Detection and Location System for Laser Interference with Aircraft

Nate Hough
Department of Electrical and Computer Engineering
George Mason University
Fairfax, VA, USA
nhough@masonlive.gmu.edu

***Abstract*— Aircraft pilots experience thousands of incidents related to green laser pointers every year, according to the FAA. The low cost and availability of high power laser diodes means it is easier than ever for malicious users to interfere with aircraft. This paper describes a compact and simple system that is able to detect and geo-locate laser pointers when they are aimed at aircraft. It is intended to mount in the cockpit of an aircraft and contains sensors such as a camera, GPS, and digital magnetic compass. An embedded processor runs a real time image processing algorithm to analyze the video feed from the camera and detect a laser strike. Data from the compass and GPS is paired with the camera imagery to calculate the location of the laser. This location data can be complied in a database to aid law enforcement in deterring laser threats to aircraft.**

***Index Terms*—Laser, Detection, Aircraft, Geo-location**

Introduction

There has been a significant increase in the number of green laser incidents involving aircraft over the last several years. From 2004-2015 there have been an average of about 3000 incidents per year [1], even though it is a federal crime to point a laser at an aircraft. Penalties range up to a $25,000 fine and 5 years in prison [2]. These laser-aircraft interactions are extremely dangerous for pilots, particularly during takeoff and landing. Although there have been no fatalities to date directly caused by a laser distraction, it occurs often enough that there is an imminent threat of a serious accident [3]. The increase of incidents may be partly attributed to the decreasing cost of high power laser diodes, meaning they are more readily available to consumers.

To better understand and track how these commercially available laser pointers interfere with aircraft, it is possible to detect and record these incidents. To date there are several "laser event recorders" that have been developed. Some can record characteristics about the laser itself like wavelength and pulse rate [4]. There is also a smartphone app that can detect and record imagery of a laser event and report it to a database along with metadata such as self-location and heading [5]. These systems have been of primary interest to the military community and have not proliferated to the commercial market.

These laser detectors have been shown to successfully record laser events, but they do not calculate a key piece of data- the location of the laser source. This is critical information that would vastly aid in the apprehension of those who wish to distract pilots with lasers. It is difficult for a pilot in a fast moving aircraft to pinpoint the location of a laser source, so an automated system is ideal. This paper will explore the feasibility of detecting and locating the source of laser illumination on an aircraft. The purpose of this project is to develop a system capable of successfully geo-locating laser sources while minimizing false alarm rates. The intended location for this system is in the cockpit of both private and commercial aircraft. Ideally the system would be relatively low cost to be accessible to all aircraft owners. Additionally the system would be self-contained and utilize its own built in sensors to simplify integration. It could be powered with a rechargeable battery to be totally independent of all connection to the host aircraft.

Methodology

It is desirable to leverage readily available and low cost technology to detect laser illumination. There is specialized equipment designed for laser analysis which could be used for laser detection. This includes spectrometers to measure wavelength, power meters to measure irradiance, fast photodiodes to detect pulse length, etc. This hardware is expensive, difficult to implement in a small form factor, and complex. For this reason, this project will utilize commercial "off-the-shelf" (COTS) hardware as much as possible. This will allow a system design with a low cost and thus a wide dissemination.

In order to calculate the location of a remote laser source, it is necessary to know the location of the detection system as well as the direction and from the system to the laser source. This telemetry data may be found using a GPS and a digital magnetic compass. Another critical piece of information necessary to determine the location of the laser source is the distance to the threat laser. To retain system simplicity and cost, it must be completely passive and may not use a rangefinder or other active means of finding distance. To accomplish this, the range may be triangulated using altitude data from the GPS and/or barometric pressure sensor and pitch data from the 3-axis digital magnetic compass. Once the system location, distance to the threat, and angular heading to the threat are known, the laser location can be calculated.

The optical detection of laser illumination is most easily accomplished using a digital camera. The laser must be pointing towards the camera and be in its field of view (FOV) to be detected. The following two figures depict the relevant angles in this problem. The 3D location space may be separated into two 2D planes, a horizontal plane for finding location and heading and a vertical plane for finding pitch and range. In the vertical plane, the distance above ground level is found from a relative altitude by subtracting the altitude at take-off from the current altitude. A local flat Earth is assumed for the sake of simplicity. The pitch is found by taking the system pitch reported by the compass and offsetting it by the vertical position the laser appears in the camera's FOV. Once the altitude of the system and pitch angle to the laser is known, the distance may be easily computed using the tangent function.

$$range = altitude * tan(90° + pitch + offset) \quad (1)$$

The range is defined as the "map range" or the ground range, not the slant range which is the straight line distance from the laser up to the aircraft. The map range is required to calculate the location of the laser because it correlates to a distance on the 2D map surface.

In the horizontal plane the data required for target location are self-location and heading. The system location is read directly from an onboard GPS module and requires no further processing. The laser heading may be computed from the system heading with an offset for the horizontal position of the laser in the camera image. As with the vertical plane, the laser must fall within the horizontal FOV of the camera to determine the offset from the center. If the laser falls directly in the center of the camera image the offset in both horizontal and vertical planes will be zero.

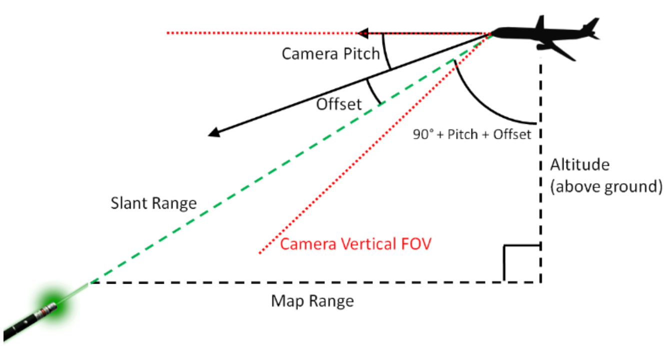

Fig. 1.Angles and distances in the vertical plane- i.e. side view

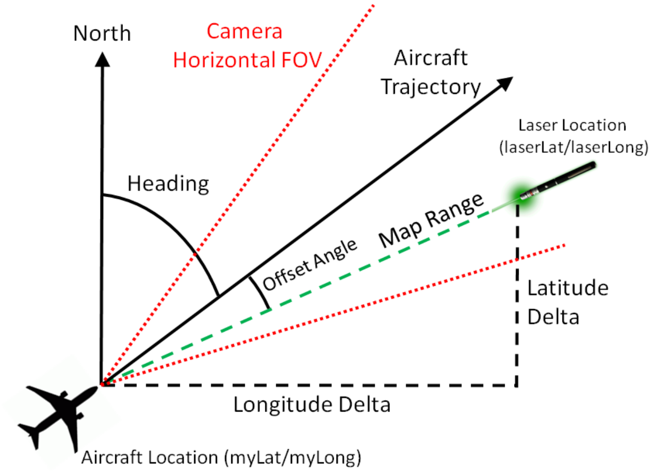

Fig. 2. Angles and distances in horizontal plane- i.e. top view

Once the self-location, the map range, and heading are known the laser location may be calculated. To find the latitude and longitude of the laser source, the latitude and longitude delta in each dimension between the system and the laser is found using trigonometry. It is known that a degree of latitude subtends about 111,111 meters on the surface of the Earth. This problem assumes a spherical Earth which is precise enough for this purpose. A degree of longitude subtends a distance proportional to the cosine of the latitude because the meridian lines come closer together as they near the poles. A correction must also be made for the magnetic declination which is the angular difference between magnetic north and true north. In the area the system was tested the magnetic declination is about 10.5 degrees. The following equations compute the final location of the laser source.

$$laserLat = myLat + (range * cos(heading + offset)/111{,}111) \quad (2)$$

$$laserLong = myLong + (range * sin(heading + offset + declination)/87832) \quad (3)$$

IMAGE PROCESSING

When a handheld laser is directed at an aircraft, it is difficult, if not impossible, for the user to keep the beam pointed at the aircraft. In reality the beam is only directly illuminating the aircraft for a small percentage of the time. This is because a laser is well collimated and the beam size gradually increases with range. This illumination profile is advantageous for detecting and locating the source of the threat laser. When the laser hits the system for a brief period, the camera image is saturated and blooms out the image, rendering it useless for analysis. The auto gain and auto exposure features of the camera cannot respond rapidly enough to compensate for the rapid high brightness of direct laser illumination. Fortunately because the laser only briefly scans across the camera's aperture, it can quickly recover from the high intensity light. The image processing algorithm takes advantage of this sequence to quickly detect and confirm a laser incident.

The image processing algorithm runs continuously on the camera feed. The Raspberry Pi's built in camera interface allows a direct feed of the image data as a 1024x1024x3 array containing the 8-bit RGB components of the image. Accessing the RGB image array directly greatly eases processing power requirements as the data is already in the ideal format. The image processing algorithm contains three stages: detection, confirmation, and location.

Detection

To detect a laser strike, the average RGB value of the entire 1024x1024 image is calculated for every frame. When a laser directly illuminates the average pixel value increases significantly due to the many saturated pixels. Once this much brighter frame is found, the next frame with a significantly lower average is found. The bright frame is only used for detection, it is useless for analysis since the majority of the pixels are saturated. This technique takes advantage of the short time the laser is directly illuminating the camera due to the difficulty of aiming a handheld laser at a distant aircraft. The following image that is less bright is more suitable for analysis, as shown in Fig. 3. The laser spot is still visible in this image because the edge of the normally distributed beam is in the camera's aperture or the atmospheric scattering deflects a portion of the light into the camera. This image sequence of dim-bright-dim constitutes a possible laser hit and the confirmation stage of the processing algorithm commences.

Confirmation

There are many possible light sources that could cause a saturated image, the most common being the Sun during the day or streetlights at night. To minimize false alarms it is necessary to determine that a laser is indeed the light source. This is accomplished by scanning the image for bright pixels and finding the centroid of the pixels above a threshold value. This threshold can be a fixed value near saturation. A more robust approach can use a dynamic threshold found by setting it to a value near the peak of the maximum value in the image. This requires a histogram calculation to determine the percentage of pixels above this dynamic threshold. There can also be pixels above the threshold not associated with the central laser spot that will skew the centroid value away from the correct location. To remove these aberrations a median filter is applied to the image which replaces each bright pixel with the median value of the surrounding predefined window. This ensures any bright pixels not adjacent to the laser spot are removed. Other filtering schemes were also explored such as a nearest neighbors filter which requires a region of adjacent pixels to be above a threshold value to include it in the centroid calculation. The centroid equation sums the indices of the pixels above threshold T and divides it by N, the number of pixels above threshold.

Fig. 3. Sequential camera frames with higher and lower average pixel values. The left image has an average value of 93 and the right image has an average of 30.

$$(X,Y)_c = \frac{1}{N}\sum(x_i, y_i > T) \quad (4)$$

The result are the coordinates of the centroid of the brightest spot in the image. There is still a significant probability for false positives due to the sun or streetlights or other bright light sources. To confirm a laser is the source a unique property of lasers is exploited. Laser light is monochromatic and in the case of commercial laser pointers is almost overwhelmingly green. For the purpose of this project only green lasers were considered, although other visible laser wavelengths are able to be detected. Green is the color of choice by laser pointer manufacturers because the wavelength is very near the peak of the human eye response, so less power is required for the same apparent brightness. For example, a red laser at 630nm appears about six times less bright to the human eye, so six times the optical power is required to achieve the apparent brightness of a green laser at a wavelength of 532nm. Detecting a single color of light is particularly ideal considering the image data is already split into red, green, and blue channels. While a saturated pixel in the middle of the laser spot appears white and has high values in all three channels, the pixels near the edge of the beam are not saturated and the color of the laser is detectable. To efficiently confirm a monochromatic light source, an array of pixels centered on the centroid of the laser spot is averaged in each color channel. The size of this confirmation array is proportional to the size of the saturated laser spot and is larger than it to ensure non saturated pixels are measured. The diameter of the laser spot D is determined by N, the number of pixels in the bright area.

$$D = 2 * \sqrt{N/\pi} \quad (5)$$

An upper bound may be set on the size to remove overly saturated images. A crosshair proportional to the size of the laser is labeled on the image for a visual confirmation that the centroid is correct, an example is shown in Fig. 4.

If the average green value is significantly higher than the average blue and red values, a laser strike is declared. This can be a very effective method to filter out false alarms in the imagery.

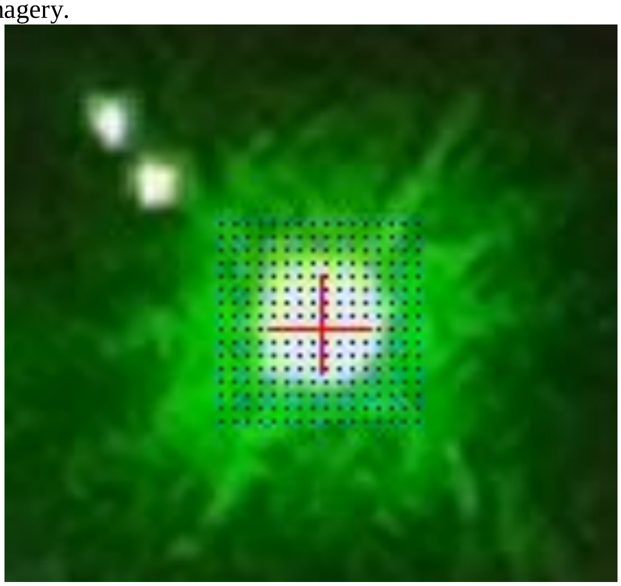

Fig. 4. Region of interest with centroid crosshairs and confirmation array labeled

Location

Once there is confirmation that a monochromatic laser spot is in the image, the angle of the laser spot relative to the camera's field of view may be determined. In the image array, the indexing of the pixels is with respect to the upper left corner (0,0), thus the bottom right index is (1024,1024). Because the camera's field of view is known (41° in this case), the horizontal and vertical offset angles of the centroid are easily found from the index of the centroid. These offset angles are added to the heading and pitch angles to find the angles to the laser threat.

$$Offset = ((centroid\text{-}center)/size)*FOV \tag{6}$$

For the example image in Fig. 5, the offset angles are calculated. The pitch offset is negative is keeping with the aeronautical convention of negative pitch angles below level.

$$Heading\ offset = ((584-512)/1024)*41° = 2.9° \tag{7}$$

$$Pitch\ offset = -((712-512)/1024)*41° = -8.0° \tag{8}$$

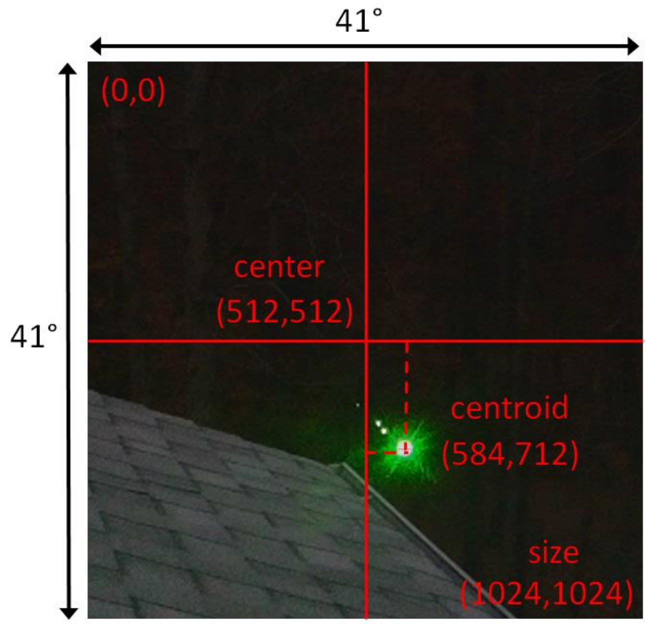

Fig. 5. Example calculation of heading and pitch offset angles from image

EXPERIMENTAL SETUP

To create a proof of concept system, low cost commercially available electronics were used. A Raspberry Pi 3 was the central processor that collected sensor data and performed all calculations. The built in wireless networking capabilities allowed it to upload result data during testing. The default operating system was used which is a version of Linux optimized for the limited processing power of the Raspberry Pi. All coding was completed using Python 3.5, this language was chosen for its ease of use and for the large number of add on "modules" available to it. The microcontroller was an Arduino compatible chip used to interface with some of the sensors. Using an Arduino based controller allowed the software to take advantage of the wide library base it contains. This approach allowed rapid prototyping of the sensor hardware and software so the majority of the effort could be focused on algorithm development.

In the same manner, the sensors were also selected for ease of use and compatibility. The GPS module is a MTK3339, a low cost but robust module with -165dB sensitivity and 66 channels. The published accuracy is given to be ±3m, which is typical for a consumer grade unit and may be worse in practice.

The digital magnetic compass is a Honeywell LSM303 surface mount component that is specified to a ±1 degree accuracy. Unfortunately there are many sources of local magnetic fields that can distort the Earth's magnetic field and give false compass headings. Accuracy of a degree is for ideal conditions and may not be realizable in practice. This can lead to large errors in the calculated laser position, as an angular error worsens with distance. Another issue with a magnetic compass is the declination between magnetic north and true north. This offset must be accounted for to obtain accurate location data. In the area the system was tested the magnetic

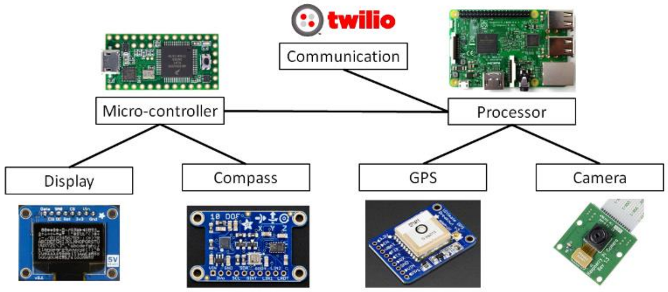

Fig. 6. Functional block diagram

declination is about 10.5 degrees, so this fixed offset was incorporated in to the calculation.

A camera was used for the actual detection of the laser illumination. The native Raspberry Pi camera was chosen because of the built in camera serial interface (CSI) and driver support. This meant the raw camera stream was directly accessible via a Python module and the image array was able to be accessed and processed without the need for external hardware or software. The camera is a 5 megapixel CCD array with 40x50 degree field of view (FOV). To ease processing requirements the resolution of the camera was limited to 1024x1024 pixels which yields a uniform field of view of 41x41 degrees. This limits the detection area to a narrower FOV, whereas an ideal system would cover the entire cockpit FOV. Figure 5 is a functional block diagram of the test system.

TESTING AND RESULTS

To simulate the scenario of a system mounted in an aircraft a location was chosen with significant altitude variation. Ideally the system would be moving but was not feasible under the scope of this project. The maximum range available was less than 100 meters, which is a reasonable distance for initial tests but further distances up to several kilometers should be tested in future efforts.

The laser used for testing was a commercially available pointer. This pen sized pointer had a 50mW output power, and it was a green laser with a wavelength of 532nm. The laser beam is well collimated to about 1 milliradian, so it very gradually increases in size with greater ranges. The beam is a few millimeters in diameter directly in front of the laser, and at 100m the beam is 10cm across. This is much larger than the aperture of the camera and will fill it completely when illuminated. The irradiance Φ at the tested range is defined as the laser power divided by the area of the beam. This will give the average irradiance assuming the beam is uniformly distributed. However, the distribution of the beam is Gaussian, so the peak irradiance is twice the average of a uniform beam.

$$\Phi = \frac{power}{area} = \frac{50mW}{\pi * 5cm^2} = 0.6\ mW/cm^2 \qquad (9)$$

This irradiance level, while below the threshold for permanent eye damage, is considered a flashblindness hazard by the FAA [2]. This level of laser illumination should be easily detectable by the system.

To test the system the laser was used to illuminate the system from a known location. When the system detected the laser and calculated its position the data was collected and compared to the actual location. The error was calculated to be 15m meters. Table I shows the test data from the system and Table II is the resulting location calculation compared to the ground truth. A visual diagram of this data is shown in Fig. 7 overlaid on satellite imagery. The output of the system is the image in Fig. 8, which is stored onboard the processor. The communication interface output is shown in Fig. 9. An API named Twilio was used to send text message notifications when a threat was detected. This is one example of how the system could inform local law enforcement of a laser incident.

TABLE I. EXAMPLE SYSTEM LOCATION DATA

System Latitude	System Longitude	System Heading	System Pitch	System Altitude
XX.XXX	XX.XXX	231°	-12°	18m

TABLE II. TEST RESULTS

Laser Lat (actual)	Laser Long (actual)	Laser Lat (calculated)	Laser Long (calculated)	Error
XX.XXX	XX.XXX	XX.XXX	XX.XXX	15m

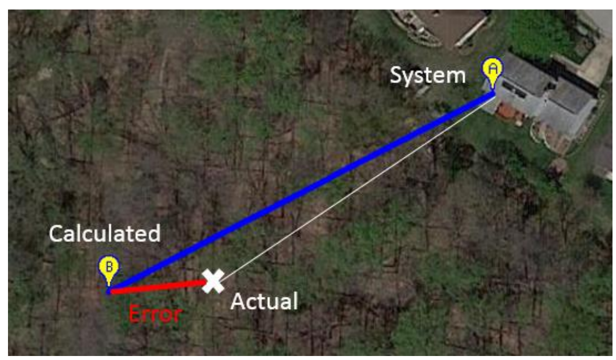

Fig. 7. Satellite view of test location

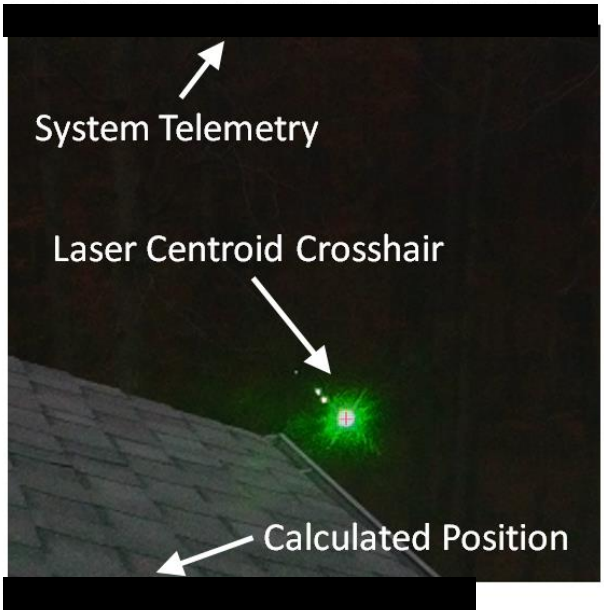

Fig. 8. Image output of system

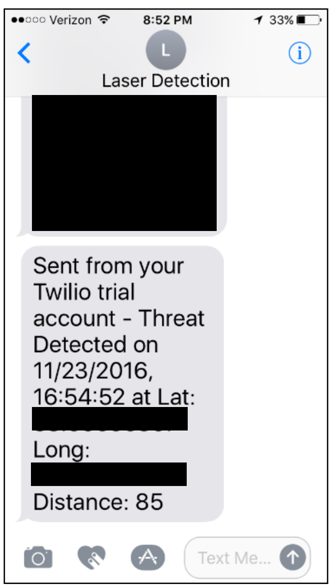

Fig. 9. Screenshot of text notification using the Twilio API

The experimental system is shown in Fig. 10. This system is fairly portable, but future work could minimize the size and increase robustness to test on an aircraft.

Fig. 10. Proof of concept system

SOURCES OF ERROR

There are many possible sources of error in this system architecture. Systematic errors such as location error from the GPS are relatively small and may only vary by several meters. The largest source of error is the heading of the digital magnetic compass. Typical consumer level compass modules have errors around 1 degree. At a laser threat distance of a kilometer, this translates into almost 20 meters of error. There are several possible improvements that could be made to the compass heading. One is to use the dynamic GPS location as the system moves to calculate heading. This technique can yield very precise headings. Another alternative is to acquire compass data from onboard avionics which are in all airplanes. However, the desire to keep the system portable and simple to integrate precludes the complexity of tapping into aircraft sensor data.

FUTURE WORK

While this work has successfully demonstrated the concept of geo-locating a laser source, there are many possible improvements to be made. The single biggest improvement may be in increasing the speed of the system to more quickly capture and process imagery. This project leveraged COTS electronics that are low cost and easy to use. Using faster processing and higher quality imagers would allow greatly improved frame rates and image processing speed [6]. In addition, more precise location sensors would improve target location accuracy. Tapping into the high quality compass and GPS sensors on a commercial aircraft, for example, would drastically improve the ability of the system. For this project, it was not feasible to integrate onto an aircraft and convince a pilot to allow lasers to be intentionally aimed at the cockpit.

As with some previous attempts to detect lasers [3], a possible implementation may be through a smartphone application. The technology available in today's phones is capable of detecting and locating laser threats. A typical phone includes a camera, compass, GPS, processor, and display which are all the components necessary to create a laser location system. The proliferation of smartphones would make an application readily accessible to all potential users.

There also exists room for improvement in the image processing algorithms. For this proof of concept system, a simple algorithm that minimized processing demands was developed. A more robust algorithm would better minimize false alarms. A detection system such as this must have an acceptably low false alarm rate to be considered valuable, otherwise it will not be used. Any improvements need to be tested on an aircraft to validate it at high speeds and high altitudes.

SUMMARY

A system capable of detecting and locating laser sources is a useful tool to aid in eliminating laser threats to aircraft. This work demonstrates a proof of concept system that can successfully detect and locate these lasers. False alarms were drastically minimized using a real time image processing algorithm, which is an important characteristic of any such system.

ACKNOWLEDGMENT

The author would like to thank his advisors Dr. Kenneth Hintz and Dr. Peter Pachowicz at George Mason University, Department of Electrical and Computer Engineering, for their support of this project.

REFERENCES

K. Barat, "Hand held lasers, a hazard to aircraft: How do we address this?", Education and Training in Optics and Photonics: ETOP 2015, vol. 9793, 2015.

P. Murphy, "Laser Pointer Safety - Different lasers' hazards compared", Laserpointersafety.com, 2016. [Online]. Available: http://www.laserpointersafety.com/page52/laser-hazard_diagram/different-lasers-compared.html. [Accessed: 06-Dec- 2016].

Federal Aviation Authority (2012) FAA Steps up Enforcement of Laser Penalties, FAA Press Release, 16 May 2012

C. Schwarze, R. Vaillancourt, D. Carlson and J. Engel, "Ground and Air Test Performance of the Laser Event Recorder", OPTRA Inc., 2005.

C. Williamson, "A LASER EVENT RECORDER SMARTPHONE APP", in International Laser Safety Conference (ILSC), Orlando, 2013.

L. Napolitano, P. Bryson, K. Berry, S. Klapp, J. Leeper and G. Redinbo, "Design of a Special-Purpose Computer for Locating Targets Within an Image", Visual Communications and Image Processing, vol. 1001, pp. 385-393, 1988.