ECE 4040

Electronics Design Project

Optical Range Measurement System
For Control of Autonomous Vehicle

Final Report

Spring 2000

Students:

Instructor:

Dr. Martin Brooke

Date Submitted: April 25, 2000
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview</td>
<td>1</td>
</tr>
<tr>
<td>Theory of Operation, Range Detection</td>
<td>1</td>
</tr>
<tr>
<td>Component Selection</td>
<td>3</td>
</tr>
<tr>
<td>Safety</td>
<td>5</td>
</tr>
<tr>
<td>Laser Module Drive Circuit</td>
<td>6</td>
</tr>
<tr>
<td>Detector Circuit</td>
<td></td>
</tr>
<tr>
<td>Design and Simulation</td>
<td>11</td>
</tr>
<tr>
<td>Assembly and Test</td>
<td>14</td>
</tr>
<tr>
<td>High Gain Amplifier Circuit</td>
<td>16</td>
</tr>
<tr>
<td>Integration</td>
<td>17</td>
</tr>
<tr>
<td>Range Results</td>
<td>18</td>
</tr>
<tr>
<td>Conclusion</td>
<td>19</td>
</tr>
</tbody>
</table>
Overview

The objective of the project was to design a laser based reflective type distance measurement module. The proposed maximum range of this device should be approximately 20 feet. This unit would directly interface and provide range information to the control system electronics of an autonomous vehicle.

One phase of the design was to develop, assemble, and evaluate transmit and detector circuitry for the laser ranging system. Main concerns were maximizing the range of the system and minimizing power consumption. The transmit circuit would consist of a single supply laser module driver while the detector circuit would incorporate a sensitive photodiode amplifier and a high-Q band-pass filter.

The last part of the design was to put together a high gain amp for the front end of the detector circuit, integrate all the components of the system, and make a determination as to the maximum range.

Theory of Operation, Range Detection

The theory behind the range detection system is to send a highly focused beam of light from the front of the vehicle and have the reflected light received and processed for relevant distance information to the reflecting object. Four possible system types will be examined in this effort. Figure 1 is a basic block diagram around which each of these systems can be designed.
The first method is based on the time of flight measurement of a single pulsed light signal. The time delay between the transmitted pulse and the received pulse would be measured, and the distance calculated from the following formula:

$$d = \frac{V_p \times t_d}{2} \text{ ft.}$$

$$V_p = \text{speed of light} = 1 \times 10^9 \text{ ft/sec}$$

$$t_d = \text{measured delay time}$$

Given that light travels approximately one foot every one nanosecond, a 1 GHz clock signal would need to be used for a resolution of 0.5 feet (1-foot roundtrip). This translates into a resolution of approximately 5 feet for a 100 MHz clocked system.

The second approach is to drive the transmitter with a periodic square wave signal and measure the phase shift of the returning signal. The distance of the reflecting surface
could then be determined from this phase shift in a mathematical manner similar to the single pulse operation, replacing the pulse return time with the phase shift time.

The third idea is to send a continuous wave of light from the transmitter and measure the power of the received signal. This power level could then be constantly monitored and interpreted to provide range information, taking into account that the level will decrease proportionally with the distance of the reflecting surface.

Finally, any of the previously mentioned systems could be calibrated and used as a set distance detector. This approach would act as an alarm for any object coming to within a pre-determined distance of the moving vehicle. This distance could be set to the maximum limit of the shorter-range sensor devices that would be incorporated into the vehicle. For example, an on-board ultrasonic distance sensor could be activated on command of this ‘alarm’ system.

**Component Selection**

The initial part of the project was to find suitable laser emitters with matching detectors. These devices would need to be capable of sending and receiving signals with the intentions of long-range obstacle detection. Also, the selected components would be required to accomplish this task while remaining within the constraints of the overall project. These constraints consisted of mainly size/weight and power consumption.

The first order of business was to search the Internet for any laser sensors currently available. Having no previous knowledge of laser devices or the availability of components, the initial scope of the search was very wide. Extensive research yielded a broad range of results, but most were useless for our application. For example, many of
the available reflective optical systems were limited to a sensing range of several inches. Some of these results included handheld laser rangefinders, industrial laser and infrared sensors, and components such as laser diodes and phototransistors. Table I, on the following page, summarizes some of the non-useable or questionable parts that were the result of the component search. As shown in the table, bulky size relative to the mounting platform (1/10 scale model car), lack of adequate range, high price, and awkward interfacing were the key drawbacks to these components.

Table I. Component search results for lasers.

<table>
<thead>
<tr>
<th>Types Found</th>
<th>Name + hyperlink</th>
<th>Major Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handheld Rangefinder Units</td>
<td>Laser Optics N-15M Series</td>
<td>High price, bulky size</td>
</tr>
<tr>
<td></td>
<td>Laser Technology Tipare Series</td>
<td>High current draw, bulky size</td>
</tr>
<tr>
<td></td>
<td>Laserdyne LSR-1600</td>
<td>Bulky size</td>
</tr>
<tr>
<td></td>
<td>CyberOptics Sensors</td>
<td></td>
</tr>
<tr>
<td>Industrial Sensors</td>
<td>Laserdyne Sensors</td>
<td>High voltage requirements, various interfaces, bulky size</td>
</tr>
<tr>
<td></td>
<td>Avantes Barcode Sensors</td>
<td>Range too short</td>
</tr>
<tr>
<td></td>
<td>Euronics Laser Products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Technology, Inc</td>
<td>Ranging properties undeterminable until after purchase and testing</td>
</tr>
<tr>
<td>Components</td>
<td>Honeywell MicroSwitch Laser Diodes and Phototransistors</td>
<td></td>
</tr>
</tbody>
</table>

Under some direction from Professor Brooke and analyzing spec sheets available at some web sites soon led to the determination that laser diodes were the component of choice for emitting, while any photodiode or phototransistor in the same wavelength range would do as a detection device. However, there were several to choose from, so a decision had to be made as to which characteristics were most important and which components showed favorable results for these characteristics.

Also vital to the success of the design was the choice and implementation of logic devices used for processing the emitted and received signals. The biggest concern here
was time. Light propagation times at the relatively small operating distances the project 
requires will be short, so to effectively process the signals received from the detector, rise 
and fall times will play a key role. High-speed logic components were chosen taking into 
consideration short propagation delays and setup times. The actual response and usability 
of each component in the overall circuit is still to be determined in the upcoming test and 
validation phase of our design. Table II, on the following page, details the components 
that have been ordered for the initial implementation and testing of the laser range 
detector, as well as a few notable characteristics of each.

<table>
<thead>
<tr>
<th>Item</th>
<th>Catalog #</th>
<th>Vendor</th>
<th>Intended Use</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR diode/phototransistor pair</td>
<td>900-6960</td>
<td>Radioshack.Com</td>
<td>Emitter Detector</td>
<td>Range is poor</td>
</tr>
<tr>
<td>Laser Diode Module</td>
<td>900-7186</td>
<td></td>
<td>Emitter</td>
<td>3 mW, Class IIIa</td>
</tr>
<tr>
<td>Opto-IR Phototransistors</td>
<td>900-696x</td>
<td></td>
<td>Detector</td>
<td>3 different models</td>
</tr>
<tr>
<td>Integrated Circuit Photodiode</td>
<td>551-PH502HC</td>
<td>Mouser</td>
<td>Emitter</td>
<td></td>
</tr>
<tr>
<td>MicroSwitch VCSEL diodes,</td>
<td></td>
<td>Pending Verification</td>
<td>Emitter Detector</td>
<td>Class IIIb</td>
</tr>
<tr>
<td>matching photodiode/transistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tri-State Latch</td>
<td>74ACT573</td>
<td>Digi-Key</td>
<td>Detection circuitry</td>
<td></td>
</tr>
<tr>
<td>8-bit Counter</td>
<td>74F269</td>
<td></td>
<td>Detection circuitry</td>
<td></td>
</tr>
<tr>
<td>2 Circuit Boards</td>
<td>923253</td>
<td></td>
<td>Detection circuitry</td>
<td></td>
</tr>
</tbody>
</table>

**Safety**

One last issue to consider in choosing lasers is safety. Lasers are classified 
according to their ability to cause damage to the eye or skin. They are divided into four 
classes as follows: Class I lasers are generally harmless and are usually incapable of 
emitting radiation at dangerous levels. A laser is classified as Class IIa if, upon exposure
to the laser for 1000 seconds, the emission does not exceed that of Class I emission limitations. A typical example is the laser scanner found in the checkout line at the drugstore or supermarket. Class II lasers are low power (below 1 mW) visible lasers that exceed Class I levels. Human reaction to “bright light” is the only real protection scheme here. Intermediate power (1 – 5 mW) lasers are considered Class IIIa, and are harmful if the beam is viewed directly. Moderate power (5 – 500 mW, pulsed) lasers fall into Class IIIb. These lasers are generally not a fire hazard, and their reflections are usually not considered a danger. Class IV lasers are high power (above 500 mW, pulsed) dangerous emitters whose beams (including reflections) are harmful to skin and eyes. They are also a fire hazard.

Finally, taking all previously mentioned factors into consideration, the laser diode selection was narrowed to a few good candidates. One or more of each of these emitter/detector pairs has been purchased, and arrival is still pending at this point. Some of the emitters ordered for the project fall into the Class III laser category. These will have to be used with care and caution to prevent unnecessary injury.

Laser Module Drive Circuit

It was determined that in order to maximize the range of the laser system, a pulsed drive system would be utilized. This would allow selective detection of the reflected light source and minimize response to ambient light. In order to decrease power consumption, a pulse mode scheme was incorporated in which a 1 kHz squarewave signal was transmitted in bursts approximately every 20 ms. A 556 timer IC (dual 555’s) was used as the main active component in the circuit. One timer was set for the 1 kHz signal while the
other timer was designed to enable this circuit at a rate of approximately 50 Hz. The
design equations to determine the component values of the circuit are shown in figure 2.

\[ T = \frac{1}{\ln(2) \times C \times (R_1 + 2R_p)} \quad \text{frequency} = \frac{1}{T} \]

Fig. 2. Formulas to determine frequency of astable 555 timer circuit.

The schematic of the circuit with the required components is detailed in figure 3
on the following page.

Fig. 3. Schematic of laser module driver circuit.

The output from the drive circuit is shown in figure 4 on the following page.

Channel 2 is the 1kHz burst signal that will drive the laser diode module.
Fig. 4. Laser diode module driver, \( V_{\text{out}} \).

To verify correct operation, a simple test circuit was assembled which used a phototransistor light detector element to determine proper output from the laser diode module. The block diagram of the test setup is shown in figure 5.

Fig. 5. Laser module test circuit.
Initially, a standard red LED was connected as the light source and aimed directly at the photodetector circuit from a range of 4 inches. The results of this test are detailed in figure 6. The channel one display is that of the detected signal while the channel two display is the drive signal reference.

![Graph](image)

**Fig. 6. Signal from direct LED transmission.**

Next, the range was increased to 5 inches to get an idea of the sensitivity of the phototransistor. Figure 7 on the following page shows the results. The channel one display is that of the detected signal while the channel two display is the drive signal reference.
Fig. 7. Signal from direct LED transmission, increased range.

Finally, the laser module was connected as the light source, and a reflected signal was detected from a plain white surface at a range of 4 inches. Figure 8 details these results. The channel one display is that of the detected signal while the channel two display is the drive signal reference.

Fig. 8. Signal from reflected laser module transmission.
Detector Circuit

Design and Simulation

At the receiving end of our laser ranging circuit, a filter was needed to remove all the light except that emitted by the laser diode. Since this laser was pulsed at a frequency of 1 kHz, a band-pass filter with a center frequency of 1 kHz and a high quality factor (also called a notch filter) was ideal for removing all unwanted responses from the photodetector. We chose a second-order Sallen-Key band-pass filter for our design since it delivered moderate gain with a very narrow band-pass characteristic. A schematic of the filter is shown in figure 9.

Fig. 9. Schematic of high-Q 1kHz band-pass circuit.

The corresponding design equations for the circuit are shown in figure 10 on the following page.
\[
\omega_0 = \frac{1}{\sqrt{\left(R_1 \parallel R_2\right)R_3C_1C_2}}
\]

\[
Q = \frac{\sqrt{(R_1 \parallel R_2)R_4C_1C_2}}{(R_1 \parallel R_2)(C_1 + C_2) + R_4C_2(1 - K_0(R_1 \parallel R_2)/R_2)}
\]

\[
K_0 = 1 + \frac{R_f}{R_4}
\]

and letting \(R_1 = R_2 = R_4 = R\) and \(C_1 = C_2 = C\)

\[
\omega_0 = \frac{1}{\sqrt{RC}}
\]

\[
Q = \frac{1}{\sqrt{2} + 1 - \frac{1}{2} K_0}
\]

\[
K_0 = 1 + \frac{R_f}{R}
\]

Fig. 10. Design equations for Sallen-Key band-pass filter.

Initially, values of \(Q = 20\) and \(C = 0.01\ \mu F\) were chosen, and using the above equations, \(R\) was found to be best approximated by a 22 kΩ resistor, while \(R_f\) was best approximated by an 82 kΩ resistor. A SPICE plot was performed to check the validity of the design. Although this showed favorable results, actual testing of the circuit revealed oscillations, which prevented correct operation. This was most likely due to the high numerical designation of the quality factor, a variable easily altered by altering the value of \(R_f\) proportionally. By lowering the value of \(R_f\) (and thereby lowering the quality factor), we were able to locate the highest quality factor before which the filter went into oscillation or heavy clipping. This value was determined, through test, to be
approximately $R_i = 60 \, \Omega$. Using this new value, another simulation was run for the design. The results are shown in figure 11.

![Graph showing band-pass response](image)

**Fig. 11. SPICE simulation band-pass response.**

The SPICE input file for this circuit is shown in figure 12.

```plaintext
2nd Order Sallen-Key Band-Pass Filter
*f=5kHz. 741 op-amp
VIN 1 0 AC 100M
R1 1 2 22k
R2 2 5 22k
R3 3 0 22k
R4 4 0 22k
RF 4 5 60K
RO 5 0 100
C1 2 0 .01u
C2 2 3 .01u
XOA1 3 4 5 OA741
*741 OP-AMP SUBCIRCUIT
.SUBCKT OA741 1 2 3
RIN 1 2 2E6
GM1 4 0 1 2 1.38E-4
R1 4 0 1E5
CC 4 5 20E-12
GM2 5 0 4 0 106
RO1 3 5 150
RO2 5 0 150
.ENDS OA741
.AC DEC 30 100 10k
.PROBE
.END
```

**Fig. 12. SPICE code for Sallen-Key band-pass filter.**
Fig. 16. Phase response of 1KHz band-pass filter.

High Gain Amplifier Circuit

The high gain amplifier circuit was designed around a 741 op-amp with feedback resistor of 1 MΩ. With this configuration, the amplifier would go to the rails with the slightest input. Tests were run and the amplifier was found to go to it's maximum output for signals as low as 5 mV_{pp}. The circuit is detailed in figure 17.

Fig. 17. High gain op-amp configuration.
Detector Circuit

Assembly and Test

Using the components derived from the simulation of the band-pass filter, a circuit was breadboarded and tested to determine functionality of the design. The values of the capacitors and resistors were tweaked slightly to achieve a center frequency of 1 kHz. An input voltage divider network was also added to the original circuit to facilitate the input of a low level (approximately 10 mV) signal for verification of the sensitivity of the circuit. The completed circuit with the new component values and the input network is detailed in figure 13.

---

![Diagram](image)

Fig. 13. Schematic of high-Q 1KHz band-pass circuit.

A ground shifting voltage divider network was put in place to allow operation of the circuit from a single low voltage supply. This circuit is shown in figure 14 on the following page.
Fig. 14. Voltage divider for dual supply op-amp.

The frequency and phase response of the final circuit is shown in figures 15 and 16 (following page). The phase response of the design would be critical in circuit time of flight range measurements.

Fig. 15. Frequency response of 1KHz band-pass filter.
Integration

Figure 18 details the integrated detection system. The detailed parts list is presented in table III.

![Diagram of integrated optical detector circuit](image)

Fig. 18. Schematic of integrated optical detector circuit.

<table>
<thead>
<tr>
<th>Reference designator</th>
<th>Part number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>BPW-38</td>
<td>Opto-infrared phototransistor detector</td>
</tr>
<tr>
<td>U1, U2</td>
<td>LM741</td>
<td>Operational amplifier</td>
</tr>
</tbody>
</table>
Initially, the high-gain op-amp circuit was connected to the band-pass filter and tested. These circuits worked together well, with the previously discussed sensitivity of 5 mV being achieved.

Next the connection of the photodetector front end was undertaken. This part of the circuit caused problems not only with noise amplification, but also level shifting of the input to the operational amplifier stage. The detected ambient light shifted the input of the op-amp causing it to rail. Capacitive coupling was then used to isolate the circuits but this approach led to feedthrough of noise and oscillatory behavior by the op-amp. A hood made from dark plastic heat shrink tubing was placed over the body of the phototransistor to limit the ambient light input. This approach reduced the ambient current, but the problem at the front end of the circuit was not rectified with this approach. Other connection methods were tried, including a current to voltage converter, but these had the same results. The sensitive input of the high-gain circuit was disturbed by any configuration of the photodetector that was implemented. Finally, in order to determine some range information for a reflected signal, the high-gain amp circuit was bypassed, and the photodetector was connected directly to the input of the filter.

**Range Results**

With the high-gain amp removed from the assembly, the range of the device was well short of the desired distance. The laser module was mechanically attached to the hooded phototransistor and aligned so that the reflected pulsed laser light would be almost perfectly incident with the lens of the detection device. With this construction, the reflected signal was detectable at a maximum range of approximately 30 inches. This was
reflected off of a plain white surface. This range decreased if the reflectivity of the surface diminished.

**Conclusion**

Our laser ranging circuit was not a complete success, but we did meet many of the goals we set for ourselves. Component selection for emitters and detectors turned out to be quite simple – a laser diode module for emission and a lensed phototransistor for detection. Perhaps specific types of components would play a much more significant role beyond the point reached in our implementation, but we do not believe this to be our immediate crux.

Ambient light played a major role in our choice of transmission circuitry. All visible light propagates at frequencies much higher than those common to circuits designed in an undergraduate curriculum. In other words, to filter out all light except that which we were emitting would prove nearly impossible unless we introduced some modulation scheme. After testing the available emitters, we chose to pulse our laser at 1kHz due to rise and fall times. Thus a pulse generator was designed and implemented perfectly. The receiver then had to take all signals received and get rid of all but the desired pulse. To do this, a bandpass filter with center frequency of 1kHz was needed.

Using the familiar Sallen-Key filter design techniques introduced in several classes, a filter was designed and tested to our requirements. These tasks were successfully completed and do not appear to be problematic.

Our biggest problems arose with the integration of various subcircuits. The filter tended to oscillate and had to be tweaked. The amplifier posed the greatest problem. Though the detector circuit and filter worked together, as did the amplifier and filter, the
integration of the three components created problems we could not overcome. We had to somehow isolate the detector circuit from the amplifier, and unfortunately this problem was realized too late in the semester to be fully researched and corrected. However, our detection range of 30 inches without significant amplification or emitter considerations suggests great possibility of improvement.

Other objectives, such as the implementation of timing and interface circuitry, were largely ignored due to the fact that we did not reach a point of need for these. For future endeavors in the laser ranging area, the designer will have to consider such objectives if this is to be integrated into the design of an autonomous vehicle. In our opinion, the greatest challenge will be getting any significant range from the unit; the rest should fall into place more rapidly.