Automatic Targeting, Point-to-Point Laser Communication System for small robots.

by

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B.S., Computer Engineer, University of New Mexico, 2012

PROJECT

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Electrical Engineering

The University of New Mexico

Albuquerque, New Mexico

May, 2105

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Abstract

There is a need for secure point-to-point communication between robots. The purpose of this project is to create a system to allow secure, point-to-point, laser communication between the pairs of robots. The use of lasers to communicate the message will guarantee that only an agent on the laser's path will be able to intercept the communication under most operating conditions. The system will be designed to be modular in order to be customized to the robot capabilities. A prototype that includes an automatic identification and targeting system is developed and demonstrated.

Introduction

Wireless communications system are notoriously easy to eavesdrop on. For instance, for home networks the most advanced encryption techniques can be defeated with easily attainable tools [1]. When more robust encryption and security techniques are used, such as military applications, just the act of transmitting over radio waves can give valuable information to an attacker, such as the location of the transmitter[2].

Laser communications are inherently point-to-point, the message being transmitted can only be read when an agent is in the laser's path, significantly reducing possible attack vectors. Laser systems have been used for point-to-point communications, for example in [3][4]. However, these systems use large, specialized, lasers and actuators. The goal of this project is to develop a system that will allow two agents to communicate over a laser beam in the lab, using off the shelve components fitted to the robot's size and load capacity.

The MARHES Lab specializes in small, autonomous, ground and air based mobile robots. The current systems include Turtlebots from Clearpath Robotics, Octoroaches developed at UC Berkeley, a Panzer unit developed in the MARHES Lab, and Quadrotors from AscTek Inc. The laser communication system and prototype are focused on these robots. Smaller robots, such as the Octoroach, will have only a laser receiver module; while larger robots, like the Turtlebot, will have a laser module capable of sending and receiving a message. This gives an operational envelope, in terms of power requirements and weight, that will cover all four platforms present in the MARHES lab.

System Overview

A laser communication module will consist of the following components:

- Microcontroller Unit (MCU).
- Laser sensor.
- Laser and laser driver circuit.
- Camera.
- Alignment actuators (motors and motor drivers).

Only the first two items will be required regardless of robot size. Each robot capable of sending a message will have the laser and camera mounted on an actuated gimbal in order to find and track the target module without affecting the sender robot current trajectory or mission.

In this project, I consider a case where a group of robots have a wireless channel for low security communication and a secure message needs to be transmitted between two robots in the network. The process will follow these general steps:

- **Stage 0:**
  Sender robot communicates its intention to send a secure message to the target robot.
- **Stage 1:**
  Sender robot commands laser communication module to find and track the target robot.

- **Stage 2:**

  If equipped, the target robot commands laser communication module to find and track the sender robot.

- **Stage 3:**

  The laser communication module on the sender robot performs precise alignment of its laser with the target's laser sensor.

- **Stage 4:**

  The laser communication module on the sender robot sends the message.

- **Stage 5:**

  Target robot acknowledges message receipt.

Stage 0: Preparation

Due that the robots will need to align their laser communication modules before the modules can be used effectively, their wireless network channel is used to perform this initial handshaking. After the modules find and identify each other, the operation is handled entirely by the laser communication modules. The initial handshaking could include relative position information to hasten the next stage.

Stage 1: Automatic Targeting and Identification

Each laser communication module is capable of showing a unique visual pattern which identifies it in the group. For an added measure of security, the pattern can be changed during operation. In the prototype developed, the visual pattern is adjusted using LEDs.

The laser communication module in the sender robot is commanded with finding a target pattern, which does by using computer vision. Once the target is identified, the laser communication actuators will continuously track the target robot until the secure communication is completed.

Stage 2: Reciprocal Alignment

If the target robot has an actuated laser communication module, it will use it to point its sensor in the direction of the sender robot. If the target robot does not have an actuated laser communication module, their trajectories might be affected in order to perform the alignment.

Stage 3: Precise Laser-Sensor Alignment

Once the tracking and base laser-sensor alignment are completed, a precise alignment phase is completed which includes turning the laser on and receiving a visual feedback from the target robot. In the prototype developed, the visual feedback is given by a LED that turns on when the precise alignment has been accomplished measured by the intensity of the laser on the sensor. Depending on the terrain conditions and smoothness of the robot trajectories, the robots might need to stop for the duration of the message to ensure a consistent alignment.

Stage 4: Message Sending

The message is sent using the laser-sensor pair. Once properly aligned and started, the input of the laser and the output of the sensor will behave like a physical cable while the signal is within the capabilities of the driver and sensor. As the baud rate increases, the error on the message interpretation is increased.

Stage 5: Acknowledgment

After the message is received, the target robot acknowledges by using the wireless network and the robots continue with their mission.

Prototype Hardware Overview

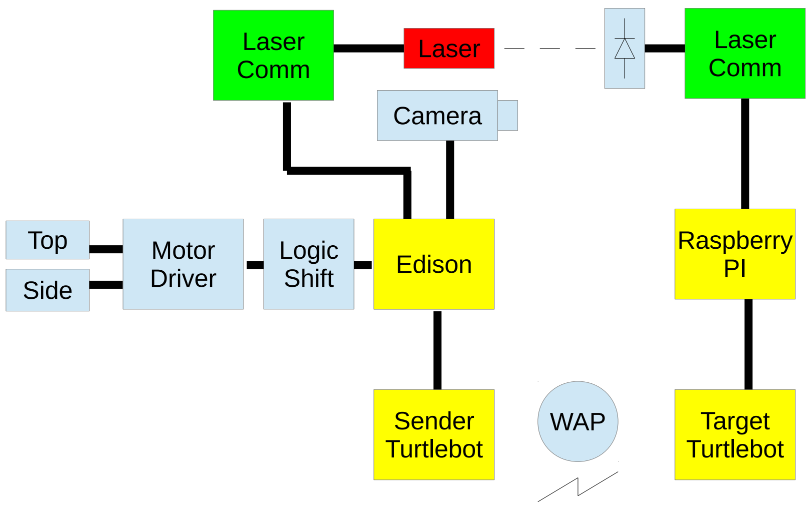


Figure 1: Hardware Overview Diagram

Agent

The current agent is a TurtleBot. Power is provided in the base of the TurtleBot at 12 Volts DC, separate regulators are used to provide power to the various modules.

Figure 2: TurtleBot Robot

Microcontroller Unit (MCU)

The MCU being used is the Intel Edison. The Edison platform has a dual core 500 MHz atom processor, 1 GB of on board memory, and 4 GB of storage. In addition it includes WiFi, Bluetooth, a USB port for power and to provide a console port, and a USB OTG port.

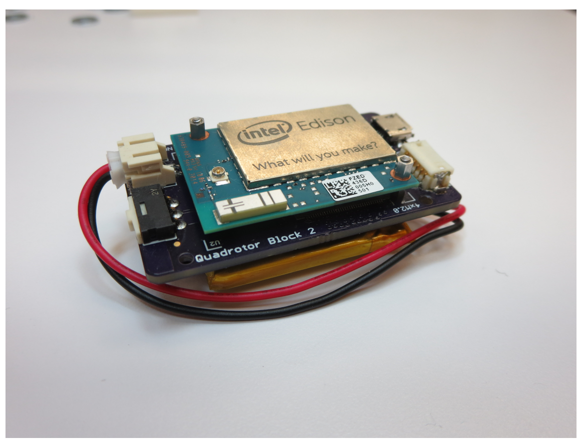


Figure 3: Edison Platform

Alignment Actuator System

The platform designed incorporates a gimbal system designed and built in house. It uses DC motors connected to an on-board motor PWM (Pulse Width Modulation) driver and H-Bridge.

The gimbal System is composed of two aluminum frames. A coordinate frame fixed to the laser is defined with the Y axis in the same direction as the laser beam and the Z axis pointing up. From the starting position, the internal frame can perform a full 360 degree rotation around the Z axis when actuated by the top motor. The electronics housed in the internal unit consist of the camera, the laser, the laser sensor, the signal strength visual feedback LED, and a cluster of 4 LEDs used for identification. The external frame allows for a +/- 15 Degree rotation about the X axis when actuated by the side motor.

The motors are Polulu Micro Metal with a gear ration of 150:1. They are driven by a Polulu Junior dual DC motor driver. The driver is controlled through a serial port using the standard Polulu command set. It is capable of delivering 2.5A of continuous current at voltages from 5V up to 24V. They are operated at 12V for improved torque.

Laser and Sensor

The current laser operates in the 450 nM wavelength and is a standard laser pointer type. It is powered from 5 volts DC through transistor driver circuit. Since it can be set to always active, it provides a means of visible confirmation during testing.

The laser sensor is based on a photodiode. It was selected to match the wavelength of the laser. When the laser strikes the photodiode current flows through it and into the input of the OpAmp. If sufficient current is allowed to pass through to drive the voltage at the pin above the negative input then OpAmp output will be pulled high. The threshold voltage is selectable by adjusting a variable potentiometer.

The output from the OpAmp goes directly to the MCU. The voltage level is selectable by the pullup voltage at the output pin.

Camera

The two cameras used for development are is a GoPro Hero3+ and Logitech Pro USB. The GoPro Hero3+ It is a Wifi camera capable of full HDMI resolution with a 90 FOV.

System Configuration

Embedded Platform

The Edison operates on a Debian 3.2 Headless kernel built from the Yocto project. It includes special libraries from Intel to support access to the extra features of the platform, such as GPIO ports and ADC ports.

Development Environment

Main developing was done in Python and C. Python 2.7 was used in this project. The Python libraries used included:

Computer Vision: OpenCV

OpenCV is a mature, robust, computer vision library available to the Open Source community. It implements some of the most advanced computer vision algorithms available. OpenCV 2.x was installed onto the Debian image directly from the apt repositories.

Camera Driver: GoProHero

The Hero3+ camera is controlled by connecting to its Ad Hoc network on the camera itself. To interface to the camera an open source tool, GoProHero, was used. It is available on [5].

Camera Driver: Logitech USB

The Logitech USB driver was built into the standard V4L2 linux drivers. The camera was controlled by the v4l2-ctl utility and images were captured directly in OpenCV.

Math: NumPy

Allows scientific computing and matrix operations.

Results

The algorithm under design needs to accomplish several tasks. It must identify a target in the image returned by the camera. It must be able to align the target to the center of the image. And it must then be able to align the laser with the receiver on the target. The algorithm developed allows the hosting agent to command the

Laser Communications Module to align the laser onto the targets receiver and send a message over the link.

Target Acquisition Algorithm

When operating, images are captured every 250 ms. They are transmitted by the GoPro as a Base64 encoded string. This string is decoded into binary values and put into a NumPy array. This array is converted to HSV values and image processing is performed. The Sift algorithm was attempted as a way of target identification but was not reliable. An alternative method was used with the Logitech USB camera. Once identified a region of interest is created around the detected agent. The distance between the center of the image and the detected agent is used as an error term for the gimbal control. Once the signal strength visual feedback LED is detected, motor movement ceases. The desired message is transmitted over the UART to the Laser Encoder / Decoder board.

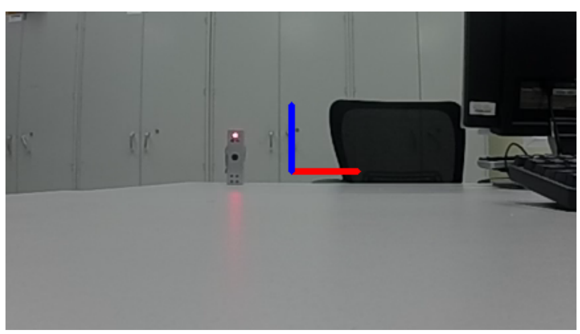


Figure 4: Raw camera image (GoProHero).

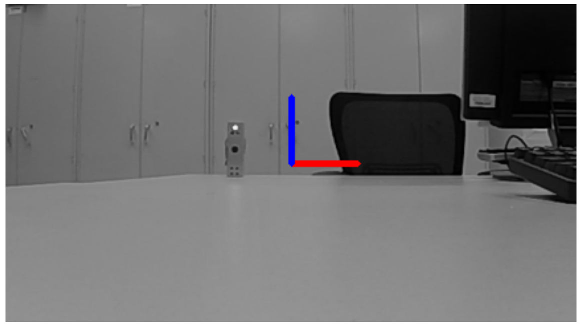


Figure 5: Red channel only from raw camera image (GoProHero).

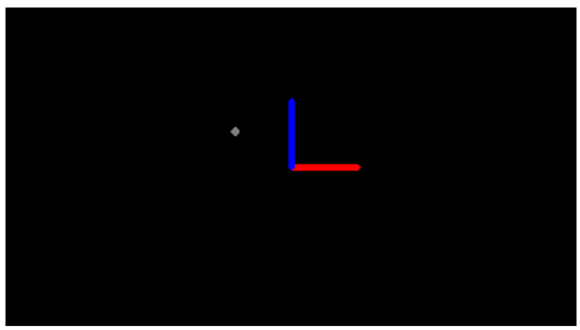


Figure 6: Location of desired target with respect to current center (GoProHero).

Visual Closed-Loop Control

The error term for the control equations is derived from the camera images. Once the target is identified the distance to the center of the image is calculated and this result is converted to millimeters. Once the image is centered the Signal Good LED is monitored to determine correct alignment. A small error input is used to cause oscillation about the center of the screen until the Signal Good LED is illuminated. At this point motor movement will cease and the signal is sent. Figure 6 shows the position of the current center with respect to the target position (white circle).

Target Identification with HSV Thresholding

Thresholding is the simplest way to track an object. It works in scenarios where the relative brightness of an object is unique in the scene. The LEDs used for identification where purposely selected to allow for just this case. OpenCV is used to perform a thresholding operation, masking out all other areas of the image whose brightness is less than the thresholded value. Once this is done then OpenCV is used to find connected regions. Since only the LEDs should be left in the image it should also be the only regions identified. The number of regions identified is the target ID.

Due to limitations in the available API for the GoPro Hero camera the Logitech USB was used for futher development. In figure 7 the raw image from the Logitech USB camera is first converted to HSV. HSV is used as it allows for the clean seperation of the colorspace. The image is thresholded to remove non-green values. The result of this operation is shown in figure 8. Then brightness thresholding is used to further eliminate other elements in the image.

Because the GoPro Hero3+ camera performs automatic gain and white balancing this technique was not feasible when using it. The LEDs were shifted to white and were not easily isolated from the rest of the image. The automatic adjustments also made the colors in the image unreliable under repeated tests.

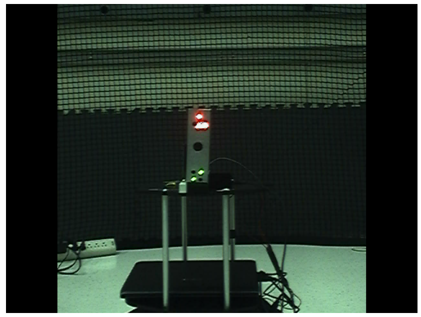


Figure 7: Raw Image before HSV thresholding (Logitech USB Camera).

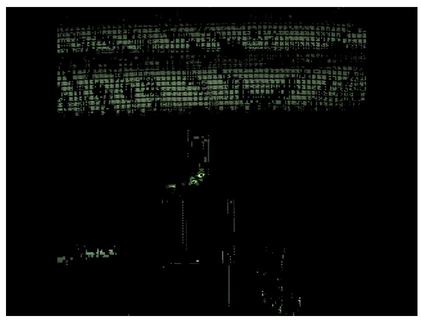


Figure 8: Image with HSV thresholding (Logitech USB Camera).

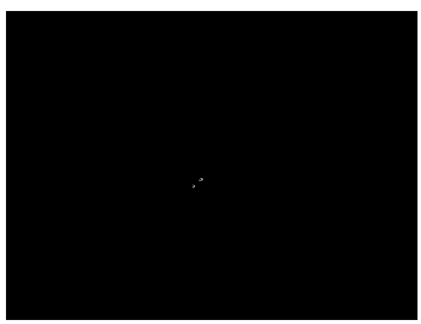
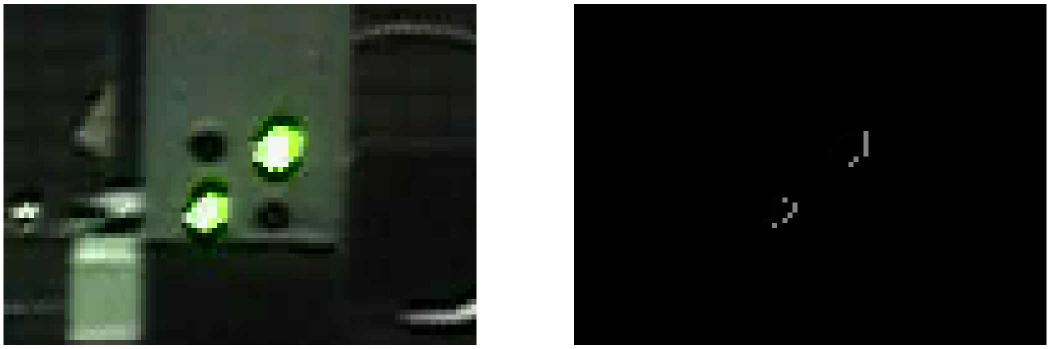


Figure 9: Processed Image (Logitech USB Camera).



(a) ROI on Raw Image (b) Processed Image

(c) Calculated Contours (d) Moments Centers

Figure 10: Image Processing and Computer Vision Steps (Logitech USB Camera).

Target Centering and Identification

The centroid of the identified region is found by using moments algorithm. Based on the ID of the target, the center of these regions is calculated and subtracted from the center of the image. An additional offset is applied, to allow for calibration of the laser and detector positions. This offset is fed into the motor control laws and the process is repeated until the image is centered.

During this stage the target can be identified. In figure 10 the steps are shown for the target identification for this particular robot. The contours of the processed image are found and their centers are identified by the moments. The angles between the centers are used to help identify the robot.

Laser Alignment

Centering of the target will move the laser close to the photodetector but will probably not strike close enough to activate it. Therefor a Laser Alignment stage is necessary. At this stage the Signal Good LED will be searched for. It should be above the ID LEDs and will also be detectable with thresholding. If the LED is not illuminated then a small random offset will be applied to the center of the image. Once the gimbal has moved the image to the new target center the LED is checked again. This process is repeated until the laser is aligned. At this point the message is sent across the laser to the target.

Because the laser and the camera are not perfectly aligned a calibration procedure needed to be developed. A small application was created to automatically calibrate the offset of the image for proper laser alignment. In figure 11 the original alignment, before calibration, is shown. The laser fails to align properly with the photodiode of the receiver. After calibration, figure 12, the laser properly aligns.

The response of the GoPro Hero3+ in figure 13a is due to latency in the images received from the GoPro Hero3+. In figure 13 the Logitech USB response is shown. The improvement of the response is due to reduced latency of the Logitech USB.

ROS

The Robot Operating System, or ROS, run on the Turtlebots in the MARHES lab. A demonstration of the system was designed for two the Turtlebots and appropriate nodes and topics created. In the demo a Turtlebot with a receiver only, termed the Target, is performing a mission. Another Turtlebot with the full gimbal, termed the Sender, is configured to request a secure message transfer to change the Target's mission. Figure **??** shows the nodes and topics used by the Target. The Sender's nodes are similar. A video of the demo is available online [6].

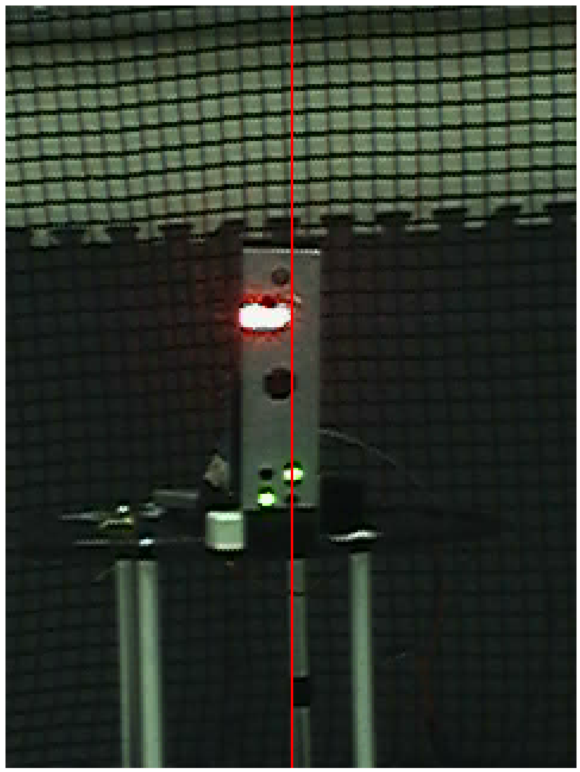


Figure 11: Camera aligned with the objective but laser alignment not calibrated. Green line represents the desired target, Red line represents current rotation (Logitech USB Camera).

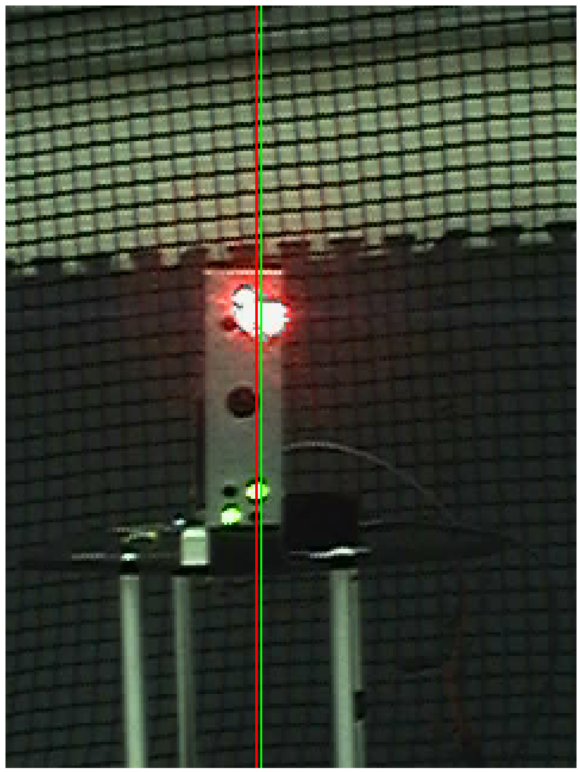
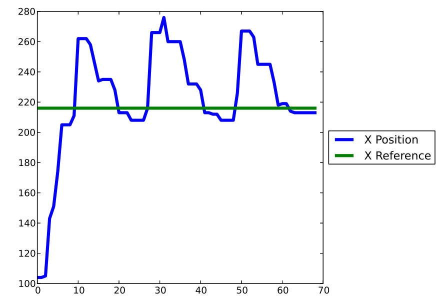
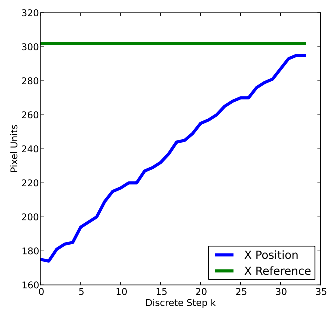


Figure 12: Camera aligned with the objective with laser alignment calibrated. Green line represents the desired target, Red line represents current rotation (Logitech USB Camera).



(a) Alignment Response (GoProHero).



(b) Alignment Response (Logitech USB Camera).

Figure 13: Alignment Response Comparison.

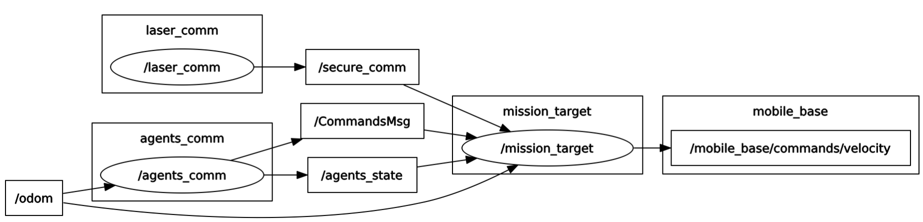


Figure 14: ROS Computational Nodes and Topics

Conclusion

My key contribution was to develop, build, and test a prototype that shows laser communications for small mobile robots. Using off the shelf components, coupled with embedded systems running open source computer vision software, a reliable and robust system can be made to allow point-to-point laser communications between robots of various capabilities.

This project involved many different areas of electrical engineering, including computer vision, embedded systems, control systems, laser optics, computer programming including Robot Operating System.

References

[1] V. Kumkar, A. Tiwari, P. Tiwari, A. Gupta, and S. Shrawne, "Vulnerabilities of wireless security protocols (wep and wpa2)," *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, vol. 1, no. 2, pp. 34–38, 2012.

[2] A. Kalis and T. Antonakopoulos, "Direction finding in ieee802. 11 wireless networks," *Instrumentation and Measurement, IEEE Transactions on*, vol. 51, no. 5, pp. 940–948, 2002.

[3] D. M. Boroson, B. S. Robinson, D. V. Murphy, D. A. Burianek, F. Khatri, J. M. Kovalik, Z. Sodnik, and D. M. Cornwell, "Overview and results of the lunar laser communication demonstration," in *SPIE LASE*. International Society for Optics and Photonics, 2014, pp. 89 710S–89 710S.

[4] A. Shrestha and M. Brechtelsbauer, "Transportable optical ground station for high-speed free-space laser communication," in *SPIE Optical Engineering+ Applications*. International Society for Optics and Photonics, 2012, pp. 851 706–851 706.

[5] J. Villbrandt. GoProHero driver. [Online]. Available: https://github.com/joshvillbrandt/goprohero

[6] P. Groves. (2015) System Demo. [Online]. Available: https://www.youtube.com/watch?v=dFVV_GYHUAE