Abstract

Laser communication has the potential to be a very effective form of wireless underwater means of communication. The goal of project 15252 is to create a prototype proof-of-concept for a functional underwater laser communication device. Laser communication is important because it can replace underwater acoustic communication used in submarines, as well its applications for other underwater robotic devices. This device’s goal is to allow for an environment in which multiple different tests can be conducted to thoroughly record different forms of data proving the validity and effectiveness of laser communication through water. Variables that were altered during the experiments were water turbidity and length between transmitter and receiver. With this, the results showed that the system was able to reach the minimum 15Kbps required through water. Finally, it was found that almost any amount of turbidity will significantly reduce the received density of the laser.

Introduction

In order to communicate underwater, the only real viable solution in use to this day is acoustic communication. The military uses acoustic communication to communicate between its submarines and their base of operation via an acoustic box and a cable line connected to land. The presence of the cable and acoustic box is because a primary goal for underwater communication is security, the idea that the data sent won’t be intercepted by anything other than the designated receiver. Inherently, this means that acoustic devices must be very close to their receiver in order to ensure a secure communication line. This project is a continuation off of a previous project that developed an acoustic communication device with similar engineering requirements. Therefore, it is important to benchmark that system with the laser communication system. The table below shows some major engineering requirements and how each system met those requirements:

<table>
<thead>
<tr>
<th>Engineering Requirement</th>
<th>Acoustic Team</th>
<th>Laser Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer Rate</td>
<td>12 Kbps</td>
<td>19.2 Kbps</td>
</tr>
<tr>
<td>Communicates through water</td>
<td>Wasn’t able to be submerged</td>
<td>Successfully tested through water</td>
</tr>
<tr>
<td>Secure Communication</td>
<td>Insecure (nature of acoustic communication)</td>
<td>Secure (only target receiver receives signal)</td>
</tr>
<tr>
<td>Water proof</td>
<td>Receiver/Transmitter Boxes were not watertight</td>
<td>Waterproof PVC system, box easily sealable</td>
</tr>
</tbody>
</table>

Table 1 - Laser vs Acoustic Benchmarking
As this table is only a few of the requirements necessary, further on in the paper, the rest will be explained and developed through the design process, testing procedures, and the final results.

**Process**

In order to measure successful communication through water using a laser, a set of requirements were created. Each requirement in this set has an importance value assigned to it, acting as a priority indicator assigned by the customer. These requirements can be seen in Table 2.

<table>
<thead>
<tr>
<th>Customer Rqmt. #</th>
<th>Importance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>9</td>
<td>Able to send/recvieve commands</td>
</tr>
<tr>
<td>CR2</td>
<td>9</td>
<td>Fast Communication</td>
</tr>
<tr>
<td>CR3</td>
<td>9</td>
<td>Waterproof</td>
</tr>
<tr>
<td>CR4</td>
<td>9</td>
<td>1 way communication</td>
</tr>
<tr>
<td>CR5</td>
<td>9</td>
<td>Short Range</td>
</tr>
<tr>
<td>CR6</td>
<td>9</td>
<td>Cost Effective</td>
</tr>
<tr>
<td>CR7</td>
<td>3</td>
<td>Energy Efficient</td>
</tr>
<tr>
<td>CR8</td>
<td>3</td>
<td>Durable</td>
</tr>
<tr>
<td>CR9</td>
<td>3</td>
<td>Easy to Repair</td>
</tr>
<tr>
<td>CR10</td>
<td>1</td>
<td>Long Range</td>
</tr>
</tbody>
</table>

Table 2 - Table of Customer Requirements with Importance Values

The highest importance (9) requirements outline the basic functionality of using a laser to communicate through water. These requirements must be met in order for the project to be considered a success. The lower priorities (3 and 1) are requirements that the customer desired the prototype to have but should not be prioritized over basic functionality. In order for these requirements to be deemed fulfilled or not, metrics with tolerances were created for each customer requirement. The requirements along with design metrics formed the Engineering Requirements that can be seen in Table 3.

<table>
<thead>
<tr>
<th>rqmt. #</th>
<th>Importance</th>
<th>Source</th>
<th>Top Level Function</th>
<th>Engr. Requirement (metric)</th>
<th>Unit of Measure</th>
<th>Tolerance (+/-)</th>
<th>Ideal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>9</td>
<td>CR5</td>
<td>Send Data</td>
<td>Short Range</td>
<td>m</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>S2</td>
<td>9</td>
<td>CR2</td>
<td>Send/Receive Data</td>
<td>Transfer Rate</td>
<td>kbps</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>S3</td>
<td>9</td>
<td>CR3</td>
<td>Minimise Risk</td>
<td>Waterproof</td>
<td>m</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>S4</td>
<td>3</td>
<td>CR7</td>
<td>All</td>
<td>Low Power Consumption</td>
<td>Vth</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>S5</td>
<td>3</td>
<td>CR10</td>
<td>Send Data</td>
<td>Long Range</td>
<td>m</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>S6</td>
<td>9</td>
<td>CR6</td>
<td>All</td>
<td>Cost</td>
<td>$</td>
<td>300</td>
<td>1240</td>
</tr>
<tr>
<td>S7</td>
<td>9</td>
<td>CR1</td>
<td>Send/Receive Data</td>
<td>Packet size</td>
<td>bits</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>S8</td>
<td>9</td>
<td>CR4</td>
<td>Send/Receive Data</td>
<td>Unidirectional Communication</td>
<td>T/F</td>
<td>NA</td>
<td>T</td>
</tr>
<tr>
<td>S9</td>
<td>3</td>
<td>CR9</td>
<td>Minimise Risk</td>
<td>Modularity</td>
<td>s</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>S10</td>
<td>9</td>
<td>CR8</td>
<td>Minimise Risk</td>
<td>Ultimate Stress/Yield Stress</td>
<td>kpa</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3 - Engineering Requirements with Metrics and Tolerances

Each Customer Requirement from Table 2 has a corresponding Engineering Requirement in Table 3. Each requirement has an ideal value, which is the target, along with an accepted tolerance. The fulfillment of these requirements will determine if the completed prototype is a success or not. The ideal values will be used as initial test thresholds that the
prototype must meet. If these metrics are not met, the design may be reworked in order to accommodate the requirement, depending on the importance. If, for example, the prototype can’t even send and receive data, the design will be reworked in order to achieve this goal. On the other hand, if the prototype works up to a range of 20m (short range, but not long range), the design may not be changed if there are time constraints that cannot be met with a redesign. Using these requirements as guidelines, different solutions that would satisfy the desired conditions were considered and weighed against each other in order to find the best solution for each requirement.

Concept Selections

After the customer needs had been translated into engineering requirements, the concept is generated. To do so, three steps were taken: creating a functional decomposition flow chart, creating a morphological table, and analyzing them using PUGH charts. First, the functional decomposition flowchart was made. This is shown in Figure[1]. The flowchart shows the six main components to achieve the ultimate purpose of transferring data under water using a high powered laser. Those components include minimizing risk, aligning the laser, providing input, sending data, receiving data and finally displaying the results.

![Figure 1 - Functional decomposition for components to be considered for data transfer](image)

Second, a Morphological table is created and that is shown in Table 4. The Morphological table shows each function of the project with possible ways of implementing them labeled as options one through five. The five functions that are considered in this table are Aim laser, User Input, Send Data, Receive Data and Display Results.

![Table 4 - Morphological table with functions vs possible options to be implemented](image)
Choosing the method for each function is determined by taking each function from the functional decomposition flow chart and comparing it to the options in the Morphological table then choosing the optimum option through the use of PUGH charts. The first function, aligning the laser, could be done by either moving the laser to the receiver or moving the receiver to the laser. The customer need of one way communication restricted the use of digital feedback for alignment. Therefore, visual feedback was necessary to insure proper alignment. Table 5 shows the PUGH chart for aiming the laser. A PVC pipe was built to contain the laser. The laser is to be aligned inside of the PVC pipe to aim at the receiver photodiode.

<table>
<thead>
<tr>
<th>Function 1: Aim Laser</th>
<th>Parameter</th>
<th>Manually Align</th>
<th>Lens</th>
<th>PVC Pipe</th>
<th>Servo Actuated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>X</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>X</td>
</tr>
<tr>
<td>Footprint</td>
<td>X</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Maintainence</td>
<td>X</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Safety</td>
<td>X</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Repeatability</td>
<td>X</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Speed</td>
<td>X</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Score</td>
<td>X</td>
<td>2/4</td>
<td>3/5</td>
<td>5/1</td>
<td>1/3/4</td>
</tr>
</tbody>
</table>

Table 5 - PUGH chart for Aim Laser function

Initially, for preliminary testing purposes, a keyboard will be used as the input method. However, a joystick is integrated into the system to be used for the final design. The next function is to send data. The microcontroller provides the digital signal to the laser driver, then the laser driver modulates the laser diode and consequently send the data to the receiver. Serial communications and amplitude modulation methods tied in pros versus cons. However, for simplicity purposes, serial communication was chosen over amplitude modulation. A photoelectric sensor placed in the path of the laser was used to receive data. The best photoelectric sensors to be used for this purpose are PN photodiode sensors. This is because they are the most responsive at around 450 nm wavelengths. Lastly, a method to demonstrate that data was being received was chosen. The available options were narrowed down to using a game and a monitor. For testing of subsystems, a monitor will be used to show the incoming data. However, the final design will use the laser to send commands to a game.

Constraints/Risks

In order for the P15252 Underwater Laser communication system to be successful, multiple risks were addressed and reaction plans were created prior to starting the build and test stage of the system. The laser diode being used created multiple risks and constraints for the project. Since the laser diode can produce a beam with a light intensity greater the 500 milliWatts, it is classified as a Class IV laser. Light concentration at these levels can easily cause severe, permanent damage to eyes or skin. Multiple precautions are taken in order to minimize the risk of injury. First and foremost, safety glasses rated for the appropriate wavelengths are worn by all team members while the laser is in operation and is outside the enclosed test rig. When fully enclosed, the system prevents prevents any team member or bystanders access to the laser beam. This restriction causes the laser to become classified as a Class I laser, so eye protection is not needed when the full system is operating. Even
though the enclosure creates constraints on troubleshooting and debugging the system, it still proves to be the most important step in ensuring the safety of team members and any other users of the system.

The budget provided for the project is, in itself, a constraint. The system must use processors, photodetectors, and lasers within a price range. This constraint impacted the selection of the laser diode greatly. The risk of project going over budget is minimized as much as possible with steps such as first simulating circuits with simulation software to ensure proper operation of the design. Other procedures followed during the build section of this project include the proper shutdown of microcontrollers, double checking solder connection, checking nodes for continuity, and various water leak tests. These steps are taken to help minimize the risk of having to replace parts which may send the project over budget.

**Building/Fabricating**

Once the concepts were selected and the appropriate risks were analyzed, it then became necessary to build each subsystem. The subsystems that required assembly were the transmitter and receiver subsystems; the ones that required machine fabrication were the PVC assembly, transmitter/receiver enclosures, internal receiver/transmitter rigs, and the support assembly. Programming the transmitter and receiver subsystems was also an important step towards completion.

All fabrication was conducted in the RIT machine shop using facility machines. Total fabrication and assembly of the mechanical subsystems took approximately 22 hours in the shop. This time was spent cutting the pipe and 2x10 to appropriate lengths for the PVC subsystem and support structure, milling the box supports and internal rigs to very tight tolerances, and drilling and sanding for appropriate assembly purposes. The setbacks that increased total fabrication time were situations such as wood warp and imperfections in the raw material that provided for an alteration to planned machine procedures. Accounting for wood warp, most tolerances were met according to their corresponding drawings.

The transmitter schematics were designed and simulated using PSpice. After the simulation results showed the expected values, the parts were ordered and used to build the transmitter circuit on a breadboard. This initial circuitry had a few issues so changes had to be made to fix them. These changes were implemented on the breadboard and the system was tested successfully. A cape that goes on the Beaglebone Black was purchased and the functioning transmitter circuitry was soldered on it. This process took approximately 40 hours from designing to the final soldered transmitter on the cape. For the receiver, the initial design was simulated with results that were satisfactory to the engineering requirements. The circuit was then built on a breadboard (following the same protocol as the transmitter) and tested successfully after some necessary debugging. The circuit was soldered on the receiver Beaglebone cape, which was placed on the microcontroller afterwards. This process took significantly less time than the transmitter. Both the transmitter and receiver were 1:1 match of the final schematics design.

In parallel to the other subsystems' fabrication, the microcontrollers were being programmed. To have this accomplished, first, an image of Debian Linux operating system was flashed to the microcontroller. Then, the open source library created by Yigit Yuce,
BlackLib, was put onto the microcontroller. This library provided a way to communicate with the UART, ADC and GPIO port pins on the P8 and P9 headers. BlackLib was used specifically to read or write to pins p32, p34, p36, p38 and p42 on header P9 for the joystick. Additionally, pins p24 and p26, on the P9 header, were used to transmit and receive, respectively. P24 was used to send the bits being transmitted to the transmitter circuit, which would control the laser. P26 was used to receive the bits from the receiver circuit. BlackLib was also used to read from pins p14 and p16 on the P9 header. These pins were used for the buttons that would help control the game. It was decided that the transmitter and receiver would run at a baud rate of 19200 as this was the baud rate that was closest to the speed which the system needed to achieve of 15 kbps.

Once all the hardware communication ports were selected and the hardware communication settings were set, the transmitter and receiver code was written. The transmitter code took the input it read from the GPIO and ADC pins and used them to construct a packet. This packet was then written to the UART transmit pin (p24) so that it could drive the laser transmitter circuit. The receiver was coded to look at the UART receive pin (p26) until it received a packet. It would store this packet in a list of 100 packets then take the most common direction and button presses from these packets and send them to the game as key presses. This was done to remove noise or corrupted packets from affecting the game. Both the transmitter and receiver code write what the code sends and receives to a text file for debugging purposes.

Test Procedures
The testing for the software subsystem started with unit testing the ports that the code would be using to make sure that they all could be read from and written to. This was done with switches and a small block of testing code for the GPIO. For the joystick pins, a small block of testing code was made to read values that would be sent by the joystick to the pins. The UART transmit pin was tested with a small block of code that would write to it at a baud rate of 19200. The transmit and receive pins were tested together by writing and reading from the respective pins. After these tests were complete the actual code was written and unit tested. The code was initially tested using only one microcontroller transmitting to its own receive pin. After this was verified, the next step was to send the transmit signal to a different microcontroller's receive pin using a wire. Once the code was confirmed to work for these scenarios the integration was done with the EE subsystem circuits treating these circuits as if they were the wire in the previous test.

As for a fully integrated system test, the key variables for testing were the overall length of the PVC assembly and turbidity value of the liquid in which the laser is traveling through. These two variables allow for a decent representation of real life situations and variables that occur in open water. Turbidity is varied because a major setback of optical communication is communicating in murky water could potentially obstruct the transmission more so than other forms of communication. This will allow for the maximum turbidity value to be found for future developments of the technology. As for varying the length, the purpose behind doing this is once multiple transfer rates are calculated at the varying lengths, a
predicted maximum range can be calculated. This would also be very useful information for future applications of this technology.

In order to implement these variations in testing, the only accessory materials needed are:

- Middle PVC sections of varying length
- 3’ tall, 2” diameter extruded acrylic tube
- 2” checkered viewing disc
- 2” plug

The turbidity of the water will be set and measured via viewing the liquid placed in the acrylic tube with a viewing disc at the bottom; once the viewing disc can no longer be seen from the top of the tube, the water level is then measured and the corresponding turbidity value is taken from Table 6 (right). Enough data will be taken until a trend is observed.

Similarly, the varying length of the middle section is conducted simply by draining any water still in the pvc assembly and replacing the center section with a larger one. The section lengths will be 1’ to 5’ in length. The above turbidity experiment will be conducted for each length of pvc as well.

### Table 6 - Turbidity tube values

<table>
<thead>
<tr>
<th>Centimeters</th>
<th>NTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7</td>
<td>240</td>
</tr>
<tr>
<td>7.3</td>
<td>200</td>
</tr>
<tr>
<td>8.9</td>
<td>150</td>
</tr>
<tr>
<td>11.5</td>
<td>100</td>
</tr>
<tr>
<td>17.9</td>
<td>50</td>
</tr>
<tr>
<td>20.4</td>
<td>40</td>
</tr>
<tr>
<td>25.5</td>
<td>30</td>
</tr>
<tr>
<td>33.1</td>
<td>21</td>
</tr>
<tr>
<td>35.6</td>
<td>19</td>
</tr>
<tr>
<td>38.2</td>
<td>17</td>
</tr>
<tr>
<td>40.7</td>
<td>15</td>
</tr>
<tr>
<td>43.3</td>
<td>14</td>
</tr>
<tr>
<td>45.8</td>
<td>13</td>
</tr>
<tr>
<td>48.3</td>
<td>12</td>
</tr>
<tr>
<td>50.9</td>
<td>11</td>
</tr>
<tr>
<td>53.4</td>
<td>10</td>
</tr>
<tr>
<td>85.4</td>
<td>5</td>
</tr>
</tbody>
</table>

Results and discussion

The finished prototype consisted of a laser firing through a water filled PVC pipe to a receiver at the other end. This design allowed varying test conditions so a large range of data could be gathered. This design was able to vary in length as well as giving the ability to alter the turbidity of the water in the pipe. While there was no requirement for altering turbidity, this design still includes an easy way to change the liquid in the pipe.

The results of the different tests show that all of the critical engineering requirements are met with the exception of the range requirement. The desired range was extremely overestimated and should be shortened. The amount of light received dropped off over length faster than expected. These results are shown in Figure 2 below. The amount of light received through air stayed mostly constant over all distances, indicating that the operational range of the laser out of water is extremely far. Through clear water, the light received dropped linearly, with a maximum range of about 15 feet. Additionally, even small amounts of turbidity, around 17 NTU, completely blocked all light from the laser at any tested distance. A much higher power laser would be needed to transmit through murky waters.

The transfer rate for the laser communication system exceeded the target speed. The previous phase of acoustic communication reached speeds of 14 kbps. The laser communication system reached speeds of 19.2 kbps which was 1.28 times faster than our target speed of 15 kbps. The bottleneck of the transfer speed was the microcontroller’s ability to process commands at that speed.
Conclusions and recommendations

In this project there had been milestone achievements and a few setbacks. The complete customer needs have been met within the working system. They had been translated to engineering requirements that are realistic and achievable with proper testing ranges. The system was able to send data over a short range with a speed of 19.2 kbps, higher than the target 15 kbps. The engineering requirement that was set for the range had been proven to be unrealistic for the system specifications. The laser power could deliver sufficient density through water for up to 20 feet. The mechanical requirements had been met by making the system durable, waterproof, and easy to repair while keeping it cost effective. The system works at low power and the most power drawn was to operate the laser diode itself. Some of the setbacks include having a system failure to what it seemed unknown reasons. After analyzing the complete system, it was found that the issue was with mistakenly grounding the microcontroller to the supporting system by resting it on a metal plate. Another problem was a concern with the transmitter. Due to the amount of power the laser diode was drawing, the transmitter circuitry was overheating rapidly. The solution, however, was simple: attaching a heatsink to the switching element.

One thing that we would have done differently if we were to build a project of this level in the future would be performing subsystem testing more frequently and in a more spread out manner across the timeline given. This would help detect physical problems sooner rather than relying on theoretical certainties. On the other hand, communication between the group members was excellent. High teamwork skills were taken advantage of and members of the group showed great collaboration skills. Also, problems were tackled efficiently and in a timely manner. Looking at the complete built system and the results gathered, the project can be considered successful in its initial intent.