Laser Rangefinder

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***Abstract* — A low-cost light radar (LIDAR) system has been developed in order to supply comparable features of higher priced alternatives. A LIDAR system is relevant for a variety of applications including topographic mapping and surface modeling. Of the many ways to implement such a system, our project will encompass the time-to-digital conversion (TDC) methodology. This design aims to provide precise range-finding and mapping at a price-point that is economically feasible for the general public. We intend to incorporate scanning functionality to our system that allows for a more natural mapping of environments. The challenges presented and solutions investigated are detailed within our paper. A variety of topics are considered from optical, power, and motor control to external communication and data visualization.**

***Index Terms* — Laser radar, measurement by laser beam, optical pulses, time measurement, visual databases.**

I. INTRODUCTION

Intrigued by the increasing popularity of Lidar technology, the Laser Rangefinder serves as a device that provides accurate distance measurements using laser technologies. Lidar devices use laser technologies to measure the distance to objects by calculation the amount of time it takes for the laser light to hit a target and bounce back. The Laser Rangefinder accomplishes this same goal but at a much lower cost. This device uses a rotating scanning process to take distance measurements of the surrounding environment. These measurements are then displayed on a computer program in the form of meters and are represented on a Cartesian graph as points within a circle to outline the differences between each distance measured. Using high-speed electronics, optics, and motor capabilities, the Laser Rangefinder successfully scans environments to determine the distance to the different targets within its detection range.

II. SPECIFICATIONS

In order to keep the making of the Laser Rangefinder at a low cost, we had to determine feasible and realistic specifications that would still make the device a considerable candidate for a senior design project. A viable detection range was crucial to adhere to the standards of this project. The detection range is defined as the distance at which the laser sensor can accurately obtain measurements from the device to the target based on the reflected light of the laser being fired. This device can measure distances of targets in the range of 0.1m to 10m, which is substantial enough considering our budget. The accuracy of the distance to the target is dependent upon the size and reflectivity of the target. If the size of the target is small, then there is less surface area for the laser beams to hit. This means that the device may not gather some of the laser beams. This will result in a skewed distance reading. Light can be absorbed by less reflective surfaces. Therefore, if the surface does not have sufficient enough reflectivity there will be less beams that make their way back to the device. The most accurate distances that the Laser Rangefinder can measure are for targets such as a mirror that provide the highest reflectivity resulting in a lower margin of error.

Another specification of the Laser Rangefinder is its field of view. The field of view is the area to be considered when measuring a point. The field of view range for the Laser Rangefinder is 120 degrees because it is has a rotating range of 120 degrees and the transmitting and receiving optical lens are displaced close enough together that no matter where the laser is transmitted it will always be received.

The Laser Rangefinder has a scanning frequency of 1Hz. This means that the device makes one full rotation per second. The amount of points measured within each rotation of the Laser Rangefinder is approximately 100 points. This gives the Laser Rangefinder enough measurements to accurately determine distances for each scan of its surrounding environment.

III. DESIGN

The high-level design of the Laser Rangefinder consists of two major components: the rangefinder module and the base module. The rangefinder module is the part of the device that actually determines the distances to targets. The base module is used to secure the rangefinder module while also rotating it between -60 degrees and +60 degrees. The rangefinder is fastened on top of the base module using McAster bearings to eliminate slipping and errors caused by vibrations as the motor continues to rotate. The Laser Rangefinder will process and output distance measurements to the connected external device, such as a computer. Once the computer receives the data, it will be presented using demonstration software. Figure 1, Figure 2, Figure 3 and Figure 4 show different views of the internal and external mechanical design of the overall system, respectively.

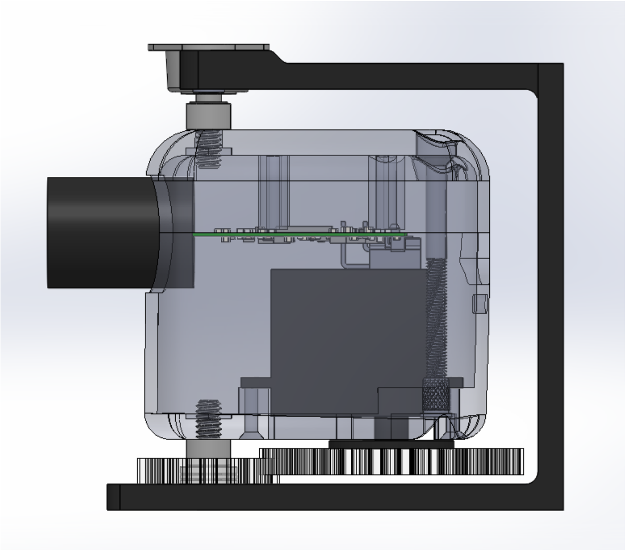

Fig. 1. A side-view of the internal mechanical design of the Laser Rangefinder. This design was used for 3D printing.

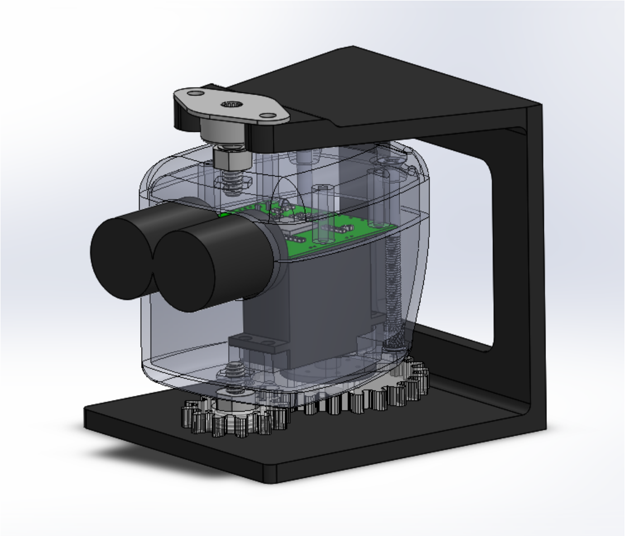

Fig. 2. A 3D view of the internal mechanical design of the Laser Rangefinder. This design shows the positioning of the microcontroller within the casing of the Laser Rangefinder.

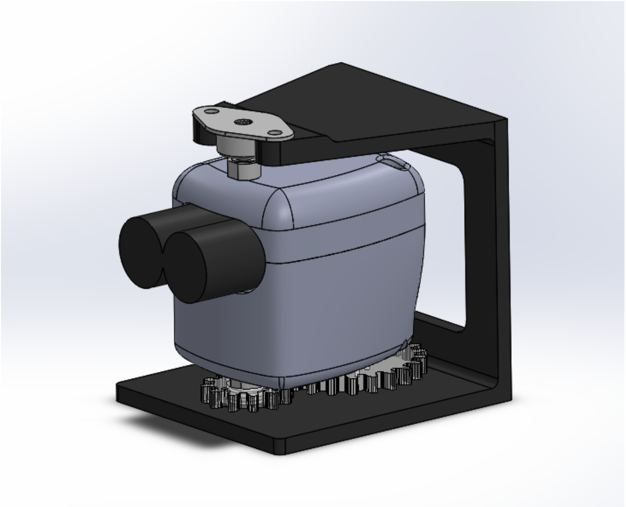

Fig. 3. A 3D view of the external mechanical design of the Laser Rangefinder. This design was used for 3D printing.

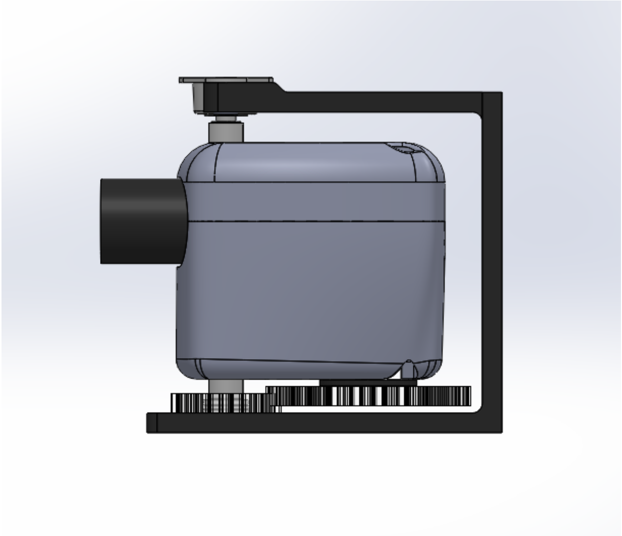

Fig. 4. A side-view of the external mechanical design of the Laser Rangefinder. This view shows the 2:1 gear ratio gear trains that were used.

A. Overall System

Figure 3 represents the communication between each component of the overall system of the Laser Rangefinder. The process begins once the microcontroller is connected to power. It then initializes and synchronizes the time-to-digital converter, the laser optics, and the motor and encoder. Once each electronic component has been synchronized, the microcontroller signals the time-to-digital converter to begin its time-of-flight process. Once the time-of-flight process has begun, the laser diode within the laser transmitter component is signaled to begin producing a laser. The laser receiver is then notified to catch the incoming laser signals and once it has accomplished that, the time-to-digital converter stops it's clock that began just before the laser was transmitted. The time is then sent back to the microcontroller, which then processes this information to convert it to applicable distance measurements. This data is then sent to an external device, where the onboard CPU relays the data to a graphical user interface for demonstration. While the microcontroller communicates with the time-to-digital converter it is also communicates with the encoder to control the speed and steps of the motor as well as to determine and control the angular position of the encoder for further data manipulation. This allows for the data from the surroundings to be mapped into a 2D area space.

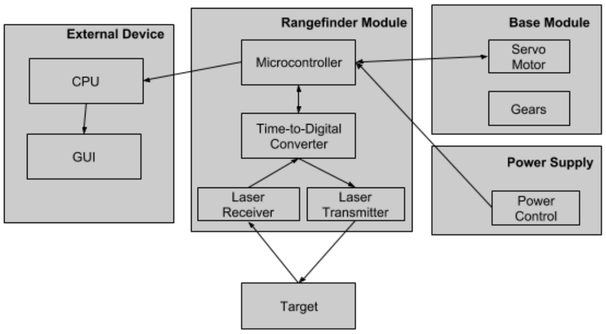

Fig. 5. A hardware block diagram of the Laser Rangefinder's components and the communication lines between each of the components.

B. Rangefinder

The rangefinder module of the Laser Rangefinder uses a STM32F427 microcontroller. This 32-bit microcontroller, manufactured by STMicroelectronics has 1024 KB of FLASH memory the will be used to store the firmware for the device. This particular chip also contains a floating-point unit, which will be used to calculate single precision floating-point operations. This precision will allow us to calculate distance within ranges of a tenth of a meter rather than having to round to the nearest whole meter. This chip is also power-effective because it has the ability to drop down to lower power mode while it is waiting to read a range from the time-to-digital converter. This allows for the device to operate for a longer constant period of time, which is necessary for accurately measuring larger environments such as a room. The final deciding factor other than the balance between the cost and features offered by this MCU was its clock speed that functions at 180MHz. This is a perfect speed that not only meets our specifications, but also keeps up with the time-to-digital converter.

One of the most crucial electronics on the rangefinder module is the time-to-digital converter. The Laser Rangefinder uses Texas Instrument's TDC7200 to count the time it takes for the laser to leave the transmitter and return back to the receiver. It interfaces with the MCU through SPI. The TDC7200 measures distance using the time-of-flight design approach. This approach is accomplished with the use of a high-speed digital counter. This counter is started at the exact time the laser diode is pulsed. The counter increments until the scattered laser beams are collected by the photodiode. At this point, the result is stored in the digital counter and which then sends a signal that it is ready to be read by the STM32F427. Figure 3 shows a vague view of the design of the measuring circuit.

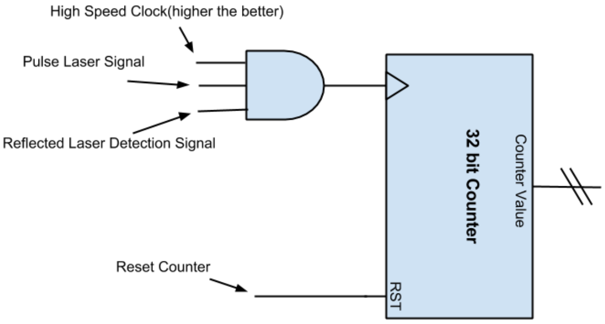

Fig. 6 Time-of-Flight Measuring Circuit: The counter is controlled by the incoming high-speed clock, pulse laser and reflected laser detection signals.

The TDC7200 has two different modes for measurement: one mode that excels at fast measurements and another that excels at slower measurements. For the purpose of the Laser Rangefinder, the TDC7200 will operate in mode 1, because laser measurements are typically measured in the picosecond range and this mode is intended for measurements times less than 500 nanoseconds. In this mode, as shown in Fig. 7, [1] says that the TDC7200 performs the entire counting from START to the last STOP using its internal ring oscillator plus coarse counter.

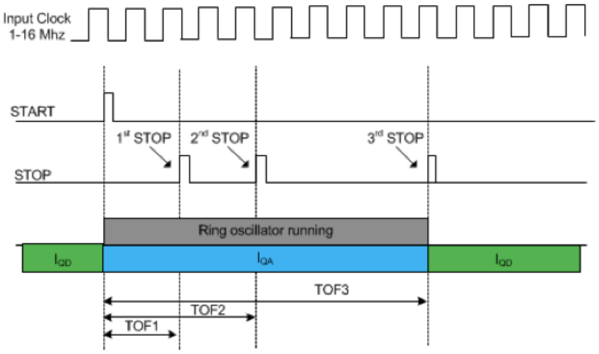

Fig. 7. Measurement method of the TDC7200 when operating in mode 1.

Under this mode, the time-of-flight between the START and the nth STOP can be calculated using the following equation:

$$TOF_n = (TIME_n)(\mathrm{normLSB}) ,$$

$$\mathrm{normLSB}=\frac{Clock_{period}}{calCount} ,$$

$$calCount = \frac{CAL2-CAL1}{(CAL2_{periods})-1} ,$$

Where:

- TOF$_n$ [sec] = time-of-flight measurement from START to the nth STOP,
- TIME$_n$ = nth TIME measurement given by the TIME1 and TIME6 registers,
- CLOCK$_{period}$ [sec] = normalized LSB value from calibration,
- CAL1 [count] = TDC count for first calibration cycle,
- CAL2 [count] = TDC count for second calibration cycle, and
- CAL2$_{periods}$ = setting for the second calibration cycle; located in register CONFIG2 (1)

The accuracy of this design is dependent upon the speed of the counter and the resulting distance based on this speed is calculated as follows

$$DISTANCE_{TICK} = SPEED_{LIGHT} * COUNT_{CLKPERIOD} , \quad (2)$$

Where $DISTANCE_{TICK}$ is effectively the distance resolution of the Laser Rangefinder. The TDC7200 allows for a counting resolution of 55 picoseconds with a standard deviation of 35 picoseconds. This allows the Laser Rangefinder to measure distances within 12 to 500 nanoseconds of the start pulse. As suggested in [1], the standard deviation can be decreased by increasing the external clock towards 16MHz as depicted in Fig. 8.

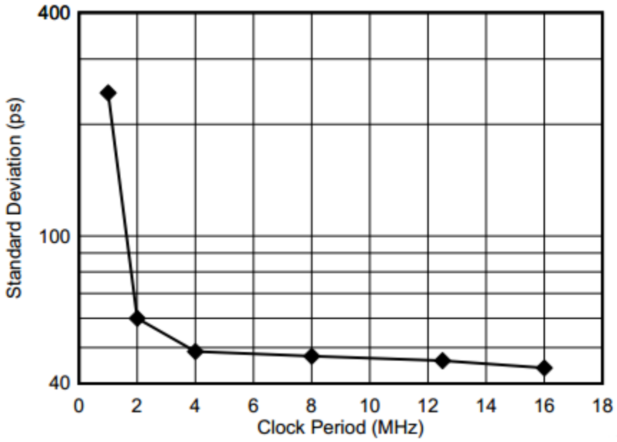

Fig. 8 The relationship between the measurements of the standard deviation vs. the clock period of the TDC7200 (Courtesy of Texas Instruments).

There are many other parameters that are worth considering when calculating the distance. These parameters include: the peak power of the laser, the amount of divergence of the laser beams, the type of optical lenses that are used, the sensitivity and bandwidth of the photo-detector, and the accuracy of the pulse shape from the photodiode as well as the accuracy of processing the signals throughout the circuitry.

The accuracy of the measurements calculated by the Laser Rangefinder are not limited to the resolution of the clock alone, but also the rise time of the laser diode. However, before discussing the effects of the diode's rise time, it is important to understand how the laser diode operates.

The optics consists of a LightWare Optoelectronic's OSLRF-01 optical lenses. As seen in Fig. 1, the Laser Rangefinder has two optical lenses, one for the transmitting end (a focusing lens) and the other for the receiving end (an optical filtering lens). The transmitting end of the optics contains an SPL_PL90 laser diode, made by Osram. It is a pulsed laser source with an optimal peak power of 25W. This laser diode is most suited for a laser pulse within the 1 to 200-nanosecond range, and therefore fits directly in the range of the TDC7200 as far as being able to count the pulse time. This laser is driven using a MIC44F18 MOSFET driver who receives voltage from the power supply and in turn transmits that voltage to a BSP318S avalanche SIPMOSFET. This controls the current that is supplied to the laser source. The SPL_PL90 laser diode has a typical rise time of 1-nanosecond, which allows for accuracy within a three-tenths of a meter. The importance of the effects of the rise time of the photodiode is best described in Fig. 9.

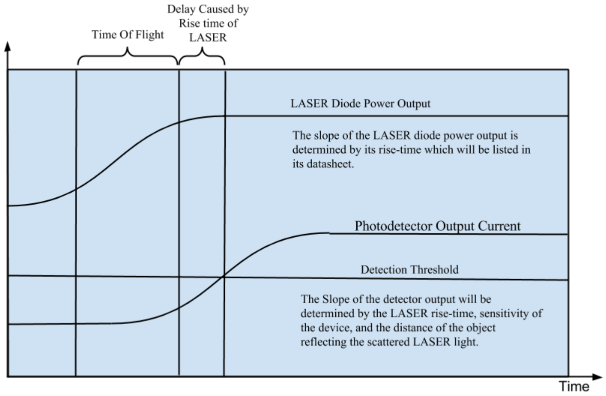

Fig. 9 The effects that the rise time of the photo diode has on the accuracy of the system.

If the delay after the time of flight delay was constant, it could be easily factored out in the final calculation of distance. Unfortunately, the delay is also dependent on the distance of the object reflecting the light back to the device. The reason the delay changes with distance is because the output of the photo-detector will be different amplitudes based on how far the object reflecting the light is from the device. The time it takes for the output to reach its maximum will be the same; however the time it takes for the output to cross the detector's threshold will change. The best way to reduce this time variation is to make sure the laser diode has a very short rise-time, and that the photodiode has a very quick response. There are also other ways of reducing the error caused by this effect. For example, using a peak detector circuit to track the maximum pulse amplitude and then using that peak to adjust the detection threshold may prove to be an effective way of canceling out this time variation. Another way to help mitigate this effect is to incorporate automatic gain control (AGC) into the transimpedance amplifier so that the smaller pulses will be amplified to be the same amplitude as the larger pulses. The way that AGC works is it measures the peak of each pulse using a high-speed peak detector circuit. If the peak is less than the desired voltage, then the circuit will adjust the gain to be higher. If the peak is larger than the desired voltage then the circuit will adjust the gain to be lower. As the peak gets closer and closer to the desired output voltage, the gain does not change as much. This system is design to be a negative feedback loop that will close in on the correct gain to use for the incoming laser pulse. Making sure each pulse has the same amplitude ensures that all of the pulses pass the threshold voltage at the same part of the waveform, which will eliminate the time variance of the detection based on distance of the object being detected.

On the receiving end of the optics lies a SFH2701 photodiode that is also made by Osram. When the incoming laser beams excite the photodiode, it produces a quick and brief current pulse. This pulse is too fast for the TDC7200 to detect, so it travels to a MAX3658AETA+T transimpedance amplifier. The amplifier receives the current pulse produced by the photodiode and converts it into a voltage. This voltage signal is then sent to the TDC7200 to stop the clock counter.

C. Base Module

The scanning feature of the Laser Rangefinder system is guided by the motor control of the base module. This subsystem makes use of controlled motor operation as well as position encoding. The motor is a typical brushed DC motor that provides a simple and efficient way to achieving rotation of our system. Our specifications have set our goal to rotate the system at 1Hz. Given this specification, a motor that provides at least 60 RPM will meet this goal. To safely operate the motors a motor driver is required which using an H-Bridge MOSFET configuration alongside a Pulse-Width Modulator (PWM) component. Using PWM, it is possible to accurately control the output of the motor by altering the duty cycle of the signal sent to the motor. Incorporating a motor driver is an uncomplicated process. A single IC can often operate several motors simultaneously, however for our purposes a single motor will be used to rotate the system.

The structure of brushed motors do not allow for accurate position or speed control natively. In such a scenario, a motor encoder will be implemented to allow the correct angular positions of the system to be obtained, communicated to the rangefinder module, and ultimately interpreted visually on an external computer. Due to the importance of high precision position and speed manipulation of our project, it is imperative to maximize the operation of our motor encoders in order to achieve our project specifications. There are many noted factors that can enhance the operation of encoders. Encoders have a measured specification known as resolution. The resolution of an encoder is the position points per turn the encoder is capable of reading. This is often expressed in terms of bits. For instance, a 10-bit encoder corresponds to 2^{10} or 1024 discrete points for each turn. The higher the resolution of the encoder the higher control of the motor and the more precise the position reading will be. Our specifications have a design goal of 100 discrete points per turn. In order to meet this specification, an encoder with at least 7 bits of resolution is required, which provides 128 discrete points per turn.

The accuracy of the encoder must also be considered when striving for high precision measurements. The accuracy of the encoder can be thought of the relation of the theoretical shaft position versus the actual shaft position. The theoretical position is what would be read by the encoder and relayed to various other components, whereas the actual position would be where the motor shaft is position is reality. The closer the theoretical position is the actual position, the more accurate the encoder is. Accuracy is not based on resolution. A high-resolution encoder can still be inaccurate if error between the theoretical and actual position remains. Accuracy is dependent on the entire operation of the encoder and can be affected by minute mechanical imperfections. When using optical rotary encoders, the function of the encoded disk is the primary contributor to overall accuracy. Typical encoders provide accuracy on the order of 0.1 to 50 arcminutes (1.67 to 833 millidegrees).

Repeatability is an important factor that deals with an encoder replicating a shaft position. This can be potentially important if our project requires a specific position to be set on the motor repeatedly or if data coming from a particular position must be manipulated. In either case, repeatability relies on the encoder reading identical codes for the motor position. This allows the motor to be moved to the same position consistently. Repeatability is not dependent on the accuracy of the encoder. It simply depends on matching coded positions. If the encoder is inaccurate, a specific position will still be correctly repeated, however the repeated position may not match the actual position the designer is intending to find. Typical encoders provide repeatability that is precise to 0.01 to 5 arcminutes (0.16 to 83 millidegrees).

D. Demonstration Software

In order verify that the device is working correctly it is important to be able to visualize the data in a meaningful way. The method used to visual the data coming off of the device was to connect it to a computer's USB port and pipe the data from the USB port to a visualizer that runs in the browser. The data visualizer displaces the data points on a 3D plot and allows the user to move the camera around to focus on different areas of interest. If the device is working correctly, then the user should be able to identify key points on the data plot that resemble obstacles that are placed in front of the device. Figure 10 illustrates the data visualizer running off of simulated data. The data points vary in color from green to red to show how old a data point is. As time progresses, the data points will slowly fade from green towards red.

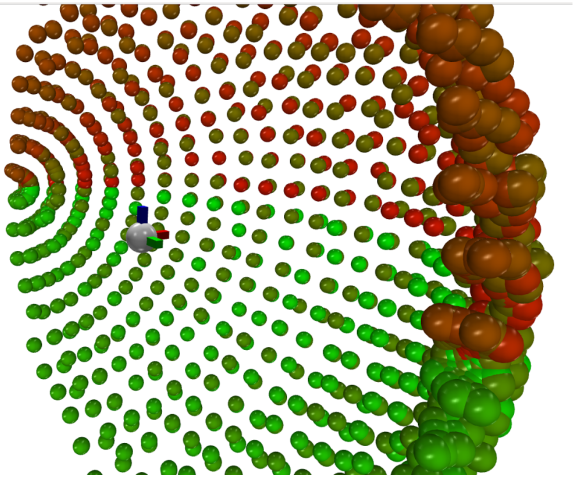

Fig. 10. Example of the data visualizer running in a browser. Note that the visualizer shown is visualizing simulated data.

One of the main benefits of being able to display the data in a browser is that other computers and smartphones are able to visualize the data without having to connect to the physical device. In order to achieve this, a main computer must connect to the device through USB. Then the computer runs the server that receives the data from the Laser Rangefinder and serves it to the web client. Once this is done, all of the devices that are connected to the same network can load the visualizer by typing the main computer's IP address followed by ':3000'. (For example: 192.168.1.102:3000). Additionally, a port can be forwarded on a router in order to allow the visualizer to be accessible on the World Wide Web.

The server is written in Javascript using a Javascript runtime called NodeJS. The benefit of NodeJS is that it allows Javascript code to be ran without a web browser and it has a bunch of built in libraries for designing server code. The NodeJS server connects to the data server using TCP/IP, and serves the web page to a browser. In order to run the server the user must make sure that they have NodeJS installed on their computer. Linux, Mac, and Windows support NodeJS so the server is very versatile.

The client is written in HTML and Javascript because it is designed to be loaded in a browser. The client using a html5 canvas to create a WebGL context. Once the WebGL context is initialized, the client begins receiving data from the NodeJS server, and plotting the data points in 3d. In order to run the client in a browser it is important to make sure that WebGL is supported and enabled in the browser settings.

Once the NodeJS server is running the user can open their browser and connect to the server by typing in the server IP and port. Any computer that is connected to the same subnet as the NodeJS server can load the webpage and view the data coming from the Laser Rangefinder. The benefit of being able to view the data in a browser is that now smart phones can access the data coming from the Laser Rangefinder, and with the correct port forwarding, the Laser Rangefinder data can even be viewed remotely.

IV. POWER MANAGEMENT

Many options are available in regards to supplying power to our system. Amongst the countless choices we selected a secondary source coming from a Lithium-Polymer (LiPo) battery. LiPo is a relatively new technology with many similarities to Li-Ion. LiPo has a higher gravimetric energy density than Li-Ion, which can allow for a lighter system while maintaining its power output. The EFLB12502S is a 2-Series LiPo battery. 2-Series refers to the two LiPo cells connected in series, which increases the output voltage. This battery has a capacity of 1250mAh, which is more than enough to support a continuously running system that can operate for hours at a time. LiPo batteries also have a better form-factor. While Li-Ion batteries typically come in rectangular and cylindrical packages, LiPo is capable of much slimmer shapes, commonly being manufactured in thin silver packs. Many LiPo packs are as thin as a credit card however these packs mostly cannot store the amount of energy needed for our purposes. Although both lithium-based chemistries require care for safe usage, LiPo batteries are more tolerant that Li-Ion in terms of handling overcharges, reducing the chances of the battery operating in an unsafe manner.

Different components have different power needs and each must be properly addressed for the successful operation of the project. To supply various ranges of power, regulation is used. Depending on the circuit, voltage can be decreased or increased to match the necessary levels of each component. Our project will make use of Series connected LiPo battery pack which gives a nominal voltage of 7.2 V. The voltage can be easily stepped-down to the specified microcontroller level using DC-to-DC conversion. The TPS62142 is a part of a family of regulators that offer a practical combination of cost, efficiency, and PCB footprint. At 87.7% efficiency the IC has only a footprint of 63 mm^2. The topology is based on the Buck regulator, which is the most common type of switching regulator, dropping the supply level to the desired output value. The set-up involves capacitor and sometimes inductor storage elements and a PWM circuit. A switch, realized as a BJT is opened and closed allowing energy to be supplied and retrieved from the storage elements. The switching frequency of the TPS62142 is 25MHz while the regulator supplies a maximum of 2A of output current. A schematic of the TSP62142 step down regulator is shown in Fig. 11.

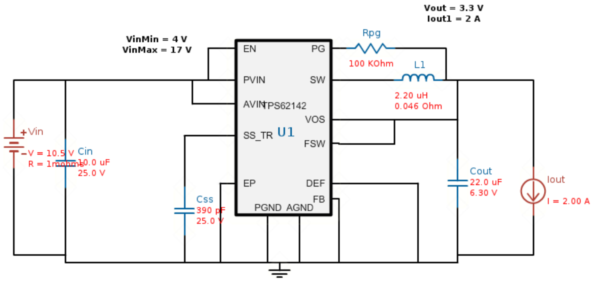

Fig. 11. Schematic of the TSP62142 step down regulator.

V. TESTING

The testing procedure of our Rangefinder module included wiring the module to a power supply and oscilloscope. Two probes were used to monitor the operation of the module. One probe connected to the output of the TDC7200. The TDC7200 connects to the transimpedance amplifier. This amplifier in turn connects to the photodiode of the receiver circuit, causing the current pulse from the photodiode to be converted to a voltage signal. The other probe monitored the output of the laser driver, which is connected to both to the laser transmitter and a timing circuit. Using these probes, the time-response waveform for the laser transmitter and receiver is displayed upon the oscilloscope. The pulse sent from the receiver is shifted compared to the transmitter and converting this time shift to a measurement of distance is a small task. Our preliminary test showed our rangefinder had a range of approximately 1.5 meters before the receiver output dropped below our comparator threshold. It was noted that lowering the threshold allowed for extended range however it was also observed that lowering the threshold made the triggering of the comparator overly sensitive and unreliable. Further tuning of the optical circuit improved the range further to approximately 3 meters. During our testing, it was found that when the rangefinder was aimed towards glossy materials, the range was lengthened even further. The information gathered from these preliminary set-ups was vital for subsequent designs.

VI. CONCLUSION

The design and development of the Laser Rangefinder has pushed us to some of our most challenging obstacles. We overcame many learning curves such as communication in a group setting to accomplish the same goal. We are extremely proud of the limits we were able to push and still be able to accomplish our desired intentions for this project. We look forward to taking the knowledge and skills we've gained from this project to benefit each of us as we endeavor into our individual careers.

The design of the Laser Rangefinder will be much cheaper than most available lidar systems that can be purchased. The reason this lidar design can be cheaper is because it does not have nearly as good performance as other available systems. The main area where more expensive lidar systems outperform this lidar is in scan rate. This design only allows for a scan rate of about 8 scans per second whereas many of the expensive systems are capable of upwards of 50 scans per second. This design is also not nearly as accurate as some of the available products that can have up to sub-centimeter accuracy. For hobbyists this is still a good option because most people do not have enough money for the high-performance lidar systems that are currently available.

ACKNOWLEDGEMENT

We wish to thank the UCF faculty who have helped support and guide us throughout the making of this project.

REFERENCES

[1] Texas Instruments, "TDC7200 Time-to-Digital Converter for Time-of-Flight Applications in LIDAR, Magnetostrictive and Flow Meters," SNAS647C datasheet, Feb. 2015 [Revised Aug. 2015]

ENGINEERS

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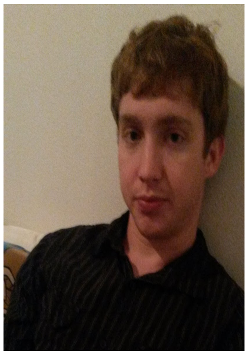

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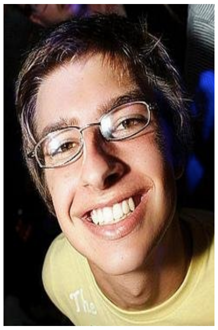
Jackson Ritchey is a senior studying Computer Engineering at University of Central Florida. He plans to graduate December of 2015. He has been working as an intern for 3 years at Tesseract Sensors where he has helped with development of a variety of different technologies. He plans to go into the field of software development when he graduates.

AARON SMEENK



Aaron is a senior studying Electrical Engineering at the University of Central Florida. He has been working at Tesseract Sensors for four years. He is currently specializing in high-speed PCB designs.