are exactly correct. This is very important because if we mount the lens at the said length from the detector and it isn't exactly at a focused point, then the detector isn't going to get the optimal amount of light. This could result in a severely attenuated response in comparison to if the beam was properly focused. This will be best tested by using a flash light pointed at the lens to determine at what distance the beam converges to a single point. We must use a flash light because we obviously can't see the infrared light.

5.3 TDC Testing

Since the TDC-GP21 will come in a QFN32 package, we will need a breakout board in order to do prototype testing. The QFN package is 5x5mm with no leads for connection. Attempting to do this without a breakout board would be very difficult. The QFN breakout board is only about 10 dollars and has DIP connections so we will be able to talk to each pin using a breakout board. We will however, still need to get the TDC surface mounted on to the breakout board using the surface mount machine available to us by the Amateur Radio Club at UCF. In our final design, we will have to take this QFN chip back off of the breakout board so we can have it permanently mounted on the PCB board.

Once we have the GP21 mounted on the breakout board, we can commence with testing the SPI functionality to the Arduino development board. We need to power the Arduino board via the USB connector and then connect the GP21 Vcc and Vio outputs to the 3.3V output of the development board. We then need to wire the SPI pins of the GP21 to the SPI pins on the Arduino and begin testing to see if we can correctly modify the registers of the GP21. The Arduino software come with a built in virtual monitor that we can use to perform register dumps on the GP21 and see if our changes are actually being made. Once we see that SPI communication is working between the Arduino and the GP21, and that the control registers are working properly, we can begin testing the TDC's START and STOP1 channels. Before going through the steps to wire the APD circuit to the GP21, we need to ensure that the START channel is functioning correctly by applying an input voltage to it. If the channel is working properly we will see the timeout code (0xFFFFFFFF) in the result register when we perform another register dump. In measurement mode 1, the TDC reaches a timeout at only 2.5µs, and the STOP1 channel is only functional when the START channel has been activated, so testing the STOP1 channel will be rather difficult. We will need to somehow implement a 2 channel voltage source that can activate the individual channels in fewer than 2.5µs, or in lieu of this we can simply wire the GP21 to the APD circuit and actually begin testing the functionality of the TDC, where the STOP1 channel must be properly function in order to see results.

We will wire the GP21 to the APD module as seen in the design portion, as well as to our laser module via the Fire Pulse Generator output. Our testing will likely be done inside of the Senior Design Laboratory, and we will be using a piece of retro-reflective tape to ensure that the pulse from the laser will be returning in the exact direction that it came from. The TDC may encounter trouble when trying to measure distances shorter than a meter (it cannot measure a time difference of less than 3ns), so for this reason our testing distances will begin at 2 meters, and no shorter. We will then use the Arduino software to send the opcode to activate the Fire Pulse Generator on the GP21, which will activate the START channel and the laser module simultaneously. We will then be able to perform another register dump via the Arduino software and virtual monitor to see if the APD module captured the pulsed laser and activated the STOP1 channel.

If all of the circuits worked properly, the timeout code will not be visible when we view the result register and instead there will be a 32 bit, fixed point number in 2's complement format that will represent the distance measure by the TDC. As stated in our design portion, wiring the output of the Fire Pulse Generator to the START channel will cause to TDC to start measuring the time interval before the laser has actually fired (due to the laser's activation time); so the result of our first measurement will actually be larger than the 2 meters that it is supposed to be. We can then find the difference between our actual measurement and what the measurement should be, and result will be the correction factor that we need to use in order to implement the dummy start configuration. To ensure that we are using the right correction factor, we will proceed to do the same test at 3 meters, 4 meters, and so on to see if the correction factor is valid, or if we need to find an average among the differences and use that as our correction factor.

Once we have recorded a solid, usable correction factor, we can implement that in our programming for use in all measurements received from the GP21. We will then begin to write the code that will be permanently loaded onto the ATmega328 for use in our final design. The code will need to initialize the GP21's registers to the correct values upon every startup of the device, as well as delay for the appropriate amount of time for the slower, higher accuracy clock to settle, which will take about 3 seconds. After delaying for the appropriate amount of time, we will then need to enter a loop structure that will constantly wait for the trigger input of the device to be used in order to know when to start the TDC measurement process. Once the trigger is activated, the opcode to start the TDC will begin, and after a delay greater than 2.5µs (to avoid retrieving a result before a result is processed) the opcode to retrieve the ALU result from the result register will be sent. After the result is retrieved the ATmega328 will add the correction factor to the number and then go through the process of converting the number to a usable ASCII character. The code will then send the appropriate text and measurement results to the LCD so the user can view the information. With the measuring process complete, the code will return to the start of the loop and wait for the trigger input from the user to start the process all over again.

5.4 Power System

When the parts arrive for the power system, we can immediately begin testing them to ensure they work. When the battery is obtained, we will give it a full charge to ensure it is at maximum voltage when we initially start testing. To begin, we will hook our battery up to our breadboard. From the looks of the product page, our battery will come with a ribbon that has a two pin connector at the end. For testing purposes, we will run wires into the end of the pins, to the positive and negative connector (denoted as red/black, representing positive/negative) and the other ends into the breadboard. We can now immediately test the voltage of the battery by running our voltmeters along the wires that attached to the pins. After ensuring that the battery has arrived and is up to spec with what the manufacturer sold it as, we can begin testing our voltage regulators. To test the regulators, we will hook them up on the breadboard one at a time, and attach our battery to the input terminals of the regulators. It will take some experimenting with different resistors and capacitors, but in the end we should be able to use our voltmeter and test the output of the regulator to ensure that we are able to get the voltage we need. Also, while our regulators are hooked up on the breadboard, we will get a decent idea of what kind of heat our chips will put off. Because linear regulators shed all excess power, there could be substantial heat dissipation. If the heat dissipated is too high, and we choose, most likely, not to heat sink the regulator, then we will have to change parts. At this stage, we will be able to better understand whether or not the regulators we have chosen will work for our application.

After the battery and voltage regulators have been tested, we can begin to test our project as a whole. When we have the complete power system circuit, we can run other diagnostics on our APD module temperature module to ensure that they will operate fully functionally under the designed power system.

In figure 5.4.1 is the Eagle schematic of our power system. We will employ dual sources, with the positive regulators (7805 and 1117V33) running off of one source and the negative regulator (7905) running from the second source. This is the final schematic that will be used, and from this schematic, we will build the board in eagle to be printed.

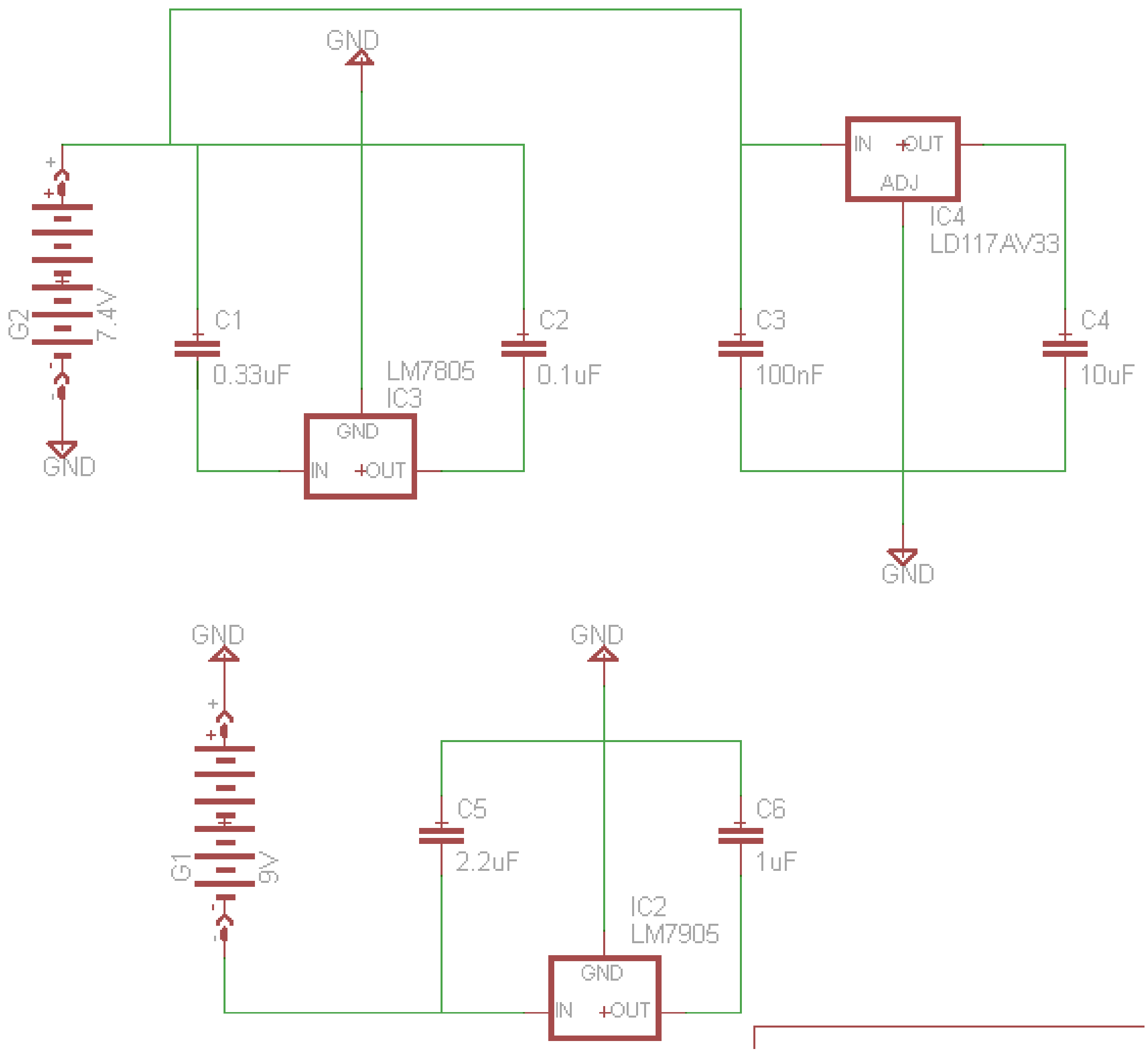


Figure 5.4.1

5.5 Completed Design Testing

The completed design testing will be one of the last steps in the prototyping process. During this testing process, we will test the portable sensing field device is all aspects of our original goal. This will occur when we have all of the separate modules incased in an enclosure with the lenses, LCD and triggering mechanism all in place. Our original ranging goal was to hit 50 meters, however our testing will begin with much shorter distances. As stated in the individual testing of the GP21, we will begin with distances of only a few meters, and progress to further distances as we see fit. Measuring in multiples of 5 meters will ensure that we are not only receiving measurements, but accurate measurement. Starting off in ideal conditions will yield the most accurate and stable results, so initial testing will all be done indoors, at around 25°C or 77°F, which is considered the average standard operating temperature for all of the vital components in our design. As we successfully measure the intermediate distances, and approach the 50m mark, we will also begin testing in non-ideal conditions.

Non-ideal conditions will be the actual proving ground for the ranging function of our device. Theoretically, our design will be able to measure distances of over 300 meters (a time difference of 2.5µs on the GP21 corresponds to round trip distance of approximately 375 meters), and it order to test the quality of our design we should be able to see how close to the 300 meter mark we can get. It will be rather difficult to find an indoor area with a length exceeding 50 meters, so our testing will have to be outdoors and in non-ideal conditions. If we manage to get readings on targets with without the use of retro-reflective tape, we will have achieved our goal for a fully functioning ranging tool. If we fail to get readings in non-ideal conditions, we will consider increasing the power output of our laser, though a 25mW output we should be able to achieve much greater than 50 meters even in non-ideal conditions.

To test the temperature sensing function is working properly, we will also begin with testing over very short distances. As the accuracy declines drastically in direct proportion to the distance of the target, we will be able to get our best results in the sub 1 meter range. We feel that testing objects that are below room temperature will be the best way to start. We can begin by filling a small container with refrigerator temperature water, wait for the surface of the container to cool down close to the temperature of the water, and then begin taking measurements to see how accurate our device is. We will use a standard liquid based thermometer to take a reference reading to compare to our results. If we see success at closer ranges, we will begin to increase the distances to the object we are taking readings of, though at each increased distance the size of the object that we are taking a reading of will have to be increase.

Chapter 6 Administrative Details

6.1 Milestone Chart

The following milestone chart is a tentative schedule of the design process for the portable sensing field device. While it is accurate for the research data, some if it may change once we get into prototype testing. The first few months of senior design 1 will be dedicated to researching different methods of implementing our design. This will include looking into the feasibility of what we are attempting to do, as well as reviewing similar projects by other people. The remaining months of the class will be spent designing the project itself. This will consist mostly of using multisim simulations as well as testing code in C. The start of senior design 2 will be spent ordering parts and beginning the prototype stage. The later end of the class will be used testing and possibly redesigning certain parts when needed. Figure 6.1.1 summarizes the milestone chart that we wish to use as a guide of goals.

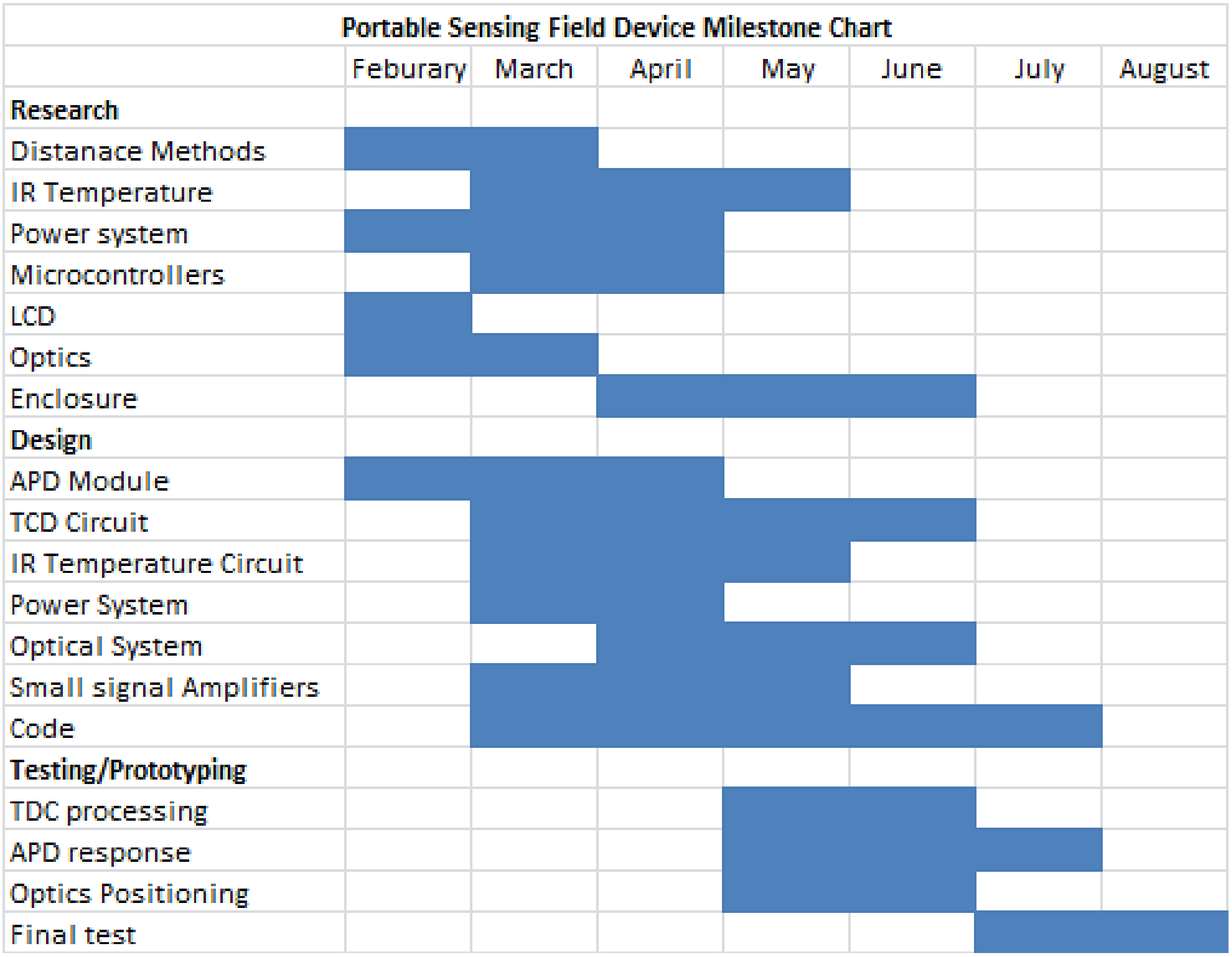


Figure 6.1.1

6.2 Estimated Bill of Materials

Our bill of materials will serve as our estimate of how much we were going to spend in materials when designing and building a functional prototype. While the following table includes most of the important parts, it cannot take into consideration parts required from redesign and broken parts. We are bound to most likely break something when designing this and will likely require us to go out and purchase another of the same part. There is also likelihood that we will redesign some parts of the system while in the prototype stage. The following table gives a brief baseline of how much we should spend.

Name	Source	Cost
TDC-GP21 (QFN)	Transducers Direct	$35.00
Arduino Dev Board: ATMEGA328	Element 14	$30.00

QFN32 Breakout Board	Proto-advantage	$13.99
780nm Laser Module	Aixiz	$13.00
16x2 LCD	Spark Fun	$13.95
Various Resistors	Anywhere	*$5.00
Various Capacitors	Anywhere	*$5.00
MSP430 Launchpad	TI.com	$4.30
PCX 25mm Optical Lens - NT65-524	Edmund Optics	$40.00
780nm Optical Filter - NT65-723	Edmund Optics	$99.00
Li-ion 7.4V 6600 mAh	Battery Junction	$62.95
LM7805 +5V Regulator	Spark Fun	$1.25
LM7905 -5V Regulator	Fairchild Semiconductor	$0.60
LD1117 3.3V Regulator	Spark Fun	$1.95
DS18B20 temperature sensor	Spark Fun	$4.25
Melexis MLX90614 IR sensor	Spark Fun	$19.95
Fresnel Lens	N/A	Salvaged
Hamamatsu S2381 APD	Hamamatsu	$76.00
Emco A02 DC - HV DC	Emco	$59.00
High Speed Op-amp x4	Various	*$10.00

**Denotes rough estimate*

Table 6.2.1

Though our aim is to keep the project “cost effective” like every company does with any product they develop, we will not skimp on parts in order to save a few bucks. Since this is a learning experience, and one we would like to take full advantage of, and using cheap parts that break or don’t work upon arrival.

6.3 Breakdown to Responsibilities

This project, being a heavily involved group initiative, required that each person achieve their individual goal and responsibility. The scope of this project is too much work for any one person, but when broken down across the talent of 4 capable engineers, it is well within reach. The individual assignments of each member included researching the function, designing a capable system, and methods of testing that function. The subsystem assignments and member responsibilities are shown in the table below:

Function	Group Member(s)
APD Module	Joel
Infrared Temperature Module	Khoa
MCU Design/Software	Rob

Power system Design	Dawson
TDC Processing	Rob
Optics System	Joel and Rob
LCD output system	Khoa and Dawson
Project Enclosure and Mounting	All
PCB Design	All

Table 6.2.1

Each group member was responsible for the individual research for their section. Weekly we met on Wednesday's to ensure that the project was coming along and that we were all working toward the same goal in the end. Also, because each individual part of the project is dependent upon the rest of the pieces, we had to make sure during meetings that each member was informed by the others how they were planning to design certain things. This kept us from researching things that would not have made sense because they wouldn't work together.

The report represents our tentative design plan. While this document includes most details of how we will build this project, much of the design is likely to change as we start building. There are always unforeseen things that will happen when building a prototype and during this, we will probably have to redesign some parts. Though we may end up changing some of the design, the core requirements should still be met. This means we will not astray from our own specifications just because something did not work first go. This project will be a difficult undertaking for the group and should be a worthy test of the skills that we've obtained over the years.

1. Ensure that the 9 volt batteries are connected to the battery terminals.
2. Put the switch into the “on” position.

FOR TEMPERATURE

1. Hold the device in your hands securely and aim the sensor in the direction of the area you wish to read the temperature of.
2. Look to the LCD on top of the enclosure for the readings.
3. In the top left is the ambient temperature.
4. In the top right is the temperature of the area you are trying to read.
5. Bottom right is a minimum/maximum reading, with the minimum on the left and the maximum on the right.
6. Bottom right of the LCD is a graph showing the rise and fall of the temperature reading.

For Ranging

1. Aim the laser mounted in the device at the location you wish to read the distance from.
2. Displayed on the LCD will be the total distance between the target and the face of the sensor.

Chapter 7 Appendices and Citations

A. References and Citations

Avalanche Photodiode

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B Permissions

- Adam Palmentieri, Hamamatsu Photonics via email.

Hi Joel,

Unfortunately, we do not have an exact equation you can use to determine the exact reverse voltage required at a specific gain. Every APD had different characteristics that will slightly change the reverse voltage/gain functionality. The information we provide on the specification sheet is a typical value only. When you purchase the APD, we also provide a sticker that informs you of the breakdown voltage for your APD.

Regarding our images/information. Please feel free to use the Hamamatsu Images and information. As you stated already, we only ask that you please include us in the citations.

If you have further questions, please let me know.

Best Regards,
Adam Palmentieri
HAMAMATSU
PHOTON IS OUR BUSINESS
Application Engineer
(P) 908-252-7747 | (F) 908-231-1539
http://sales.hamamatsu.com

- Todd Danko

Todd Danko to joel.yello show details 10:44 PM (8 hours ago) Reply

Hello Joel Yello,

Thank you for asking permission. You may use any materials on the website that you found for your class report. I would also suggest that if you wish to implement something like this that you use OpenCV rather than what I initially did.

Good Luck,
Todd

From: joel.yello@knights.ucf.edu [mailto:joel.yello@knights.ucf.edu]
Sent: Tuesday, April 19, 2011 6:14 PM
To: todd.danko@gmail.com
Subject: Permission to use images

Hello,
I found your work about your web cam based range finder to be quite useful. I am a student at the University of Central Florida and am working on a similar project. I would like to ask your for permission to use your images and/or research in my class report (with proper references and citations of course). I am speaking mainly of the following page.
http://sites.google.com/site/todddanko/home/webcam_laser_ranger
Thanks for your time,

-Joel Yello

Hello Robert,

We will allow you to use the images in your paper as long as you mention Transducers Direct / ACAM in your paper. Also, we would like to feature your paper on our website, promoting how engineers and engineering students are using ACAM parts on innovative projects. The way I envision it, this will be a new section on our site featuring papers like yours and other engineers that have published. Let me know what you think. It might be an opportunity to put it on your resume that your work is being featured. Just a thought...

Best Regards,
John

John Monteith
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Cincinnati, OH 45249
Office: 513-583-9491
Cell: 513-720-7597
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www.acam-usa.com

RE: Contact Us - Technical Support - United States

To see messages related to this one, group messages by conversation.

Full view

Robert Pribyl
To steve briggs

4/23/11
Reply

Steve,

I just want to thank you for all of you help with this subject, things are beginning to come together for this project. As a part of this class, we are required to provide a document summarizing our work and research efforts, and I would like to include some of the images from the Edmund Optics website, specifically the transmission properties of various lenses and filters. Are you authorized to give permission to use these images in our report? There will be no profit made on this paper, however it will be published electronically for anyone to use as reference.

Regards,

Robert Pribyl
Student-UCF