A Controllable Laser Projector for Diverting Traffic
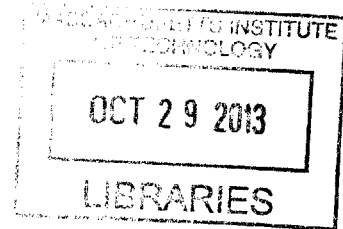
by

Brian Xiuken Wu

Submitted to the Department of Electrical Engineering and Computer
Science
in partial fulfillment of the requirements for the degree of

Master of Engineering in Electrical Engineering and Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2013
(June 2013)

Author . . . .
Department of Electrical Engineering and Computer Science
May 24, 2013

Certified by. . . . .
Seth Teller
Professor of Computer Science and Engineering
Thesis Supervisor

Accepted by . . . .
Prof. Dennis M. Freeman
Chairman, Masters of Engineering Thesis Committee

A Controllable Laser Projector for Diverting Traffic

by

Brian Xiuken Wu

Submitted to the Department of Electrical Engineering and Computer Science
on May 24, 2013, in partial fulfillment of the
requirements for the degree of
Master of Engineering in Electrical Engineering and Computer Science

Abstract

For this Master's thesis, I designed and implemented a combined laser and controller system that can receive and convert commands from a computer into useful laser projections.

In the last 10 years, on average, one police officer, who is conducting a vehicle stop or directing traffic, is struck and killed by an oncoming vehicle per month in the United States. Most of these instances occur at night. Current literature proposes that for some drivers, especially those who are fatigued, the combination of bright, rapidly flashing emergency lighting causes them to drive closer to a emergency vehicle rather than away from it. An effective solution to this problem is to extend the visual range of warning lights.

Existing methods of lane diversion are time consuming, bulky and/or dangerous to deploy. The project is a system that allows the officer to quickly delineate a series of laser points to simulate a line of road-side flares. This will result in a commonly-used, perceptually salient visual signal that will induce traffic away from the cruiser.

The controller interfaces with the police officer's computer over a USB 2.0 interface. Internal EEPROM allows the system to store up to 100 unique coordinates and intensities. The communication protocol is handled with the SerialPy library. Testing and calibration of the laser projector is integrated with a simple UI and rear-facing cameras. The UI also allows the user to select arbitrary points for the laser spots to be projected on to, creating a series of virtual flares.

Using a cylindrical lens to expand the laser beam and reduce divergence, we were able to focus the laser spot accurately to 50m, increasing optical power density and increasing visual recognition at a distance. The laser output power can be configured from 0.2mW to 1W using a PWM driver.

Thesis Supervisor: Seth Teller
Title: Professor of Computer Science and Engineering

Acknowledgments

3

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Incidence of Roadside Accidents

Despite the use of vehicle-mounted emergency lighting (VMEL) systems to alert drivers, police cruisers parked along the roadside are still frequently struck by drivers, leading to injuries or fatalities. In the years 2000–2009 inclusive, 120 officers were killed by being struck by a vehicle, an average of one fatality per month. 47 of these deaths occurred while the officer was conducting a "Traffic stop, roadblock, etc.", and the other 73 occurred while the officer was "Directing traffic, assisting motorist, etc" [U.S. Department of Justice, Federal Bureau of Investigation, Criminal Justice Information Services Divison, 2009]. The majority of these fatalities happened when the police cruiser was stationary.

A large proportion of traffic accidents with stopped police vehicles happened between midnight and 6 AM; major factors were determined to be drunken driving and fatigue [Agent and Pigman, 1990]. Other researchers have found that most roadside accidents with police vehicles occur along straight, dry roads in clear weather [Solomon and Ellis, 1999]. Inclement weather is not the key or even leading cause of the accidents. There must be a failure, end-to-end between the police vehicle current diverting scheme, and the ability of drivers to comprehend and maneuver around it.

1.1.1 Human Visual Response

Much resarch has been done on the human visual system and its response to luminous cues. Mortimer [1969] proved that spatially extended light sources are more conspicuous than point sources. Croft [1971] noted that moving light sources are more conspicuous than static ones. Bullough et al. [2002] stated "[A]n array of small point sources can be more effective than an equivalent diffuse source at eliciting rapid visual responses." Bullough et al. [2001b] evaluated "sweeping" rear brake lights vs. instant-on LED sources, and found that LEDs yielded faster response times. The combination of these factors lends themselves to a large, modulating, and optically 'moving' light source, such as the VMEL system.

Olson [1993] describes a condition called "night myopia", when the eye focuses closer than infinity when dark-adapted, making objects at visual infinity (usually 20 feet or more away) out of focus. It becomes more difficult for night drivers to accurately assess the location and distance of the police officer at night.

Smith et al. [2001] states that the apparent expansion rate of an object is the main factor of a driver's response to it. The faster the object expands in one's field of view, the more attention it will receive. Chemical flares are invaluable in this regard. When drivers pass near the flares, the spatial movement alerts the driver on how fast he is moving at some distance away from the police officer. The driver now has time to react before passing the cruiser itself.

The Moth Effect

The "moth effect" is when a driver inadvertently steers a vehicle towards a bright light in their field of vision. Clark et al. [1953] noted that pilots experienced a narrowed field of attention which excluded perception of visual stimuli when faced with a bright light source.

Helander [1978] found a 1-degree change in steering angle toward oncoming traffic, for several seconds before the passing event, after initially steering away. He attributed the effect to a perceptual-motor phenomenon. Readinger et al. [2002]

reported seeing a steering bias in the direction of the driver's view.

Charles et al. [1990] suggests that highly visible lighting "decreases the ability of oncoming traffic to recognize and respond to other information salient to safe driving". Kitamura et al. [1994] concurs with this assessment, and demonstrated that noticing a flashing light on a parked car actually caused the driver to steer closer to the car, more so than if the driver did not notice the light. The "moth effect" suggests that the VMEL system on cruisers may have the opposite effect on certain drivers, causing them to drive closer instead of being diverted away. The reduced distance between the oncoming vehicle and police cruiser will result in a higher accident rate.

Olson [1993] rejects the existence of the moth effect, countering that the failure to accurately estimate differences in speed is the cause of many highway collisions with stopped vehicles. Olson also notes that a tall light source, or light sources spaced closely together, will make the stopped behicle appear farther away than it actually is. He attributes this effect to driver expectation in lighting placement on cars. VEMLs are currently used and mounted on the roof of the car; using Olson [1993], as a guide, this would make the police vehicle subjectively appear twice as far as it actually is, giving oncoming drivers false information on where the cruiser is and how much buffer space they have.

Design of Emergency Lighting Systems

Berkhout [1979] studied lighting configurations and color compinations, and had subjects gauge speed and directions under a variety of experimental conditions. The expected advantege of traditional blue emergency lighting at night was not observed, as blue light was not thought to 'ruin' night vision like green light does. The best light configuration depended on relative motion between the light source and driver. Some light schemes unfortunately produced the illusion of receding motion when the source was at rest, again confusing the driver on the relative velocity between his/her vehicle and the cruiser.

Bullough et al. [2001a] identified factors that determined visibility of an emergency vehicle to other drivers: mounting location; temporal light characteristics; spatial

light characteristics; spectral characteristics and luminous intensity. He noted that people reacted much faster to changes in vehicle speed when the vehicle employed a steadily changing light, rather than a quickly flashing light. Common VMEL patterns utilize quickly strobed lights, potentially reducing the signals efficacy.

Sensor Technology Integrated into Police Vehicles

Police cruisers are currently installed with sensing equipment to aid law enforcement, such as radar and lidar systems to gauge the relative speed of other vehicles from the cruiser [Kustom Signals, 2011]. The feedback is an audible tone that changes pitch and volume based on the relative velocity of traffic. The police officer can estimate the passing traffic speed based on the relative tone of the radar speakers.

1.2 Current Light Solutions

1.2.1 Pyrotechnic Flare

Figure 1-1: Pyrotechnic Roadside Flare; source: Wikipedia

Pyrotechnic flares, or fusee, use intense exothermic combustion to generate a red-yellow light. Current flares are ignited by striking the phosphor tip against the road and can last for 10-60 minutes, depending on the exact model. Fusees are common in emergency kits and are the de facto deployed signals. The intense heat generated can cause severe burns and leave behind residue and metal when complete. Interviews with Massachusetts State Police [MSP] indicate their reluctance to use pyrotechnic flares due to their long set-up time and physical danger involved in deployment on the roadway.

1.2.2 Chemical Flare

Figure 1-2: SnapLight^{TM} Flare; source: disclose.tv

The SnapLight^{TM} flare uses chemiluminescence to generate light. Like the pyrotechnic flare it is a one-time signalling device. It has the advantage of generating a low amount of heat, making it safe to handle and use. The Snaplight still requires considerable transport space, and requires time to deploy and clean-up.

1.2.3 LED/Strobe Flare

An LED Flare (Figure 1-3) uses a high-intensity LED to emit light. The electronic flare is reuasable, rechargable, lightweight and can modulate different patterns. However, they are more expensive than single-use flares, and require time to set up and retrieve.

1.2.4 Evaluation of Current Solutions

The main method of traffic diversion for a police vehicle is the roof-mounted light bar component of the VMEL. The light bar, although highly visible to normal drivers, also impairs night-vision and spatial resolution. The light bar is effective in signalling the presence of a police cruiser, but does not effectively indicate the position of the vehicle with respect to traffic lanes.
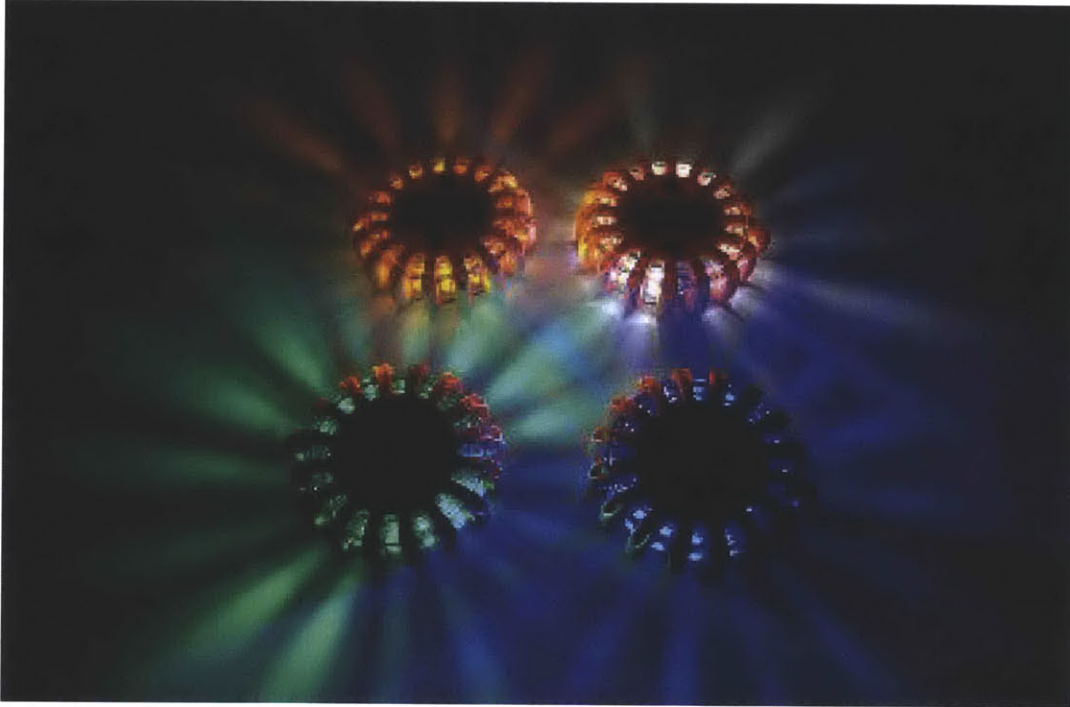
Figure 1-3: PowerFlare™; source: powerflare.com

In addition to the strobing effects of the light bar, officers often place traffic cones and flares if a stronger visual cue is required. However, traffic cones are bulky and take up vital carrying capacity in the police vehicle. Pyrotechnic flares are dangerous to operate, requiring constant attention lest the officer injure themselves or others. Pyrotechnic flares have a relatively short duration, and clean up of debris is time-consuming and difficult. The varying conditions of a traffic stop will absorb significant time and manpower if the officer chooses physical traffic diverting means. The average traffic stop takes less than 20 minutes, of which the officer pays most of their attention to the target driver. [MSP interview, March 2012]

A diverting system that can be quickly established while the officer maintains control of the traffic stop would be optimal.

1.3   Proposed Solution

The overall objective of the project is to reduce the occurence of roadside casualties caused by collisons between a moving and a stationary vehicle; primarily when the

police vehicle is the stationary one.

The project is a subset of a research effort for the National Institute of Justice (NIJ). The goal is to create a vehicle-mounted module that will *divert* oncoming traffic efficiently, reducing the rate of collisions; and *alert* police officers of imminent threats, so they can take appropriate measures to prevent becoming casualties.

The proposed solution detailed in this thesis is the preliminary design and construction of a vehicle-mounted laser projector to divert oncoming traffic away from a stationary police vehicle. The following goals serve as a guide and target to facilitate acceptance within the law-enforcement community.

- The device should be compatible with existing cruiser hardware and officer training.

- The device creates images on the road pavement that are visually similar to current roadside flares.

  The visual familiarity helps in communicating the intent to oncoming vehicles, reducing time and cost in educating the public in proper driving procedure.

- The device should have optical presence beyond 30m [100ft], which is an average distance for roadside flares to be deployed from the cruiser.

- During normal operation, the device should be eye-safe for both oncoming traffic and police officers using the device.

- The device should work in darkness, when the incidence of road-side collision is highest.

1.4   Outline

Chapter 2 describes the background information for the technology used in the device, as well as design contraints and safety concerns. Chapter 3 describes a specific implementation that meets the goals proposed. Chapter 4 describes the tests and results gathered. Chapter 5 describes future improvements on the path to public usage.

Chapter 2

Technical Background

2.1 Optics

2.1.1 Divergence

Any light that exits an aperture of finite size will have some divergence associated with it (see Figure 2-1). The divergence is defined as the angular spread of the light source. The choice to use lasers as the light source is due to the laser's extremely low divergence factor, which will be a factor in the upcoming subsection. The narrowest portion of the laser beam, W_0, is the 'beam-waist'.
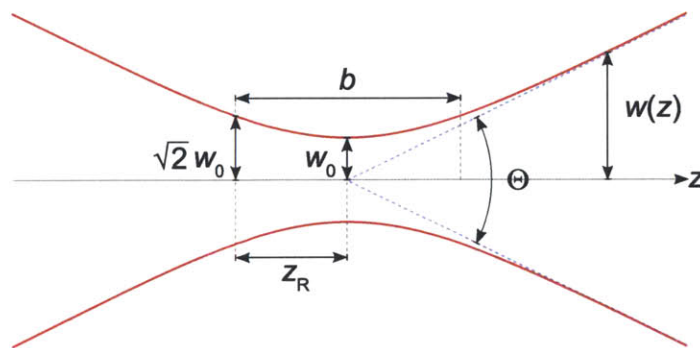
Figure 2-1: Laser Beam with divergence Source: Wikipedia
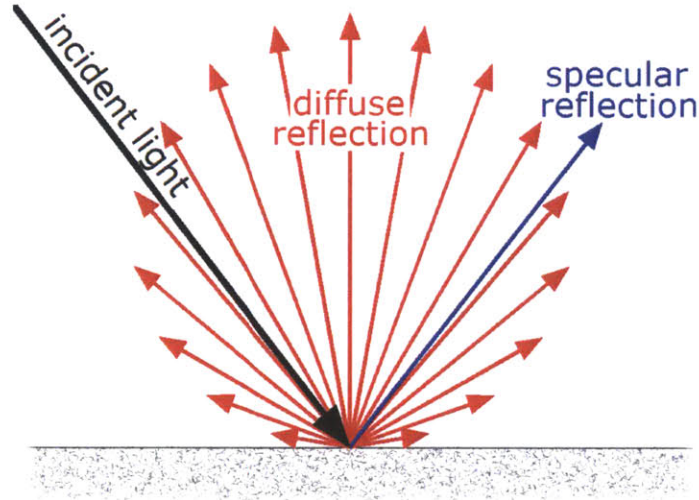
Figure 2-2: Specular and Lambertian Diffuse reflection; source: Wikipedia

2.1.2 Reflectivity of Pavement

The laser projection system discussed in this thesis is intended for projecting onto road-grade asphalt. The asphalt is made of small gravel less than 0.25 inches wide bound by bituminous tar. Asphalt has a total reflectivity of 0.05 to 0.1, while concrete's reflectivity is 0.5 to 0.2. The age, dirt, and composition of the road surface significantly affects the road reflectance. The reflectivity at low incident angles is less than 10% at normal (perpendicular) incidence. The rough texture of the asphalt results in a mostly diffuse reflection of the primary beam, with decreased reflectance at low angles due to the self-shadowing effect and multiple scattering surfaces [Adrian and Jobanputra, 2005]. Figure 2-2 illustrates the difference between the specular reflection and the diffuse reflection. A powerful laser is needed to overcome the luminous absorption properties of asphalt.

The reflectance of the asphalt may also change depending on local thermal properties and time elapsed. At low incidence angles, the reflectance of the asphalt may change as much as ±3% [Jiang et al., 2012].

The divergence of the specular reflection is higher than the incident beam due to the irregularites in the road surface. This reduces the irradiance, making it safer to observe the reflections at closer distances. However, debris on the road can be
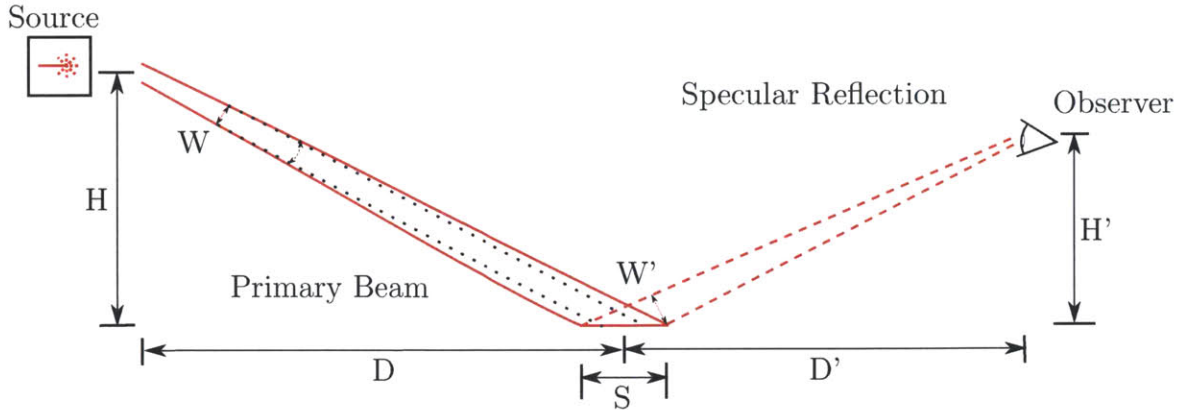
Figure 2-3: Foreshortening and Reverse Foreshortening Effects

hazardous, as glass, chrome and steel have high specular reflectivity. At low angles of incidence, glass approaches 100% reflectivity while only increasing beam divergence by 1mrad [Marshall, 1995]. The reflection caused by the debris results in a higher radiant intensity, potentially injuring nearby observers. The reflected beam may also violate FAA radiation limits (FAA Advisory Circular 70-1).

2.1.3 Foreshortening Effect

(See Figure 2-3) For a large projection distance D, cruiser height H, and divergence angle Θ, The foreshortening effect can be approximated as $S \approx \frac{W + \Theta \cdot D}{\frac{H}{D} - \frac{\Theta}{2}}$. This means that as the distance increases from the projector to the projection point, the laser creates an increasingly large spot size onto the pavement. The foreshortening effect is dominated by the divergence of the beam rather than the beam diameter. A larger spot size results in lower optical power per unit area, resulting in a dimmer projected flare. The higher the projector is mounted on the vehicle, the further the projector can illuminate the road surface while still maintaining luminous intensity.

2.1.4 Reverse Foreshortening Effect

Since the target observer is part of the oncoming traffic, this puts constraints on the distance and viewing angle of the reflected beam. This projection onto the observer counteracts the forshortening effect as such:

$$W' \approx \frac{W + \Theta \cdot D}{\frac{H}{D} - \frac{\Theta}{2}} \times \frac{H'}{D'}$$

Therefore, an observer at a distance from the projected point would see a small spot again. The result is a lower laser power necessary for visual recognition, but also lowers the maximum safe laser power if the specular reflection of the pavement is high.

2.2 Lasers

Lasers have been used to display images for the last 40 years. Lasers use a resonant cavity in a heterojunction semiconductor diode to emit coherent light in the visible region [400-700nm]. The number of emitted photons is linearly dependent on the diode current above a certain threshold [Ganguly, 2007]. The laser then is exponentially dependent on the voltage applied to it, making current control a preferred option for power modulation.

2.2.1 Hazards

Lasers are intense sources of coherent light. If carelessly implemented, can cause permanent harm to the user and/or oncoming traffic.

The human eye (see Figure 2-4) uses the cornea and lens to focus incoming light onto the retina in the back of the eye. The retina is composed of light-detecting cells, blood vessels, and supporting vascular tissue. The lens can focus a collimated light beam 10,000X its incoming diameter, thus a laser beam 1mm wide is focused onto a point on the retina $10\mu m$ wide [Barat, 2006]. In this project, the lasers used emit light in the visible spectrum [400-700nm], so the retina is the easist body part to be injured (ANSI Z136.1).
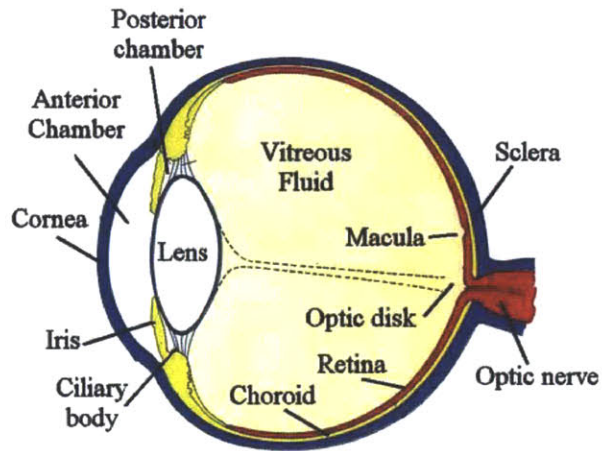
Figure 2-4: Cross section of an eye

Class	Power Range	Protection	Notes
1	< 0.1mW	None	Safe for all conditions of normal use, even when under magnification
1M	< 0.1mW	No Magnification	Safe for normal use, large diameter beams, do not view under magnification
2	< 1mW	Blink Reflex	Safe under normal blink reflex
2M	< 1mW	Blink Reflex and no Optics	Safe under normal blink reflex, do not view under magnification
3R	< 5mW	Limiting Viewing angles	Safe as long as eye does not enter direct beam path
3B	5mW-500mW	Optical Filter	Diffuse Reflections from matte surfaces are considered safe. Interlock required
4	+500mW	Optical Filter and Protective clothing	Skin damage can result from direct contact of beam. Eye damage can result from diffuse reflections.

Table 2.1: Laser Classes for Continuous Visible Light (400nm-700nm) (FDA)

2.2.2 Safety Standards

Lasers in class 3B operation are required to have a key switch and interlock. The interlock will power down the laser beam if the device is 'open'. The keyswitch is to prevent accidental activation of the laser source (ANSI Z136.1). Due to constant modifications to the laser beam optics and alignment, the laser beam was driven at class 3R power during scanning modes when not on protected laser ranges.

ANSI

American National Standards Institute (ANSI) is a 3rd-party research institution, and is influential in determining safe expsoure levels for viewing lasers and acceptable operating procedures. Many of the following government agencies refer to the ANSI guidelines for issuing legal compliance. The ANSI Z136.1 and ANSI Z136.6 guidelines are of particular importance to this project. ANSI Z136.1 defines the Maximum Permitted Exposure (MPE), Nominal Ocular Hazard Zone (NOHZ), and diffuse hazard zones.

ANSI Z136.6 defines the operation guidelines for using a laser outdoors. It also details the maximum light permitted for critical visual tasks, such as driving. The institute recommends establishing a buffer around the laser projection zone, as seen in Figure C-7.

FDA

All commerical laser devices used in the US must be vetted by the Food and Drug Administration (FDA) by way of Center for Devices and Radiological Health (CDRH), specifically under the Federal Laser Product Performance Standard (FLPPS) covered under 21 CFR 1040.10. The operator must get approval from the FDA before using a Class 3b or 4 laser outdoors (Figure C-9).

FAA

For outdoor lasers that intersect with US airspace and exceed Class 3R power rating, the Federal Aviation Administration (FAA) must be notified of its operation. An application must be filed with the FAA before the laser can be actived (Figures C-11 and C-12). The operator must detail the laser's location, heading, intensity, and safety precautions during its planned operation. The FAA may respond requesting procedure changes or additional safeguards be installed. For the outdoor laser operation to continue, the operator must obtain a letter of no-objection from the FAA (Figure C-13).

OSHA

The Occupational Safety and Health Administration (OSHA) requires the laser operator must have sufficient training and control of the laser while it is operational. OSHA also mandates sufficient safety margins, warning signs, and restricted access to the primary beam while the laser is in operation [Occupational Safety and Health Administration, 1993].

IEC

The International Electrotechnical Commision (IEC) is a global 3rd-party organization that prepares international standards for all electronic technologies. The relavent laser safety and operation standards are located in IEC 60825-1. IEC laser safety is based on AEL derived from the ANSI, as it incorporates how the laser is viewed.

Massachusetts State Law

Massachusetts state law 105 CMR 121 prevents the general use of class 3B and 4 lasers outdoors near an audience without sufficient margins of error. The law also requires that the laser operator can only be exposed to at most Class 2 radiation. Following ANSI Z136.1 guidelines is required for compliance with this law. A copy of the FDA approval for outdoor laser use must also be filed with the Massachusetts

Radiation Control program [Massachusetts Department of Public Health, 1997].

Safety Analysis

The lasers used in the project are rated as class 3B. The guidelines detailed above make outdoor high-intensity laser tests difficult to complete. A class 3B laser cannot be used outdoors without sufficient notification of relevent authorities (FAA & Massachusetts). The officer's conduct (Appendix D) during a traffic stop violates safety margins detailed in ANSI Z136.6. There is insufficient warning and zone restriction for oncoming traffic concerning the NOHZ. Therefore, all testing with the scanning laser will be done in limited access areas or with a class 3R laser.

The laser beam is intended to reflect off of the road surface, and intended targets observe the diffuse, or scattered reflection from the pavement. The specular magnitude, or collimated reflection, of the laser beam is small, due to the rough texture, low reflectance, and self-shadowing effect of the asphalt. For compliance with estabilished safety calculations, we assume that the laser source and observer are stationary. Since the intensity of the laser is very high, and the divergence is low, the blink reflex is insufficient in protecting a person from harm. Direct exposure of the primary beam to the eye will cause thermal damage to the retina, resulting in injury and/or permanent vision loss. Sufficient distance margins and appropriate safety equipment will be required for high-power laser tests.

2.3   Galvanometers

The laser beam is projected onto the desired points on the pavement with precision galvanometers with mounted mirrors. A galvanometer is an electro-mechanical device that given an input electrical signal, turns a mirror at a specific angular position. The galvanometer system used consists of an mirror that deflects the incoming laser beam in the X axis, and another mirror that deflects the laser beam in the Y axis (Figure 2-5). Since the mirrors are orthogonally mounted and close together, we simplify the optical transform as two orthogonal and independent angular deflections.
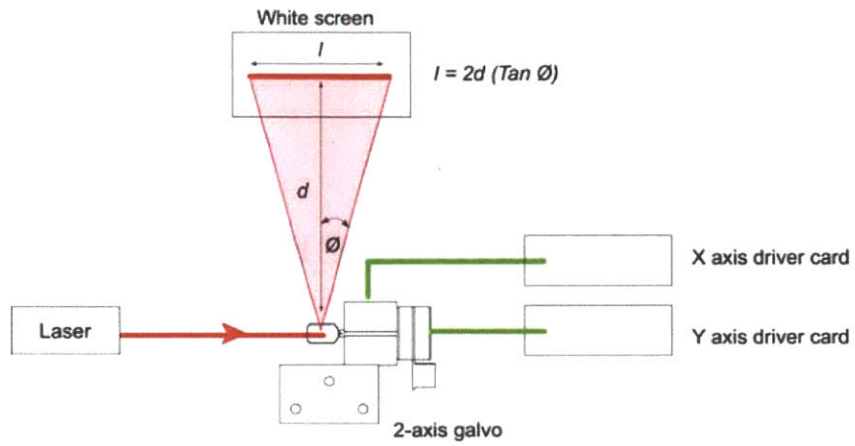
Figure 2-5: Layout of 2-axis Galvanometer; Source: Thorlabs

Figure 2-6: Galvanometer; source: Thorlabs

Chapter 3

Design and Components

3.1   Structure

The projector is composed of the physical hardware, and a driver program that operates on the local computer.

The Local Computer has a Publisher routine that exports data structures detailing where, when and how intense the laser should be.

The Listener routine receives the message data and parses it into appropriate byte-sized packets. The packets travel over the USB line to an FTDI232 converter, which converts the data into a serial signal.

The Controller communicates with the FTDI232, processes input data, and stores the current state. The outputs of the Controller are the X and Y deflection data that are processed by the Digital-to-Analog Converter (DAC) and the Single-to-Differential converters. The X' and Y' output voltages that are fed into the Galvanometer result in an angular deflection of its X axis and Y axis mirrors respectively.

The Pulse-Width Modulator (PWM) generator sets the intensity of the laser beam from the Laser Source.

The laser beam goes through a Beam Expander, making it larger and reducing its divergence, and is then deflected by the galvanometer and intersects the pavement.
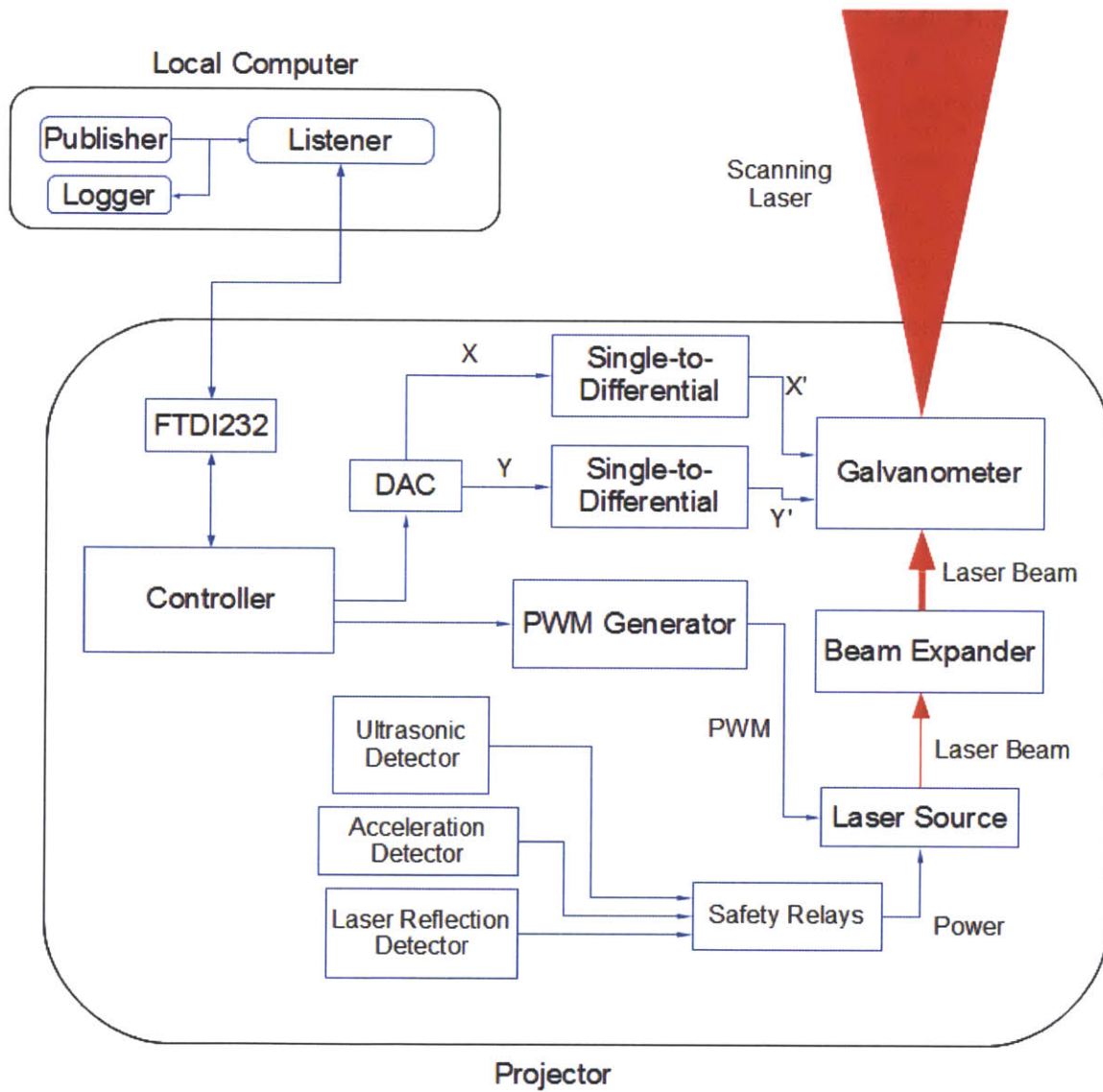
Figure 3-1: Top Level Component Layout

The Safety Relays are a power interruptor for the Laser Source, if the Ultrasonic detector, Acceleration Detector, or the Laser Reflection Detector peceive an emergency situation.

3.2   LCM

The Lightweight Communications and Marshalling (LCM) protocol is used to send and handle messages over the network between different processes. A publisher process generates the desired locations for the projected laser, and the listener process converts the LCM packets into appropriate commands for the FTDI chip.

The LCM also integrates well with a GUI that allows the user to place flare points corresponding to locations that a rear-view camera is displaying.

The Listener program was written in Python and executed in Ubuntu Linux. First it locates the port with the FTDI attached. It then sends a test command to make sure the Controller is active and functional, then defaults into a 'standby' state. The packages the Listener recieves is an array, with each point corresponding to a flare angular position, laser intensity, and time duration. The Listener then sends the commands to the Controller to recieve position, intensity and duration data as sequences of bytes.

3.3   Data Protocol

Commands are sent over the serial port in byte packages. The serial port is a virtual port over a USB connection; and is set at 9600 BAUD, 1 stop-bit, 0 parity bits, most significant bit first (Figure 3-2).

To load in N number of coordinates in an internal array, the computer would send a command to load data, then the target array, then the data array, split into upper and lower bytes (Figure 3-3).

The controller would return a sequence of acknowledgement bytes to the computer, keeping everything in sync (Figure 3-4).

```
7 6 5 4 3 2 1 0
┌─────────────────┐
│     Verify      │
├─────────────────┤
│    Command      │
├─────────────────┤
│     DATA        │
└─────────────────┘
        ⋮
┌─────────────────┐
│     DATA        │
└─────────────────┘
```
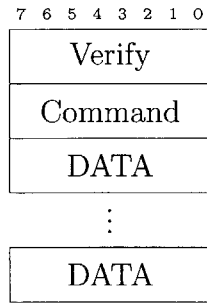
Figure 3-2: Example of a command to the Controller

```
7 6 5 4 3 2 1 0
┌─────────────────┐
│     Verify      │
├─────────────────┤
│   Load Data     │
├─────────────────┤
│     Array       │
├─────────────────┤
│                 │
│    Word 0       │
│                 │
├─────────────────┤
│                 │
│    Word 1       │
│                 │
└─────────────────┘
        ⋮
┌─────────────────┐
│                 │
│    Word N       │
│                 │
└─────────────────┘
```
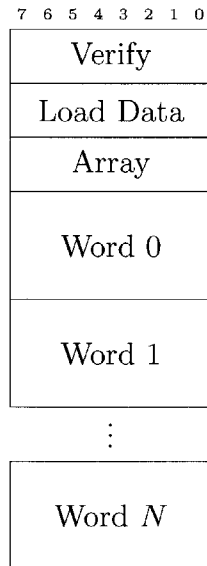
Figure 3-3: Example of loading a word array of size N to the controller

```
7  6  5  4  3  2  1  0
┌──────────────────────┐
│        Verify        │
├──────────────────────┤
│       Command        │
├──────────────────────┤
│       Address        │
├──────────────────────┤
│         'U'          │
├──────────────────────┤
│         'L'          │
├──────────────────────┤
│         'U'          │
├──────────────────────┤
│         'L'          │
└──────────────────────┘
            ⋮
┌──────────────────────┐
│         'U'          │
├──────────────────────┤
│         'L'          │
├──────────────────────┤
│         End          │
└──────────────────────┘
```
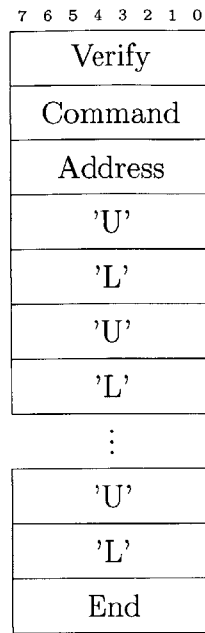
Figure 3-4: Acknowledgement sequence returned to the Computer

The validation byte is always the first byte in the message. It guards the controller against random serial noise and buffer overflows. The controller currently uses a message-based handshaking protocol. For every byte that is sent from the computer to the controller, the controller board must reply with a byte message before the computer can send another byte. This allows the computer to check the alignment of input data, as well as remove the potential for buffer overflows.

If the reset command is sent, the controller sends an acknowledgement message, and then activates the internal watchdog timer to reset the internal laser variables.

3.3.1 FTDI232

The Massachusetts State Police and the Cambridge Police Department use Windows XP as the operating system on their local computers, so compatibility and driver footprint were a concern. Communication between the controller board and the computer is handled over a USB port in low-speed mode.

The communucations co-processor is an FTDI232RL chip set to emulate a virtual serial port. The chip can be interfaced with a small [1.3MB] driver provided from

the manufacturer. The communication board is powered by the host computer. The schematic is located in Appendix A, Figure A-8. The CTS pin is set low, so that messages from the computer are not held in a buffer and are immediately delivered to the controller.

3.4 Controller
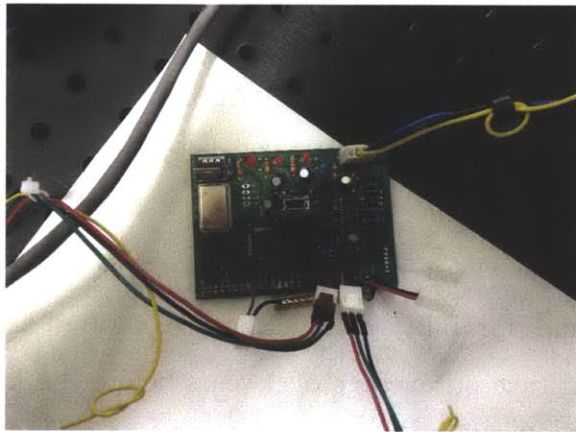
Figure 3-5: Controller Board

The controller board takes in serial input for driving the galvanometer position and laser power. It is the heart of controlling where, when, and how powerful the laser projection is. The microcontroller handles the state of the laser system, galvanometer positions, timing and intensity.

The controller board is an ATMEGA324P microcontroller. The AVR-8 chipset was chosen due to its extensive support, low development costs, and flexibility. The microcontroller code was written in C using AtmelStudio 6, and uploaded via the SPI port using the AVRISP mk.II programming peripheral. Firmwarre code was compiled in debug mode with AVR-GCC with target chip as ATMEGA324PA. JTAG interface and debugging was not used due to the need for Port C for controlling peripheral chips.

The ATMEGA324P communicates to peripheral chips using the SPI interface on Port B and enable lines on Ports A and C.

The microcontroller is clocked at 20MHz, which is generated by an external crystal for stability.

3.4.1 State and Memory

The internal state of the microcontroller is stored in RAM. In the event of a power-interrupt or reset, the system would reset to a safe bootloaded state.

The default state is STANDBY, in which the galvanometers are idle and the laser is disabled. Different states include projecting a single point (SINGLE_SHOT) and projecting multiple points (SEQ_POINTS). Appropriate commands from the serial port set the running state of the controller. Code for SEQ_POINTS execution can be found in Section F.4 on page 106.

Galvanometer position, laser intensity and duration data is stored in EEPROM due to its longevity and durability. The EEPROM is rated at 100,000 writes; at 30 rewrites/day, it would take on average of 9 years before the EEPROM would suffer from write failures. The longevity is far superior than higher-density FLASH [10,000 writes before failure], and can store data in the event of a power failure [unlike SRAM]. The EEPROM in the present microcontroller can store up to 1024 bytes or 512 words of data. Current utilization of EEPROM is 90%.

3.4.2 Digital to Analog Converter (DAC)

Due the high precision required for the galvanometer voltage input there must be a high-precision voltage source. The DAC8554 was chosen as the DAC due to its low integrated noise level, high precision (16-bits), and multiple independent buffered outputs. The DAC has an output voltage range of 0V-5V. The DAC supports power down mode and simultaneous updates using internal registers. The chip communicates to the controller over the SPI port.

3.4.3 Single-to-Differential converter

The DAC has insufficient voltage range [0V-5V] to drive the input of the galvanometer [$\pm 10V$]. The project uses two single-ended to differential converters to expand the voltage output ranges of the X and Y signals so that the full range of the galvanometer can be utilized. The output voltage $V_{out} = -4V_{in} + 2 \times 5V$. An LM336-5V shunt diode is used as a precision 5V reference source. High precision [.1%] resistors are used to improve linearity. LT1679 Operational Amplifiers were used for their high gain-bandwidth product [100MHz], and low noise pickup from the power lines.

3.5 Galvanometer
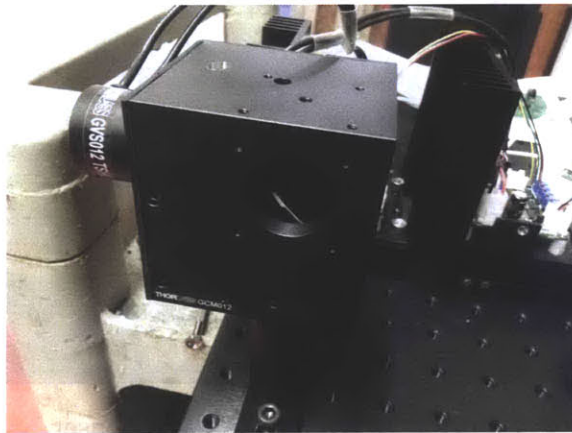
Figure 3-6: Galvanometer System

The galvanometer selected for the project is a Thorlabs GSV012. The galvanometer uses voltage-controlled mirrors that can deflect the laser beam in the X and Y axes independently. The mirrors are able to reflect an input beam of up to 10mm in diameter.

The galvanometers are supplied with motor drivers that map a voltage input to an angular deflection. The controllers are PID compensated at a 300Hz bandwidth for large signals, and at 1KHz for small signals. The galvanometer is also very reliable, repeating the same voltage in will result in a drift less than 15μrad. For maximum range, the galvanometers are set in the $2\frac{\text{degree}}{V}$ configuration, therefore a 1V input

results in a 2° angular deflection.

The galvanometer drivers have numerous test points including angular deflection, angular speed, angular error, drive current and stall detection.

3.5.1 PWM Generator

A PCA9685 chip is used as the PWM driver interface between the controller and the laser source. The chip can drive 16 independent PWM channels at 12-bit accuracy. In the current configuration, an Arduino Uno is used to initialize and communicate with the chip using a third-party library. The output PWM is then controlled by a designated laser operator.
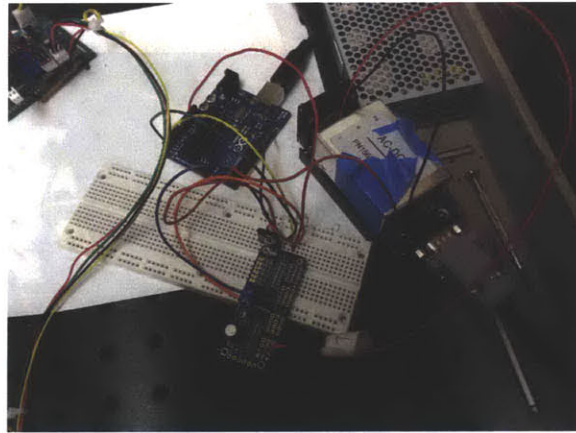
Figure 3-7: Driver for PWM Laser

The PWM generator is also connected to the Laser Source logic supply by a diode (1N418). This ensures that whenever the laser source is enabled, the PWM Generator is also active as well. The output power of the laser is thereby controlled.

3.6 Laser Source

The Pulse-Width Modulated (PWM) laser (Figure 3-9) uses a injection layer diode (ILD) with a coupled linear power supply. This off-the-shelf device comes with an AC-DC power converter with integrated cooling heatsinks and fans. The device was
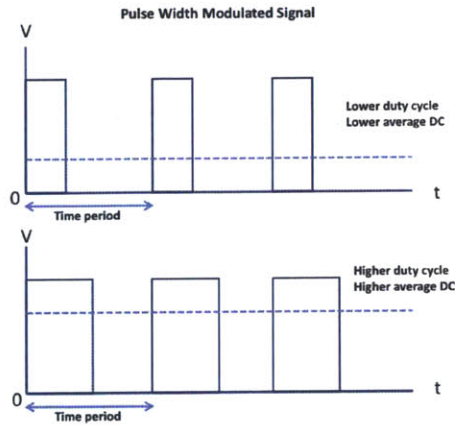
Figure 3-8: Pulse Width Modulation and Average Power; source: embedded-labs.com

measured to have a low beam divergence, simple start-up operation, and low unit cost.

However, the device is difficult to align the laser output with the main optical path, has no easily available test points for measurment, lacks appropriate interlocks, and has a low modulating frequency.
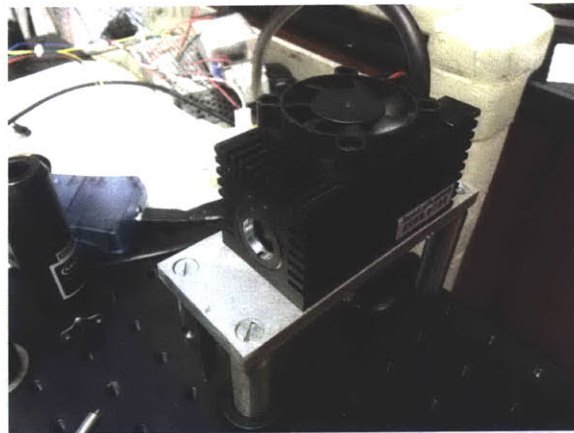
Figure 3-9: PWM Laser

The laser supply takes in a TTL PWM signal up to 2KHz as the control for the power source (Figure 3-7). The laser rapidly turns on and off at 1W intensity to create an average power profile (Figure 3-8). It takes the diode laser 16.8μseconds for the laser to reach full intensity.

The PWM frequency can be increased to 60KHz-100KHz to induce the laser to enter an analog regime. The output power is then continuous and exponentially
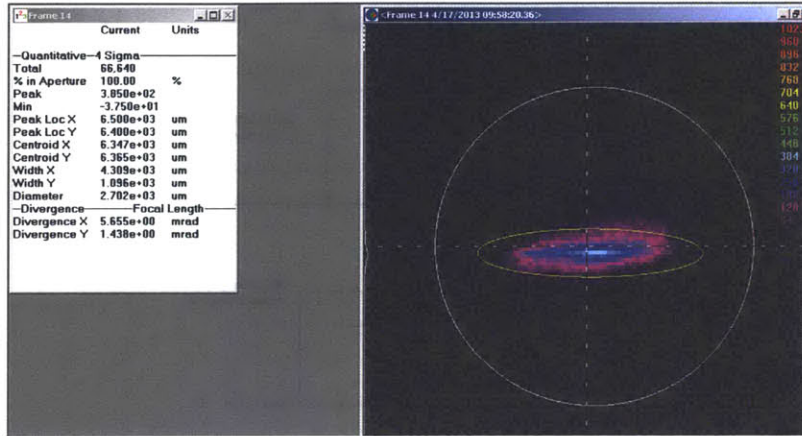
Figure 3-10: Optical Properties of PWM Laser

dependent on the PWM duty cycle, see Graph A-3.

3.7 Optical Assembly

The current optical assembly is to correct for the foreshortening effect by expanding the laser beam in the Y-Axis. The optical assembly is constructed on an 1/4"-20 optical breadboard, mounted on 1/2" optical posts. The lenses and galvanometer are aligned using a 30mm cage-rail system, which allows lateral adjustment for focusing the laser beam.
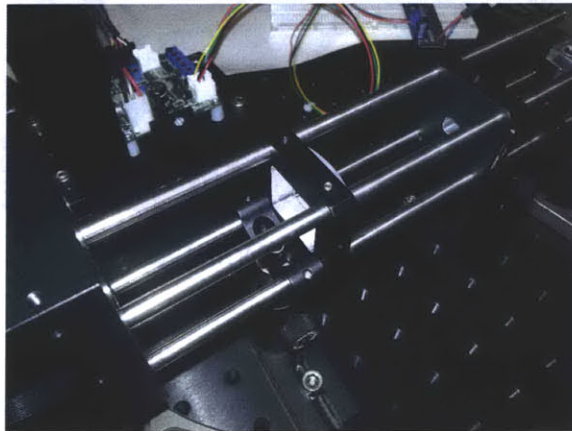
Figure 3-11: Cylindrical Lenses in Galilean Beam Expander

The foreshortening effect causes the vertical component of the laser to spread out over a large area (Appendix E). Using cylindrical lenses we can reduce the divergence

along the Y axis. With appropriate focusing, the beam waist is now focused up to 50m. Since the divergence is the critical component of the foreshortening effect, reducing it by a factor of 10 reduces the effective spot size by 10 as well.
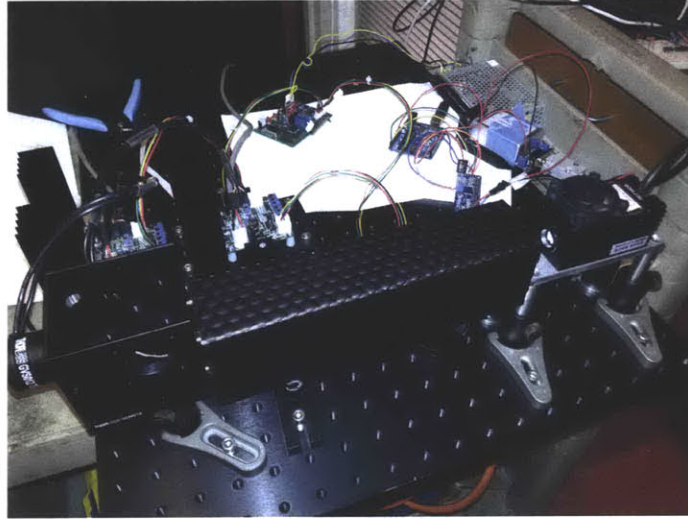
Figure 3-12: Complete Setup

The galvanometer and lens assembly are aligned and held in place using the 30mm cage system. A folded sheet of anodized aluminum is used to optically block stray laser beam refactions from leaving the optical path.

3.8 Safety Circuit

The proposed safety circuit is to enforce safe operation of the laser, and to disable the laser power if unsafe conditions occur. The user should be able the reset the safeties iff the failure conditions are cleared. The safety circuit is intended to interrupt power to the laser diode itself, which is quicker than using a mechanical shutter.

3.8.1 Acceleration Detector

In the current iteration, an accelerometer can used to detect sudden shifts in movement of the vehicle. Such instances include when the vehicle is struck, or when the police cruiser is accelerating into motion. Since this causes the laser beam to move

39

toward an unknown location, the laser beam should be turned off instead of risking the beam entering restricted areas. The accelerometer chosen is a 3-axis, analog output, with $\pm 3g$ range. An arduino microcontroller detects when acceleration along an axis exceeds $|1g|$, and triggers an output pin to alert the emergency condition (Figure A-9).

3.8.2 Ultrasonic Detectors
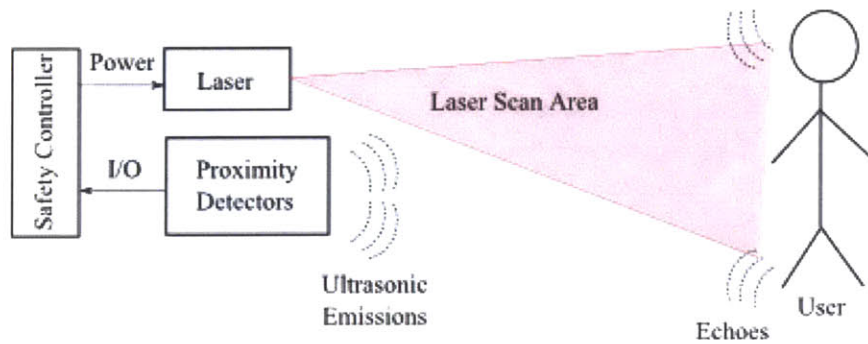
Figure 3-13: Ultrasonic Detector Layout

The goal of the ultrasonic detectors is to detect whenever the police officer and/or oncoming vehicles enter the laser scan area.

The RangeMax ultrasonic detectors return an analog voltage corresponding to the distance to the nearest solid object inside the field of view. The emergency condition occurs if the distance measured is below an acceptable minimum. The ultrasonic detectors use a narrow beam path, and can detect human-sized objects up to 15 meters away. The ultrasonic detectors currently suffer from a slow refresh rate [10 Hz], and must be triggered individually, lest they interfere with each other. The ultrasonic detectors have an overall refresh rate of 5Hz, and are susceptible to interference. An Arduino microcontroller is used to enable and measure the distances to obstructions, and triggers an output pin to alert the emergency condition (Figure A-12).

40
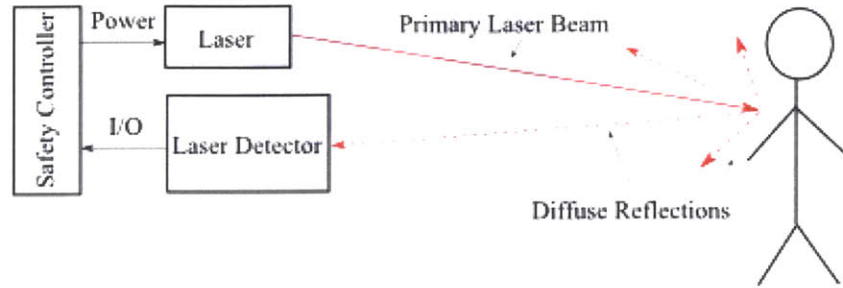
Figure 3-14: Light Magnitude Detector Layout

3.8.3 Laser Reflection Detector

The Laser Reflection Detector returns an emergency signal if the laser beam is reflected back into the projector. The worst case is the laser beam is reflected back due to a person or vehicle entering the primary beam path. The detector is composed of a sensitive photodiode [PDB-C154M] protected with a narrow bandwidth light filter [$\lambda = 650$nm]. The photodiode current is converted into a voltage output with a AD818 Amplifier in a transconductance configuration. An MAX232 chip is used as a charge-pump voltage source to generate the +12V and -12V used in the magnitude detector (Figure A-11). The -12V source is used to bias the photodiode to reduce its small-signal capacitance, thereby increasing signal speed. The output of the Light detector is a voltage signal that is linearlly dependent on the intensity of the incoming light with $\lambda = 650$nm (Equation A.1). The circuit has a small signal bandwidth of 10KHz.

The output of the light magnitude detector can be connected to a comparator or microcontroller with an ADC to trigger the failure condition when the reflected light intensity is above acceptable levels.

3.8.4 Key Switch

For Class 3B and 4 lasers, an key switch is required to prevent the laser from activating unless the switch is activated (ANSI Z136.1-2000). The switches used in this project are normal-open key-switches and are soldered into the mains power of the laser source.

Figure 3-15: Key switch

3.8.5   Relay Driver

The relay driver converts the logical state of the emergency conditions and the user reset path and activates the relay coils when appropriate. The Relay Driver can handle up to 4 different emergency conditions. For each detector, the emergency output is high when there is nothing wrong, and goes low when the corresponding emergency trigger is activated. i.e. The Ultrasonic emitter goes output goes low when there is an obstruction close by, or the Laser Reflection Detector output goes low when there is a high reflection of laser light.

Each logic cell uses a S/R latch to latch whenever the emergency trigger is activated. Combinational logic prevents the reset signal from clearing the latch until the emergency trigger is resolved. The latch output is buffered by an L298 current buffer that powers the corresponding relay coil. Each logic cell is independent from each other. The last input is the start input, which only activates the relay controlling the laser power if power is applied to it. All relay switches must be closed in order for the laser module to receive power.

Currently, the Relay Driver is not integrated with the projector due to difficulty in determining efficacy in the detector circuits.

The relays chosen are SCHRACK, 24V, 6A, DPDT safety relays. They are DIN-rail mountable, a standard in safety circuit integration.

42

3.9 Safety Observations

As high power lasers are involved, it is required to have appropriate safeguards in place to prevent accidents and injuries. In order to reach compliance with ANSI, FDA, FAA and OSHA requirements, all laser operators have received laser operation training with the MIT Environmental Health and Safety Office (EHS). Output power of all lasers used was set at or below Class 3B requirements. Appropriate eye protection (OD4) was used by all nearby personnel when the laser was in Class 3B operation. Laser power was measured with a Thorlabs PM100D integrating optical power detector. The location and relative intensity of the laser was determined using CCD digital cameras. Alignment of laser optics was conducted while laser power was at Class 2 or Class 3R.

When testing indoors, and scanning different positions, the laser power was kept at Class 3R. A laser safety room was designated on campus, and room warning symbols, door interlock, and outlet controller were installed. The lasers was kept inside the laser safety room for Class 3B intensity testing. During Class 3B operation, the galvanometer scanning feature was disabled and a matte aluminum backplate was deployed as a backstop.

Outdoor projection tests with the laser at class 3B were conducted at the BAE laser range in Merrimack, NH. The outdoor scanning test was supervised by Dan Creeden, the range laser safety officer. A covered 2.5m high fence was used as a backstop. The test pavement was clear of debris.

3.9.1 Hazard Zones

We used the ANSI Z136.1-2000 and Z136.6-2000 for determining the range of safe operating distances and hazard zones for the laser (Appendix E).

The Nominal Ocular Hazard Zone (NOHZ) is the distance in which the radiance can cause damage to the eye. Using Equations E.3.4, E.3.4, and E.6, and characteristics of the laser (Figure 3-10) we can the MPE. Select intensities and the ranges are given below (Table 3.1).

Sensitive and critical visual interference zones are calculated in the same manner as the NOHZ, but using the interference thresholds divided by the optical efficiency given the wavelength. Since the eye is not as sensitive to 655nm light we find that the sensitive visual interference range is comparable to the NOHZ range.

The critical interference distance is the minimum distance that traffic should be from the projector laser source if they interset the primary beam. This is quite telling, as oncoming traffic is only safe when intersecting a 5mW beam up at 35m or further. Running the laser at a more intense 100mW means that the safes distance a vehicle can intersect the beam is over 300m away!

The laser free range of the beam is the distance at which the laser does not interfere with vision at all. It is also the distance the projector must be from the Airport's laser-free are if the projected beam enters airspace.

Interestingly, increasing the laser power to a higher intensity [x20] and pulsed signal dramatically increased the interference distances by 940%, rather than the 450% [$\sqrt{20}$] as expected from the NOHZ equation. This is due to the multiple pulse response of the eye reducing the MPE in the PWM case.

Region of Visual Inter-ference	Laser Source		
	5mW Continuous	100mW, 1.6KHz PWM 10% Duty	1W Continuous
NOHZ	5.4 m	53m	79m
Sensitive Interference	8 m	73 m	108 m
Critical Interference	35 m	324 m	484 m
Laser-Free Interfer-ence	342 m	3.24 Km	4.84 Km

Table 3.1: Hazard Distances for the PWM primary laser beam

The reflections of the laser beam off of asphalt do not pose a threat to the operator or motorists outside of 1 m from the road surface. The visual interference distances of the diffuse reflection are much smaller than the NOHZ of the primary beam thus the main threat is the primary laser beam path. The diffuse reflections are also at laser-free intensities at short distances (Table 3.2).

44

	Laser Source		
Region of Visual Interference	5mW Continuous	100mW, 1.6KHz PWM 10% Duty	1W Continuous
NOHZ	2.5 mm	2.5 cm	3.5 cm
Sensitive Interference	1.5 cm	12 cm	18 cm
Critical Interference	6 cm	53 cm	80 cm
Laser-Free Interference	56 cm	5.34 m	8 m

Table 3.2: Hazard Distances for the PWM diffuse reflection

Chapter 4

Tests and Results

4.1 Optics

The reverse foreshortening effect causes the projected laser spot to appear small to oncoming traffic, increasing its visual intensity once again. Careful alignment of the cylindrial lenses can set the focal point between 1m to 30m away. Additional tests with the PWM laser show that the reverse foreshortening effect creating a small optical point (Figure 4-4). Even when running at 5mW, the laser is visible under indoor-lighting conditions.

From the projector's perspective, the diffuse reflection is dim. Therefore calibration of the laser scanner is more difficult if the road surface exhibits specular reflection. The laser scanner also demonstrates reduced visibility when under bright light sources.

4.2 Electronics

4.2.1 Power Consumption

The system is currently powered by a standard 110VAC outlet. Data was collected using an inline power meter. As Table 4.1 shows, the system uses less than 350W of power at peak usage, and can thus be powered by attaching the system to the

Figure 4-1: Laser Projection, with Observer 30m away

cruiser's 12V alternator power supply.

4.3 Laser Projection

4.3.1 Calibration

Since the laser system does not collect visual data, calibration of the projector is necessary to derive the transform between desired projection points, and actual points driven. The Alert aspect of the NIJ project provides the user with rear-mounted cameras. The cameras provide a convenient and consistent medium for indicating

Figure 4-2: Foreshortened PWM Laser spot on Asphalt Sample

Device	Idle Power	Average Power	Peak Power
Galvanometer	100W	180W	250W
Laser	4W	10W	50W
Controller	1W	2W	3W
Safety Board	1W	2W	2W
Total	106W	193W	305W

Table 4.1: Power Consumption of Device Elements

where the laser projection points should be.

The calibration scheme used in this project requires that the camera and galvanometer output be located close together, and pointing in parallel. The user has an input screen for pointing out 4 calibration points (Figure 4-5). The listener converts the coordinates into binary data and instructs the controller to project a pattern (Figure 4-6). The user then marks out where the projection points actually are, and then the computer calculates the transform between camera data and galvanometer data (Figure 4-7). Finally the user can mark the pattern they desire onto the pavement (Figure 4-8), and the projector displays it as soon as they are done (Figure 4-9).

For commercial usage, the calibration needs only happen once when the device is built, as the distance/angle/placement between the camera and galvanomter will be

Figure 4-3: View of Laser Spot from Projector

fixed. The calibration scheme helps compensate for galvanometer bias, static vehicle tilt, and pavement grade.

4.3.2 End to end testing

The project has completed end-to-end testing. The user can define the calibration points, and then send in a sequence of desired points. The listener breaks the sequence into appropriate commands for the controller. The controller enters the scanning state and repeatedly displays an arbitrary set of flare points. A virtual flare line can be created quickly, such as the one displayed in Figure 4-11

Power is modulated by the PWM generator under control of the laser operator. The visible spots between the designated flare points were kept in to illustrate the dynamic motion of the galvanometers while they are moving. The laser spots generated are repeatable to 0.04 mrad.

The controller, once set, does not need additional commands from the host computer, as demonstrated when the host computer crashed repeatedly, and the projector continued to operate as normal.

Figure 4-4: View of Laser Spot 15m away
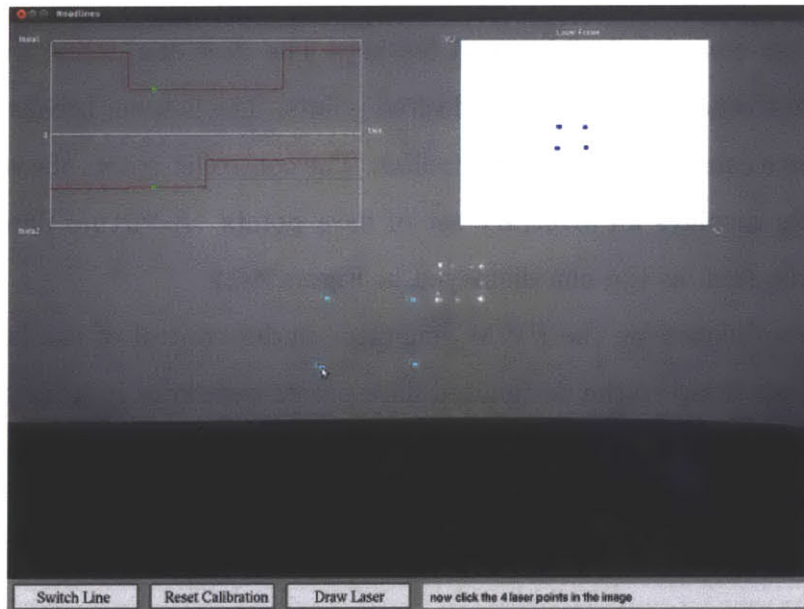
Figure 4-5: Defining Calibration Points
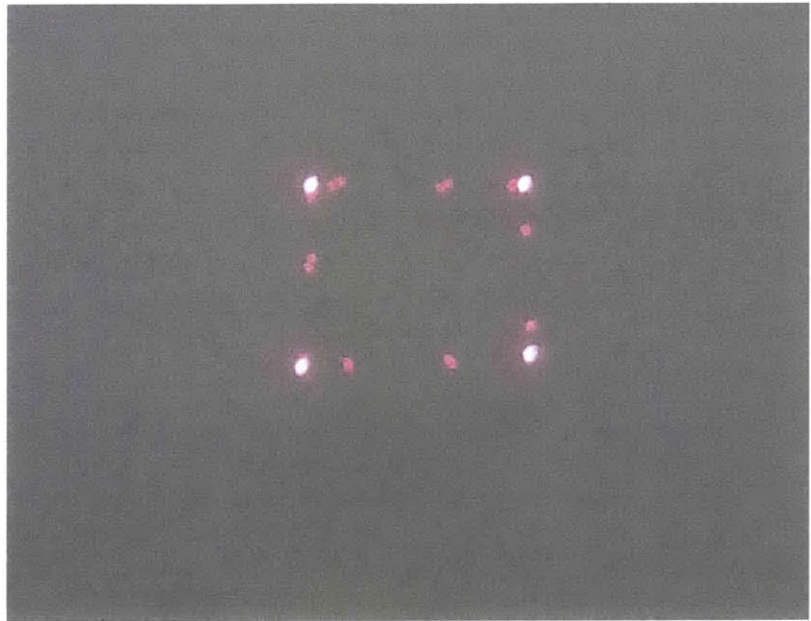
Figure 4-6: Calibration Rectangle
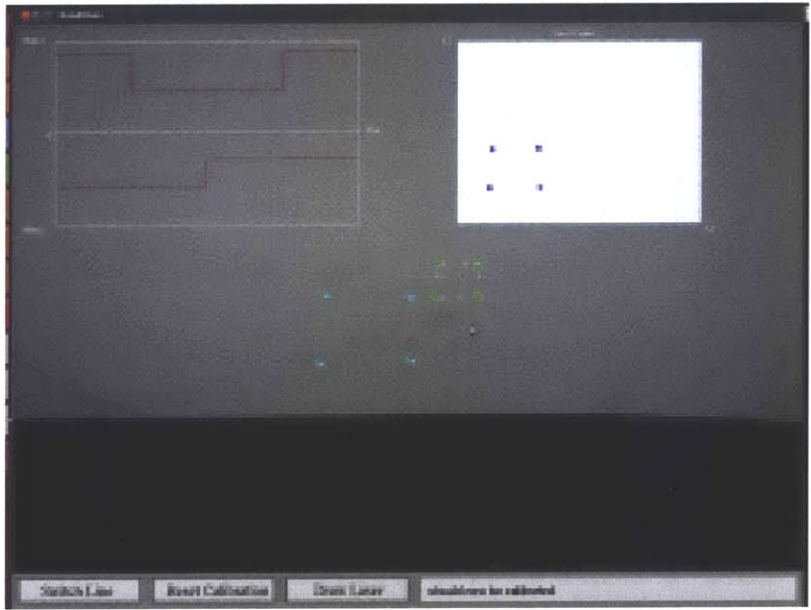
Figure 4-7: Mapping input and output points

Figure 4-8: Selecting Flare Positions
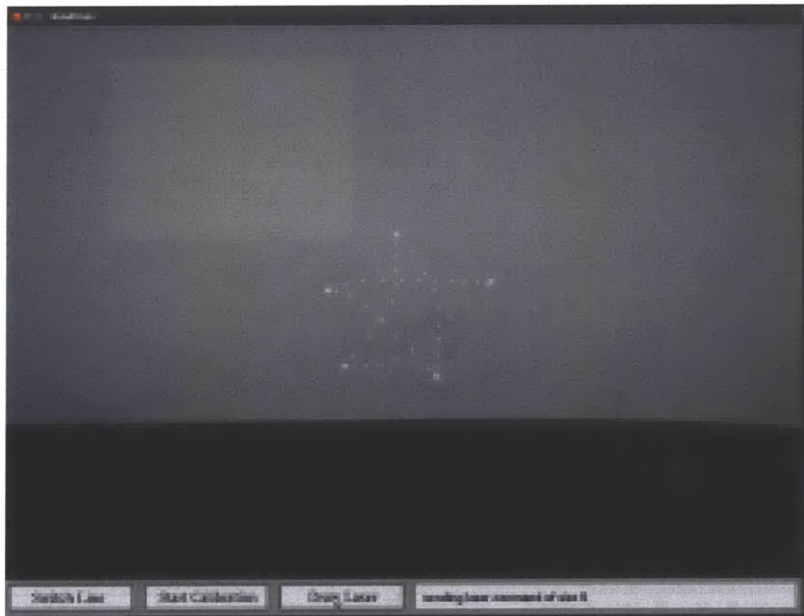
Figure 4-9: Generation of Flares
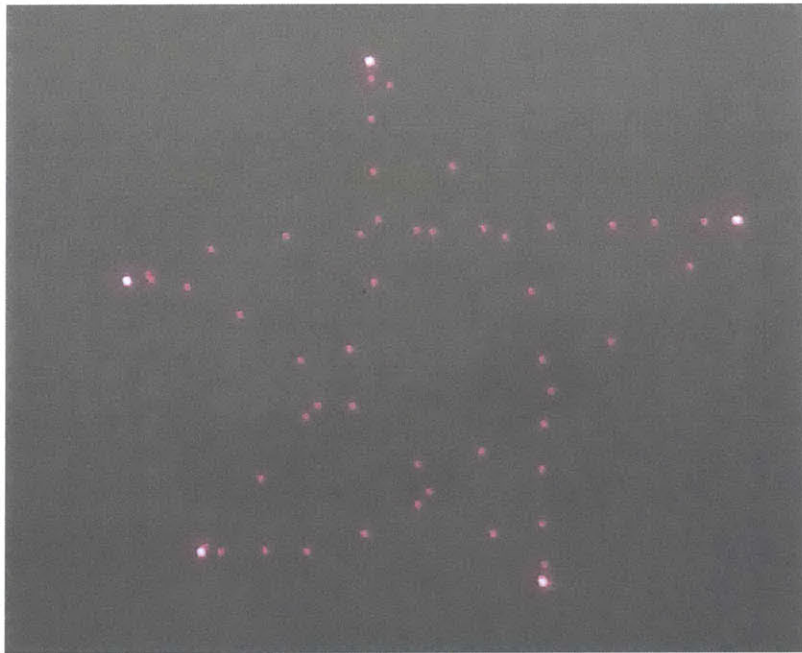
Figure 4-10: Star (5 Points)
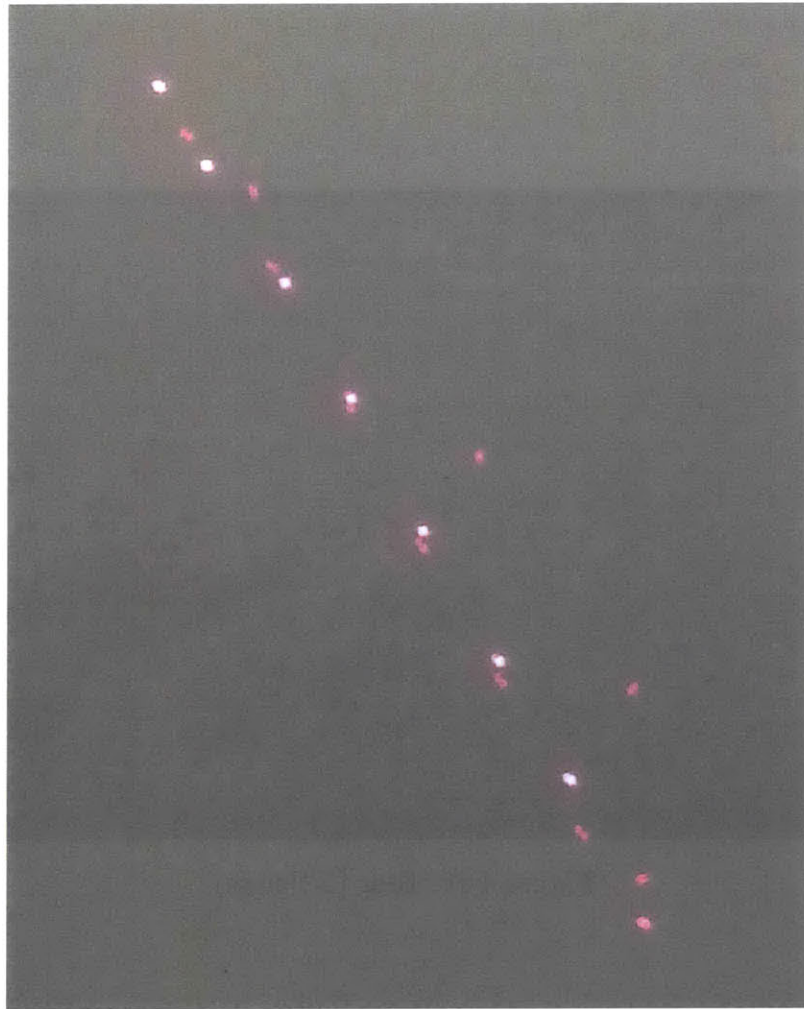
Figure 4-11: Series of Flares (8 Points)

Chapter 5

Future Developments

As this project examines the feasiblity of using lasers to create visual cues, many topics arose that can be explored further to improve the system's efficacy.

5.1 Optics

5.1.1 Multiple Laser Sources Integration

A red laser beam was chosen due to its visual similarity to a flare, as well as its correlation with warning signs. However the human eye is much more sensitive to green laser light [American National Standards Institution, 2000a]. Combining lasers allows for experimenting with differing intensities to determine correlation between familiarity of intent, and visibility.

Figure 5-1 from Adrian and Jobanputra [2005] shows that on asphalt, the total reflectance of Green [532nm] light is 5x better than Red [652nm], increasing visual awareness for the same amount of luminous power. The current PWM implementation can support the modulation of power for additional laser sources. Another EEPROM lookup table must be created in the controller for each laser source, as well as accounting for the different laser intensities when plotting out the projection.

The implementation proposed in Chapter 3 can support the addition of another laser beam. The two beams can be combined using a cage-mounted dichoric beam

A Comparison of Total Reflectance between Asphalt and Concrete
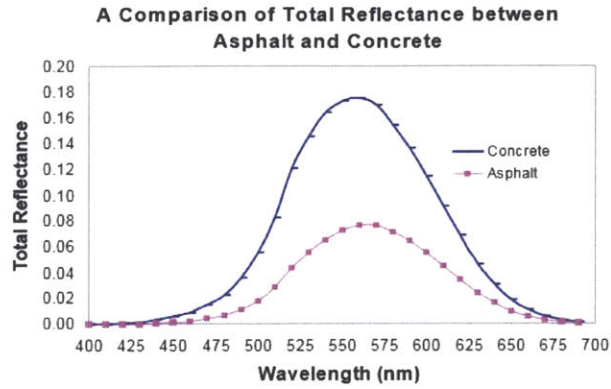
Figure 5-1: Comparison of Total Reflectance of Roadside surfaces

splitter. The dichoric mirror permits the red laser beam to transmit through, while reflecting the green laser beam. Proper alignment will result in a combined beam that appears to be yellow. The lenses in figure 5-2 are configured as galilean beam expanders; increasing the size of the beam and decreasing divergence.
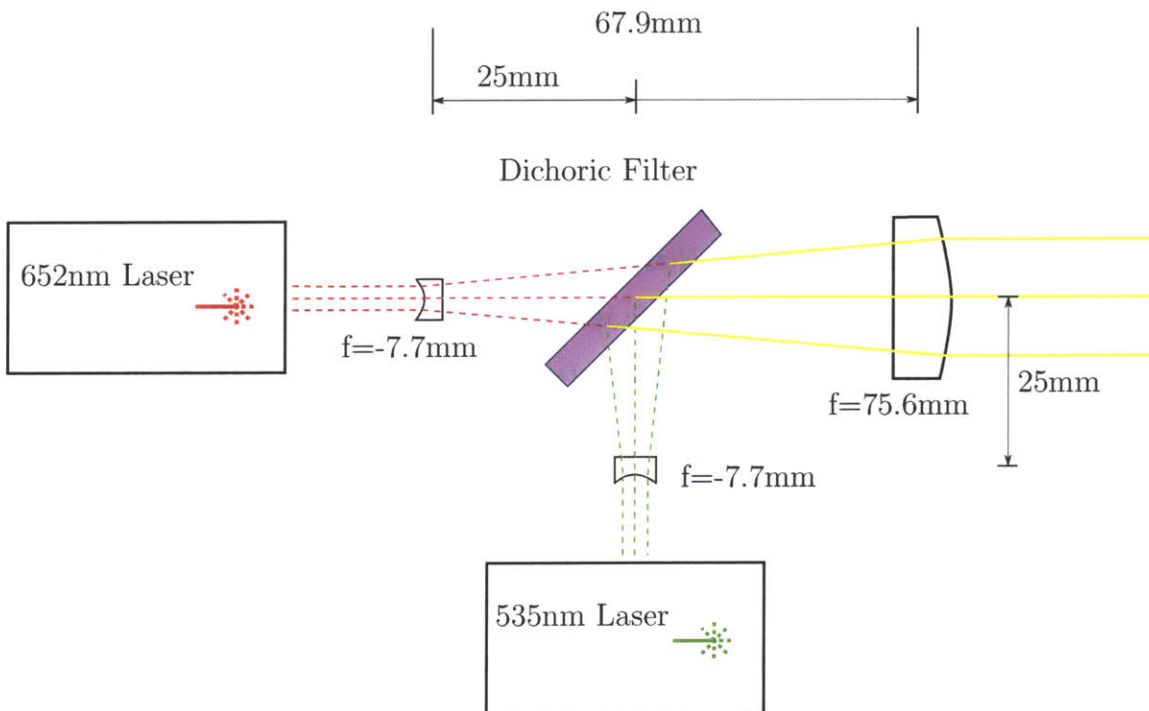
Figure 5-2: Beam Mixer with Beam Expander

5.1.2 Optical Alignment

The current optical path does not account for the slight tilt to the x-axis mirror in the galvanometer. The resultant tilt affects the vertical foreshortening effect, increasing the projected spot size and lowering illuminance.

The optics are mounted and aligned using the Thorlabs 30mm cage system. Development of an axially-rotated system can be used to counteract the rotational distortion caused by the galvanometer.

5.1.3 Wide Angle Projection Accuracy

Fig. C.1 Field Distortion in a Two-way Mirror Deflection System
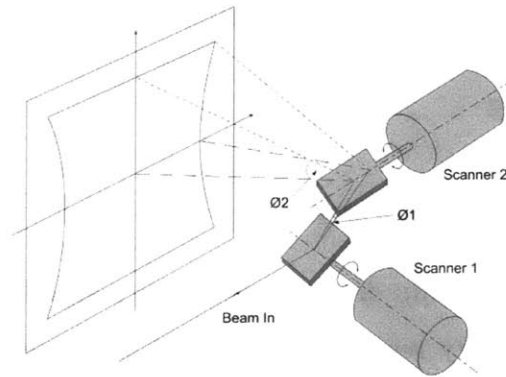
Figure 5-3: Large Angle Distortion of Galvanometer Projection

In the current implementation that the galvanometer projection axes were orthogonal, which is accurate for small angle deviations. However, for large angles, the optical path of the galvanometer becomes apparent (Figure 5-3). Therefore at large angles, the error between input and actual projection increases, and is highest at the edges. Fortunately the error is less than 1 degree.
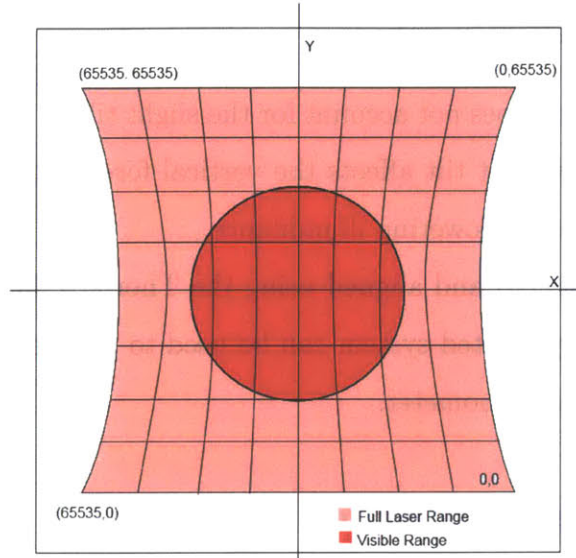
Figure 5-4: Large Angle Distortion of Projection

5.2 Electronics

5.2.1 DC Power conversion

The current laser projector setup draws power from a standard 110VAC outlet and has demonstrated satisfactory results with a 2KW portable gasoline generator. In order for the electronics to work efficiently with a vehicle it must be able to draw power from the vehicle's 12V power supply generated from the alternator. Current police cruisers use the 12V line for powering the light bar, sound system and radar detectors. The critical factor for the DC-DC converters is temperature tolerance, as the projector unit will be under a wide variety of weather conditions.

5.2.2 Inertial Feedback

The proposed device currently assumes that the vehicle is fixed to the road surface. The calibration scheme currently corrects for static misalignment of the vehicle with respect to the road surface. However, the vehicle is a 2nd-order damped system, as any motion of weight on/in the vehicle will cause oscillations in pitch and yaw. An Inertial Measuring Unit (IMU) with a compass can be used to determine the vehicles current pitch and yaw and its effect on the projection.

58

5.2.3 Improved Galvanometer Feedback

As discussed in Chapter 2, we assumed the axes in the projection are orthogonal and independent. However, at high angles the orthogonality condition no longer holds due to the large deflection angles present. Improved characterization of the laser projection at large distances can be used for a more robust calibration scheme.

Also assumed is the time needed for the galvanometer to reach the target flare position. High-speed ADCs can be used to check when the galvanometer has reached an appropriate location and enable then laser when it does so.

Chapter 6

Conclusion

A police officer conducting a roadside stop works very close to passing traffic. Sometimes, an oncoming vehicle fails to grant enough clearance, risking a collision. In the past decade, on average, one police officer per month has been killed by an inattentive driver. There exists a failure of sufficiently warning drivers about the police cruiser's spatial location and the means of travelling around it. The project initiative is to reduce the rate of fatilities caused by roadside collisions.

Currently, vehicle-mounted emergency lights indicate the presence of the police cruiser, but impair night vision and distract drivers. A product to expand the optical range around the police cruiser would decrease the rate of collisions. Current solutions for diverting traffic by luminous markers are bulky, dangerous, expensive, and/or time-consuming to deploy.

This thesis detailed the design and implementation of a laser projector for use in diverting traffic. The projector uses a galvanometer-steered high-power laser to illuminate spots on the pavement, simulating the appearance of road flares. The user can calibrate the projector with a rear-mounted camera, and marks the position on where the flares should be located.

The computer interface used is geared towards fast and intuitive use, and the laser projector continuously displays flare lines without need of constant input. The projector uses accurate steering the generate consistent patterns at 30m away.

Topics concerning improving the efficiency and safety of the laser projector were

explored. A galilean beam expander is used in the optical path to reduce the fore-shortening effect and improve laser visibility. The safety circuit tested could shut off the laser power if unsafe operating conditions exist. A reactive safety system to prevent people from entering the primary laser beam shows great promise and may be necessary for implementing the projector for commercial production.

The laser-based diverting projector can be used in various road-marking applications, such as road crews and tow-trucks. The further vehicles are diverted away from the cruiser, the safer everyone is.

Appendix A

Schematics and Board Layouts

Schematics were generated in CadSoft EAGLE(C) Schematic Editor. Corresponding Board layouts were generated in CadSoft EAGLE(C) Board Layout Editor. Boards were fabricated on a 1 oz. / side, 2 layer, silk-screened manufacturing house.

A.1   Galvanometer Controller

The Galvanometer Controller, or Controller, takes in serial commands from the computer and acts on them (Figures A-1and A-2). The Controller can output 4 different analog channels. Channels A and B are differential and range from -10V to +10V. Channels C and D are single-ended and can output voltages from 0V-5V.

A.2   PWM Driver

A.3   Safety Relay Driver

The Safety Relay Driver circuit takes in TTL inputs regarding the safety conditions of different parts of the device. The safety interrupt also takes in a RESET signal driven from the switch board. If conditions are unsafe, the SRD will open the power connection to the laser driver, thus unpowering the laser source.

In Figure A-7, Channel 1 [Yellow] is the emergency state input, Channel 2 [Blue] is

the Reset signal, Channel 3 [Purple] is the Relay output. When the emergency input goes LOW, the output goes LOW. When the emergency state goes HIGH again, the output remains low until the reset signal is triggered HIGH. Notice at T=30ms, the output does not go HIGH when the RESET is HIGH and the emergency state is LOW.

A.4   Communication Board

The board was purchased from SparkFun Electronics. The chip was preconfigured at 9600 Baud, 1 stop bit, no parity bits, Most Significant Bit first. The CTS pin was pulled low for zero propogation delay.

A.5   Accelerometer

Figure A-9 is the schematic connection for the Acceleration Detector. The detector uses the internal ADC in a microcontroller to evaluate acceleration in the X, Y and Z axis, and triggers an output pin (D10) when an acceleration value exceeds safe margins.

A.6   Laser Reflection Detector

The Laser Reflection Detector (Figure A-11) uses a photodiode with a transconductance amplifier. An bandpass optical filter $f(\lambda)$ is used to act as a delta function, allowing only light corresponding to the laser emission to enter the photodetector. Therefore the voltage output of the Laser Reflection Detector is linearly dependent on the reflection of the laser (Equation A.1). The bypass capacitor C is to limit the high-frequency noise inherent in the photodiode.

Voltage	Current	Voltage Ripple	Component	Function
+15V	6A	1%	Galvanometer	+ Power Supply
-15V	6A	1%	Galvanometer	- Power Supply
+15V	0.5A	1%	Controller	+ Voltage Supply
-15V	0.5A	1%	Controller	- Voltage Supply
+5V	6A	5%	Laser Driver	Power Supply
+24V	1A	5%	Safety	Driver Supply Voltage

Table A.1: Voltage Sources for the Projector

$$V_{out} = i_d \left(R || \frac{1}{Cs} \right)$$

$$i_d = \int F \cdot S(\lambda) I(\lambda) f(\lambda) d\lambda$$

$$f(\lambda) \approx 1 \mid \lambda = 650 \pm 10 \text{nm}, 0 \text{ otherwise}$$

$$i_d \propto F \cdot S(650 \text{nm}) I(\lambda = 650 \text{nm})$$

$$V_{out} \propto F' \cdot I(\lambda = 650 \text{nm}) \cdot \frac{R}{RCs + 1}$$

(A.1)

A.7 Ultrasonic Detector

The Ultrasonic Detector (Figure A-12) uses 2 MB7060 ultrasonic emitters to determine the distance an sound-reflection obstruction is. The output of the emitters are analog voltages, which are then fed into the Arduino's internal ADC. The value can then be compared to an acceptable minimum, and the output (D10) is triggered low if the data returned is below a threshold value. The emitters operate in an alternating manner, so that the sound emissions of one detector does not trigger a false positive in the other.

A.8 Power Conversion

The goal of the power convertors is to transform the 110VAC outlet power into the various voltages needed for the sub circuits (Table A.1).

64
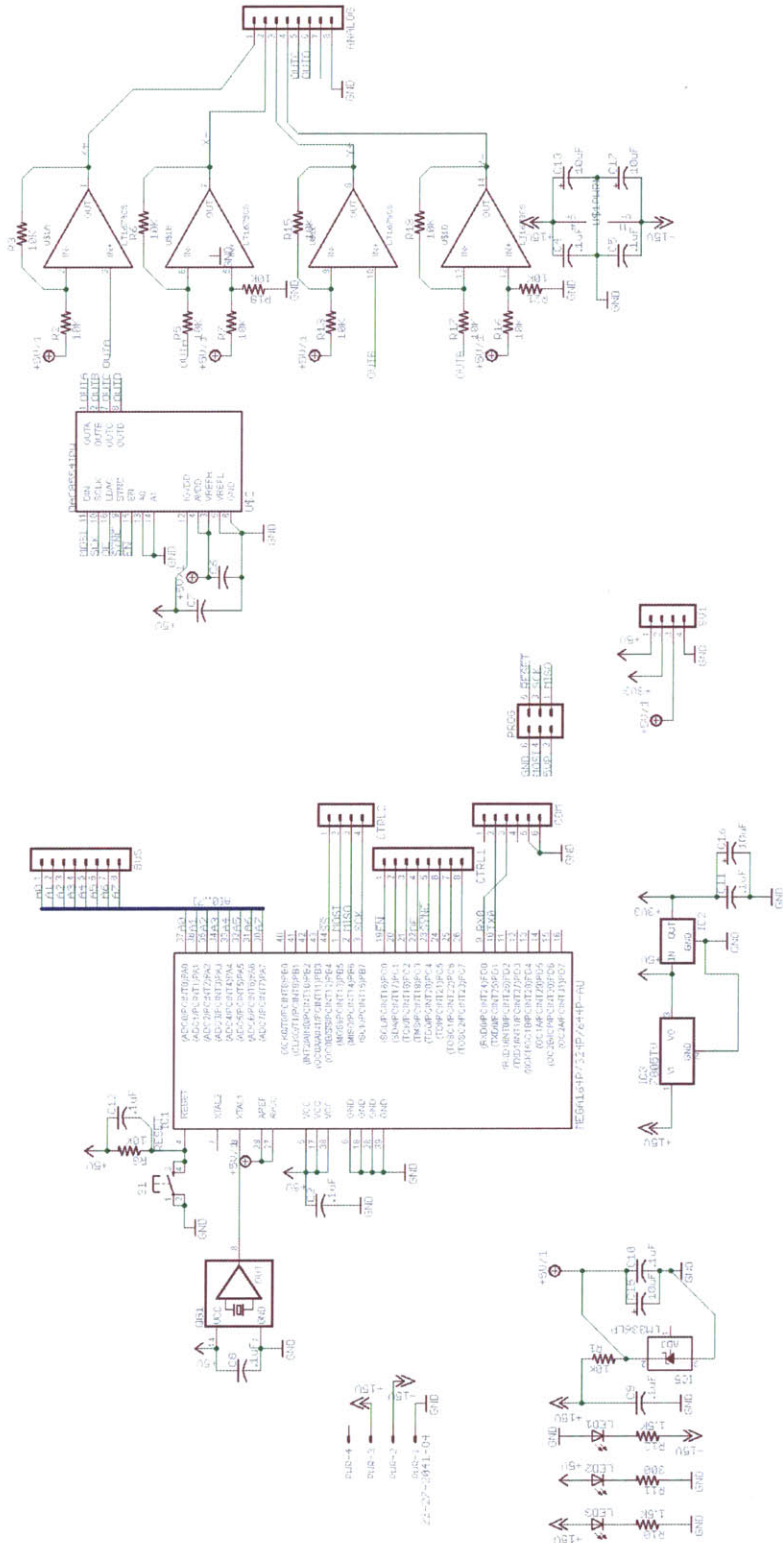
Figure A-1: Controller Board Schematic
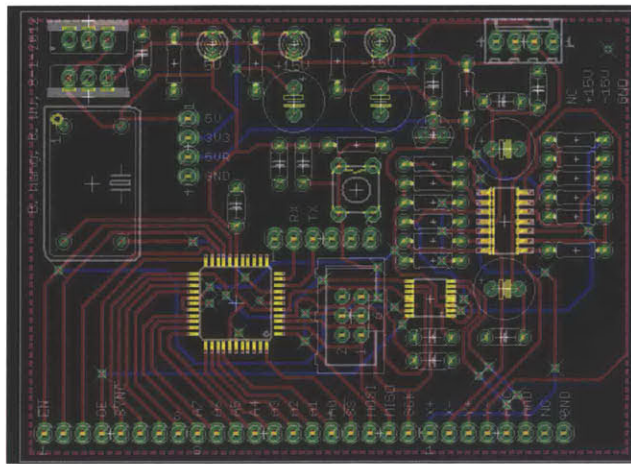
Figure A-2: Controller Board Layout
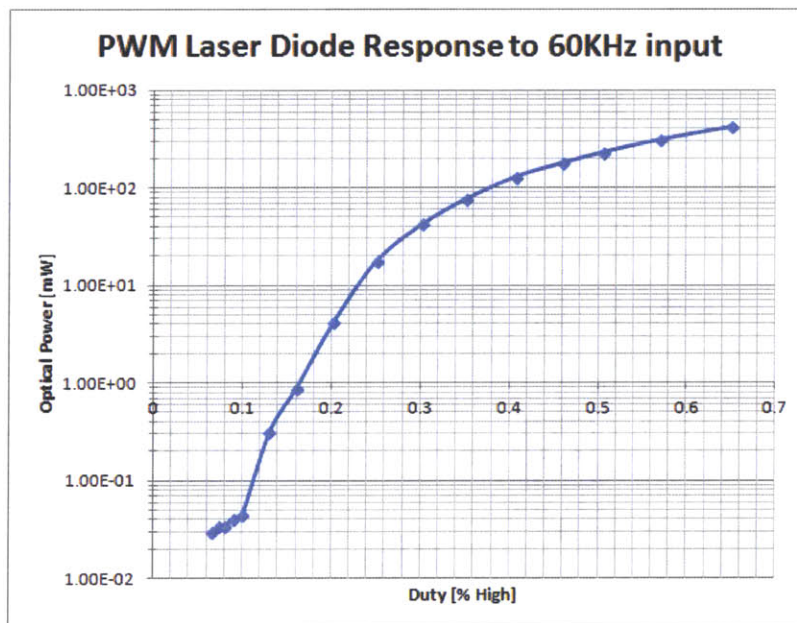
Figure A-3: PWM Laser Response to High Frequency PWM
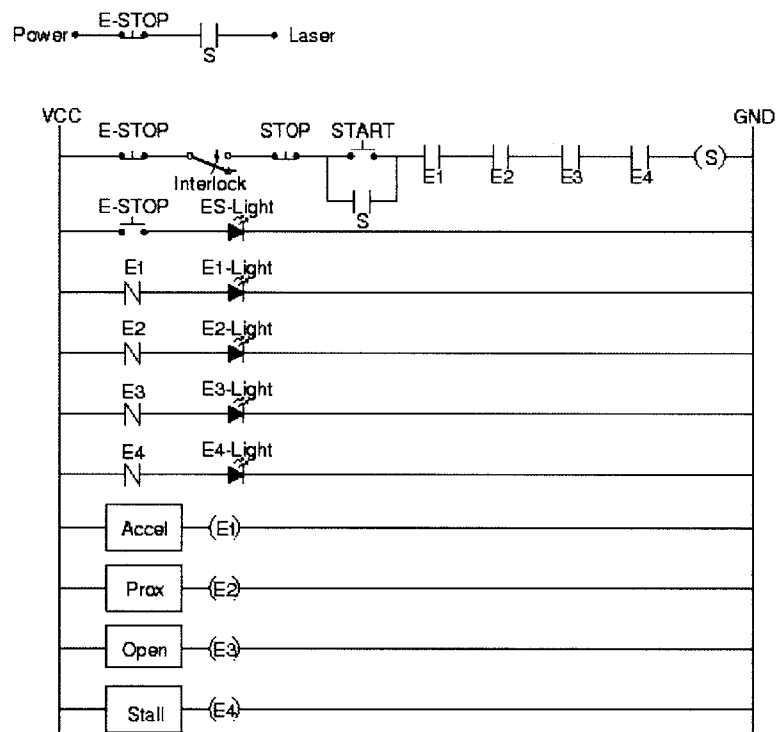
Figure A-4: Safety Relay Overview
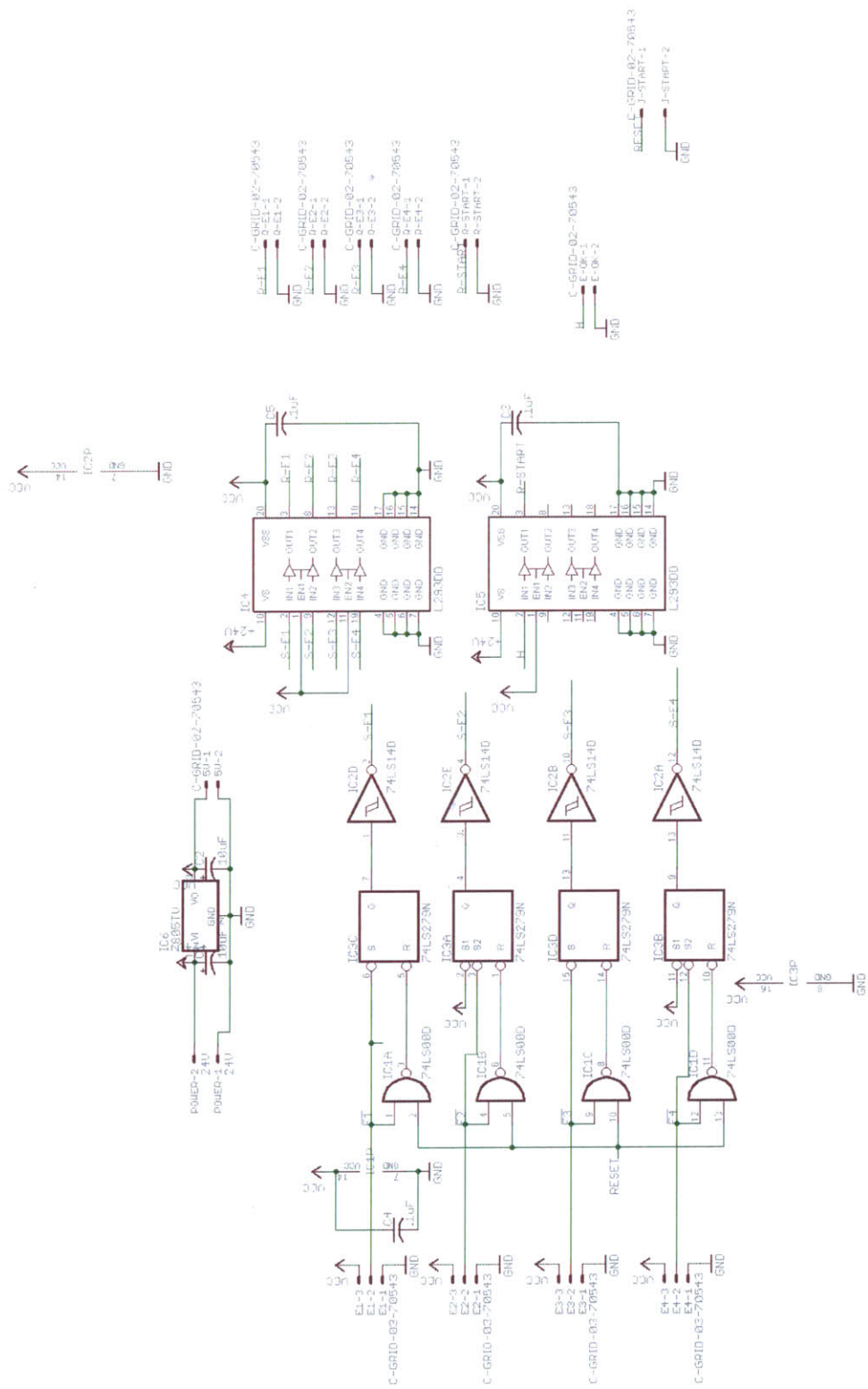
Figure A-5: Safety Relay Driver Schematic
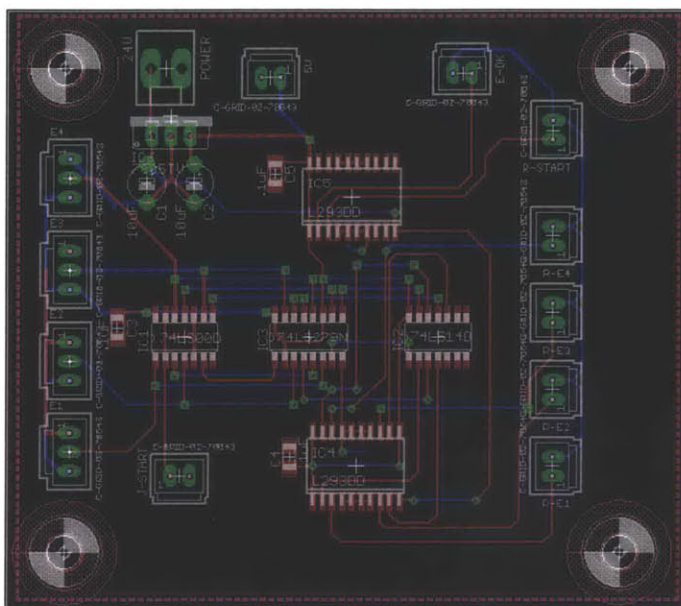
[htb]

Figure A-6: Safety Relay Driver Board
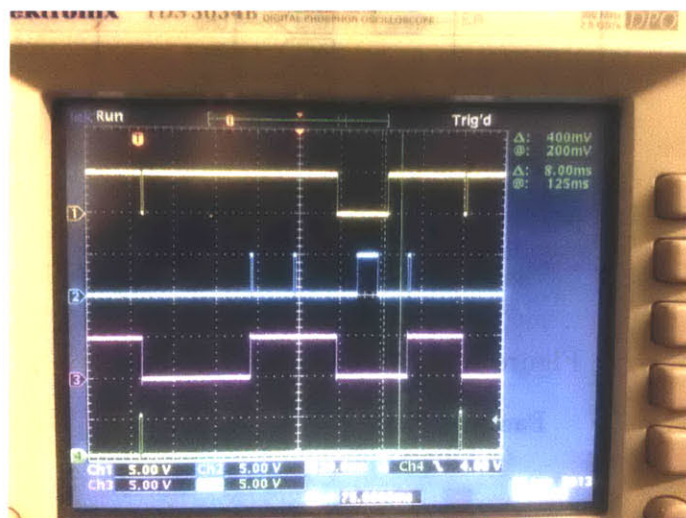
Figure A-7: Relay Logic Test
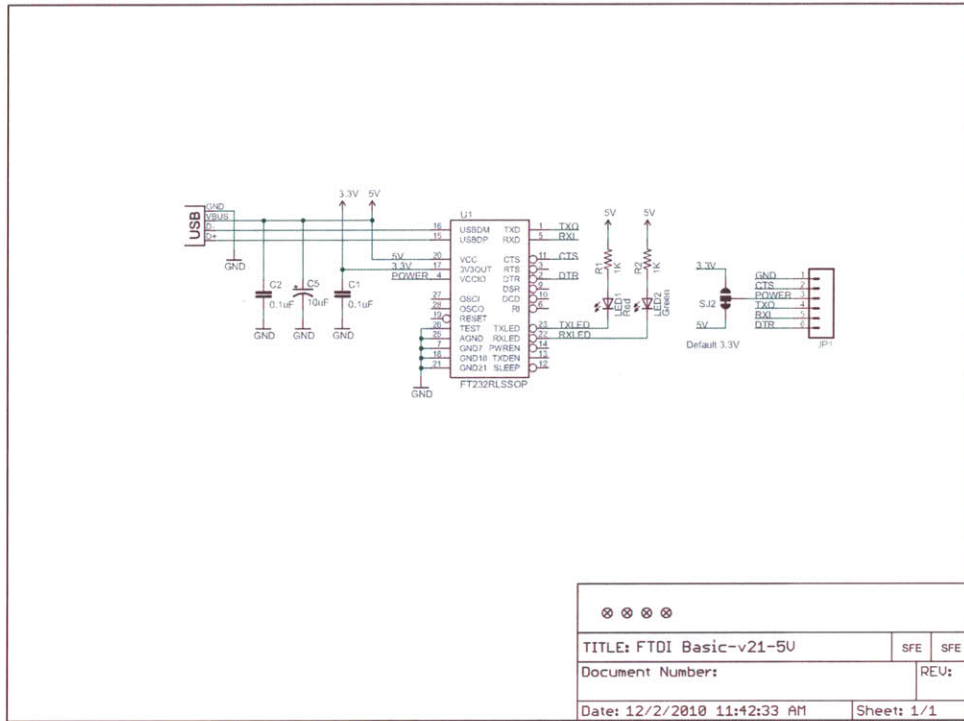
Figure A-8: FTDI232 Board; source: SparkFun
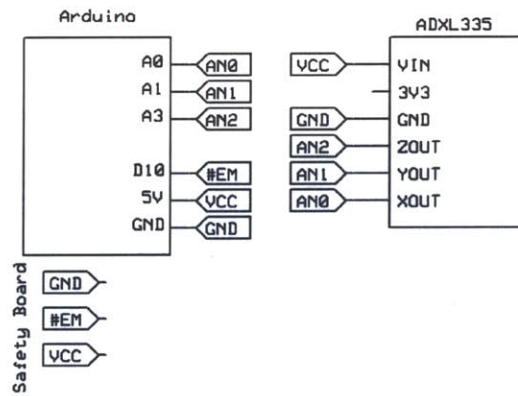
Figure A-9: Acceleration Detector
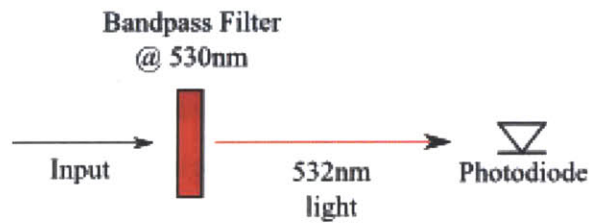
Figure A-10: Optical Detector Filter
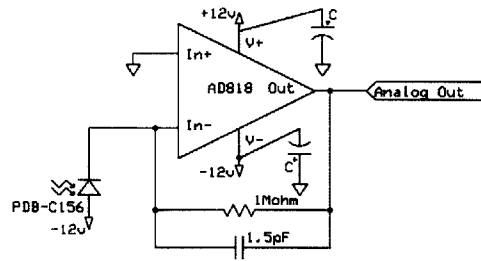
Figure A-11: Laser Reflection Detector
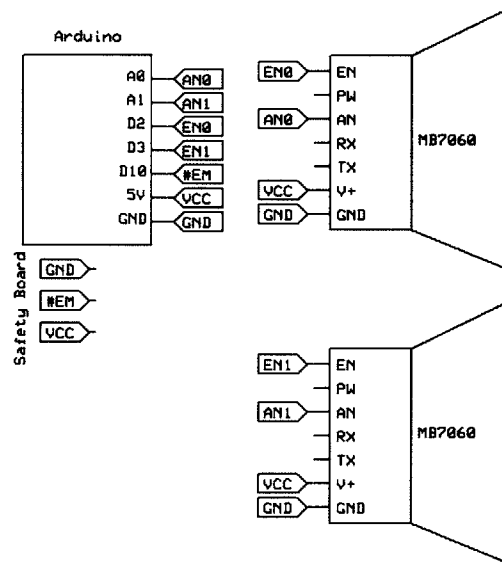
Figure A-12: Ultrasonic Detector

71

Appendix B

States and Instruction Protocol

Table B.1 is the list of serial commands that can be issued to the controller board and the controller's responses. Command is the command byte sent to the controller. The Direction refers to the information flow with respect to the controller. The Data Format is how the information after the command byte is formatted.

Table B.2 describes the different operation states that the controller can be engaged in. The controller can only be in one state at a time.

Table B.3 is the logic states for each relay. Each emergency detector drives a corresponding relay. That relay is controlled by a logic cells that latches the relay OFF if the emergency detector senses an unsafe event, and resets ON if the RESET signal is sent while the emergency detector does not sense an unsafe event.

Table B.4 illustrates the logic output of the entire safety circuit. The laser should not be powered unless all of the other Relays R_i and START are ON.

Command	Direction	Data Format	Description
[0x00]	Input	None	Disable the DAC, galvanometers return to inital positions
[0x01]	Input	None	Enable the DAC, galvanometers can move
[0x02]	Input	None	Set internal state to STANDBY
[0x03]	Input	None	Set internal state to SEQ_POINTS_FIXED_T
[0x04]	Input	None	Set internal state to SEQ_POINTS_VAR_T
[0x05]	Input	None	Set internal state to LINE_SEG
[0x0B]	Input	None	Set internal state to LINE_SEG
[0x0C]	Input	None	Enable Laser output, the laser can be driven by a PWM signal
[0x0D]	Input	None	Disable Laser output, the laser is off, regardless of PWM signal
[0x0F]	Input	None	Set internal state to SHUT-DOWN
[0x10]	Input	[0xZZ]	Set the length of the scan sequence to [0xZZ] long. Maximum length is 100.
[0x11]	Input	[0xTT] 0xZZ*([UPPER][LOWER])	Set the [0xTT] table variables, requires table length * 2 additional bytes to fill table
[0x12]	Input	[XWORD] [YWORD] [IWORD] [TWORD]	Send in 8 bytes corresponding to a single position, set internal state to SINGLE_SHOT
[0x13]	Input	None	Set table length to 0
[0x14]	Input	None	Clear all data from internal EEP-ROM Tables
[0x30]	Output	None	Returns the internal state value
[0x31]	Output	None	Returns the length of the EEP-ROM table [0xZZ]
[0x31]	Output	[0xTT]	Returns 2*[0xZZ] bytes that correspond to the data stored in table 0xTT
[0x40]	Output	[CHAR]	Echoes [CHAR] back through the serial port

Table B.1: Controller Instruction Set

State Name	EEPROM Used	Laser Active?	Cycle Length	Description
STANDBY	None	No	$100\mu s$	Laser is inactive, and waiting for further instructions
SINGLE _SHOT	X_Single, Y_Single, I_Single, T_Single	Yes	T_Single *$100\mu s$	Laser will fire at single spot for a limited amount of time. Transistions into STANDBY after T_Single*$100\mu s$.
SEQ_POINTS _FIXED_T	X,Y	Yes	4ms	Laser will scan points at X_i, Y_i at low power continuously, used as a debug command.
SEQ_POINTS _VAR_T	X,Y,I,T	Yes	$T_i * 100\mu s$	Laser will scan points at X_i, Y_i at I_i for $T_i * 100\mu s$ in sequence. Default user operation.
LINE_SEG	X,Y,I,T	Yes	$T_i * 100\mu s$	Laser will scan line segments between (X_i, Y_i) and (X_{i+1}, Y_{i+1}) at I_i for $T_i * 100\mu s$ in sequence. Experimental operation.
SHUTDOWN	None	No	15ms	Laser is shut off, galvos are deactivated, internal watchdog timer is set to reset controller.

Table B.2: Controller States

Emergency State	Reset	Relay
L	L	OFF
L	H	OFF
H	L	Previous State
H	H	ON

Table B.3: Logic States of Relay Driver

L: Logic Low; H: Logic High

R1	R2	R3	R4	Start	Laser
X	X	X	X	OFF	OFF
X	X	X	OFF	X	OFF
X	X	OFF	X	X	OFF
X	OFF	X	X	X	OFF
OFF	X	X	X	X	OFF
ON	ON	ON	ON	ON	ON

Table B.4: Overall Relay Driver Logic

X: Don't care

Appendix C

Safety Regulations

In this Appendix tare datasheets from relevent agencies, as well as notes that are of interest to the project.

C.1   ANSI

Equations for calculating MPE, NHZ, NOHZ and Visual Interference are in Appendix E.

C.1.1   ANSI Z136.6-2000

Notes come from the American National Standards Institution [2000a] Laser Safety manual and American National Standards Institution [2000b] Outdoor Laser Safety manual. Figures C-1 to C-8 are from the ANSI manuals and are useful in deriving safe exposure levels.

- (1.1.2) Variance from the Federal Laser Standard is required for all Class 3b and Class 4 outdoor lasers display products

- (1.1.3) If used in airspace, shall receive a variance from FDA/CDRH, and permission from the FAA

- (1.1.4) If laser beams cross property lines, property owner should be informed if personal exposure exceeds MPE

- (1.1.5) If laser beams cross military borders, should coordinate with local authorities to ensure use will not interfere with military or DoE ops, regardless if MPE is exceeded

- (1.3) Class 3b and Class 4 lasers need have a Laser Safety officer, evaluate hazards, determine procedures, and enforce safe operation

- (3.2) Classification of the laser source is determined at the most hazardous position along the beam path

- (3.3.1) Hazards from Class 2 and 3a should be considered during night time use

- (3.3.5)For specular reflection, worst case assumption is made: Polarization, distance between laser and reflector, size of reflector, composition of reflector material, flatness of reflector, incident angle

- (3.3.6) Buffer angle is usually set at 5X pointing inaccuracy

- (3.3.7) Diffuse and Specular reflections during inclement weather are hazardous within one meter of the laser beam path. Water on surfaces are considered to be reflective specular objects.

- (3.4): Visual interferenece: dazzle, glare, startle, flashblindness, temporary visual impairment, most severe at night. Standards outlined are during reduced ambient lighting

- (4.2.3) For a laser device to have remote operation, should be class 1, reliable shutdown mechanism should be employed to prevent exposure above level 1. Otherwise remote operation is acceptable only if laser area is accessible by personnel trained in laser safety only.

- (4.2.6) 3b and 4 lasers can be used outside laser controlled areas if NOHD is greather than 100m. The Operator must be laser safety trained, must be able to cease laser operation before potentially hazardous situations arise, and takes full responsibility of the safety of personnel who enters the laser beam. Lasers with NOHD less than 100m should only be used with specific controls and safeguards in place, and should have a separate safety observer. If safety observer is deployed, laser controlled area can be extended to 700m.

- (4.3.2) Lasers need to be labeled

- (4.3.2.3) Class 2-4 Device must include LASER APERATURE warning.

- (4.3.3.2) Laser interlock needs to have visual feedback on powered state.

- (4.3.3.3) System cannot reactivate without an intentional reset.

- (4.3.3.4) Emission Indicator must be lit when laser is prepared to fire, and must be visible through protective eyewear.

- (4.3.3.8) Scanning laser products shall include a feature that prevents laser emission exceeding the AEL of the Class of the product upon failure of any component.

- (4.5.4.5) If specular surfaces cannot be removed from the laser area, the high-power laser emissions can only be done in designated laser safety areas and safe airspace

- (8.3.1) For determining visual interference levels, no correction is made for extended sources. The levels are Sensitive, Critical, Laser Free. Use Effective radiant exposure for exposures less than 0.25 Seconds, and irrandiance for exposures greater than 0.25s when doing calculations.

- (8.4) Visible Light pulsed at 8-16fps should be avoided to prevent interference with brain alpha rhythms.

C.2 FDA

Figures C-9 and C-10 are procedures and images that help compliance with FDA standards [Food and Drug Administration Center for Devices and Radiological Health, 2012].

C.3 FAA

Figures C-11,C-12 and C-13 are examples of application and variance letters for public tests [U.S. Department of Transportation Federal Avaiation Administration, 2012a], [U.S. Department of Transportation Federal Avaiation Administration, 2012b].

Table 10

Control Measures for the Four Laser Classes

Control Measures	Classification				
Engineering Controls	1	2	3a	3b	4
Protective Housing (4.3.1)	X	X	X	X	X
Without Protective Housing (4.3.1.1)	LSO shall establish Alternative Controls				
Interlocks on Protective Housing (4.3.2)	∇	∇	∇	X	X
Service Access Panel (4.3.3)	∇	∇	∇	X	X
Key Control (4.3.4)	—	—	—	•	X
Viewing Portals (4.3.5.1)	—	MPE	MPE	MPE	MPE
Collecting Optics (4.3.5.2)	MPE	MPE	MPE	MPE	MPE
Totally Open Beam Path (4.3.6.1)	—	—	—	X NHZ	X NHZ
Limited Open Beam Path (4.3.6.2)	—	—	—	X NHZ	X NHZ
Enclosed Beam Path (4.3.6.3)	None is required if 4.3.1 and 4.3.2 fulfilled				
Remote Interlock Connector (4.3.7)	—	—	—	•	X
Beam Stop or Attenuator (4.3.8)	—	—	—	•	X
Activation Warning Systems (4.3.9.4)	—	—	—	•	X
Emission Delay (4.3.9.1)	—	—	—	—	X
Indoor Laser Controlled Area (4.3.10)	—	—	—	X NHZ	X NHZ
Class 3b Indoor Laser Controlled Area (4.3.10.1)	—	—	—	X	—
Class 4 Laser Controlled Area (4.3.10.2)	—	—	—	—	X
Laser Outdoor Controls (4.3.11)	—	—	—	X NHZ	X NHZ
Laser in Navigable Airspace (4.3.11.2)	—	—	•	•	•
Temporary Laser Controlled Area (4.3.12)	∇ MPE	∇ MPE	∇ MPE	—	—
Remote Firing and Monitoring (4.3.13)	—	—	—	—	•
Labels (4.3.14 and 4.7)	X	X	X	X	X
Area Posting (4.3.9)	—	—	•	X NHZ	X NHZ

LEGEND   X - Shall

       • - Should

       —— - No requirement

       ∇ - Shall if enclosed Class 3b or Class 4

       MPE - Shall if MPE is exceeded

       NHZ - Nominal Hazard Zone analysis required

51

Figure C-1: Required Control Measures, Page 1

79

Table 10 (cont.)

Control Measures for the Four Laser Classes

Control Measures	Classification				
Administrative and Procedural Controls	1	2	3a	3b	4
Standard Operating Procedures (4.4.1)	—	—	—	•	X
Output Emission Limitations (4.4.2)	—	—	LSO Determination		
Education and Training (4.4.3)	—	•	•	X	X
Authorized Personnel (4.4.4)	—	—	—	X	X
Alignment Procedures (4.4.5)	—	X	X	X	X
Protective Equipment (4.6)	—	—	—	•	X
Spectator (4.4.6)	—	—	—	•	X
Service Personnel (4.4.7)	∇ MPE	∇ MPE	∇ MPE	X	X
Demonstration with General Public (4.5.1)	MPE†	X	X	X	X
Laser Optical Fiber Systems (4.5.2)	MPE	MPE	MPE	X	X
Laser Robotic Installations (4.5.3)	—	—	—	X NHZ	X NHZ
Eye Protection (4.6.2)	—	—	—	• MPE	X MPE
Protective Windows (4.6.3)	—	—	—	X NHZ	X NHZ
Protective Barriers and Curtains (4.6.4)	—	—	—	•	•
Skin Protection (4.6.6)	—	—	—	X MPE	X MPE
Other Protective Equipment (4.6.7)	Use may be required				
Warning Signs and Labels (4.7) (Design Requirements)	—	•	•	X NHZ	X NHZ
Service and Repairs (4.4.7)	LSO Determination				
Modifications and Laser Systems (4.1.2)	LSO Determination				

LEGEND   X - Shall

         • - Should

         — - No requirement

         ∇ - Shall if enclosed Class 3b or Class 4

         MPE - Shall if MPE is exceeded

         NHZ - Nominal Hazard Zone analysis required

         † - Applicable only to UV and IR Lasers (4.5.1.2)

52

Figure C-2: Required Control Measures, Page 2

Table 6
Parameters and Correction Factors

Parameters/Correction Factors	Wavelength (μm)	Figure*
$T_1 = 10 \times 10^{20(\lambda - 0.450)}$ **	0.450 to 0.500	9a
$T_2 = 10 \times 10^{(\alpha - 1.5)/98.5}$ ***	0.400 to 1.400	9b
$C_B = 1.0$	0.400 to 0.450	8c
$C_B = 10^{20(\lambda - 0.450)}$	0.450 to 0.600	8c
$C_A = 1.0$	0.400 to 0.700	8a
$C_A = 10^{2(\lambda - 0.700)}$	0.700 to 1.050	8a
$C_A = 5.0$	1.050 to 1.400	8a
$C_P = n^{-0.25}$ ****	0.180 to 1000	13
$C_E = 1.0 \quad \alpha < \alpha_{min}$	0.400 to 1.400	—
$C_E = \alpha / \alpha_{min} \qquad \alpha_{min} \leq \alpha \leq \alpha_{max}$	0.400 to 1.400	—
$C_E = \alpha^2 / (\alpha_{max} \alpha_{min}) \qquad \alpha > \alpha_{max}$	0.400 to 1.400	—
$C_C = 1.0$	1.050 to 1.150	8b
$C_C = 10^{18(\lambda - 1.150)}$	1.150 to 1.200	8b
$C_C = 8$	1.200 to 1.400	8b

* See figures for graphic representation.

** $T_1 = 10$ s for $\lambda = 0.450$ μm, and $T_1 = 100$ s for $\lambda = 0.500$ μm.

*** $T_2 = 10$ s for $\alpha < 1.5$ mrad, and $T_2 = 100$ s for $\alpha > 100$ mrad.

**** See Section 8.2.3 for discussion of C_p and Section 8.2.3.2 for discussion of pulse repetition frequencies below 55 kHz (0.4 to 1.05 μm) and below 20 kHz (1.05 to 1.4 μm).

Notes:

1. For wavelengths between 0.400 and 1.400 μm:
   $\alpha_{min} = 1.5$ mrad $\alpha_{max} = 100$ mrad

2. Wavelengths must be expressed in micrometers and angles in milliradians for calculations.

   The wavelength region λ_1 to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$, e.g., 0.550 to 0.700 μm means $0.550 \leq \lambda < 0.700$ μm.

47

Figure C-3: Optical Parameters

81

ENERGY
(mJ)

BEAM
DIVERGENCE
(mr)

INTEGRATED
RADIENT
INTENSITY
(MJ/sr)

RANGE
(km)

RADIANT
EXPOSURE
(μJ/cm^2)

POWER
(mW)

RADIENT
INTENSITY
(MW/sr)

CLEAR   HAZE

IRRADIANCE
(μW/cm^2)
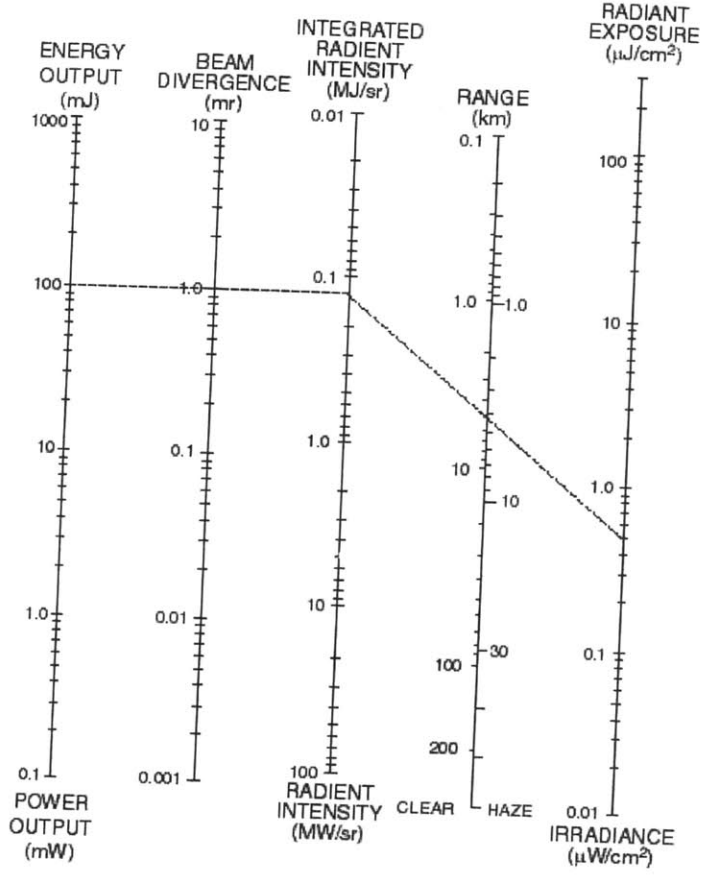
Fig. B8
Laser Range Equation Nomogram.

(See Section B6.4.2 and Example 39)

127

Figure C-4: Range Nonogram Calculator

Table 5. Visual Interference Levels.*

Flight Zone or Region of Visual Interference	Visual Interference Levels		
	Effective Radiant Exposure $(J \cdot cm^{-2})$† $T_{max} \leq 0.25$ s	Effective Irradiance $(W \cdot cm^{-2})$† $T_{max} > 0.25$ s	Illuminance $(lm \cdot cm^{-2})$ $T_{max} > 0.25$ s
Normal	$1.8 \times 10^{-3} \times T_{max}^{0.75}$	2.5×10^{-3}	1.7 (for 0.55 µm only)‡
Sensitive	25×10^{-6}	100×10^{-6}	6.8×10^{-2}
Critical	1.25×10^{-6}	5.0×10^{-6}	3.4×10^{-3}
Laser-Free	12.5×10^{-9}	50×10^{-9}	3.4×10^{-5}

*Interim levels are listed from visible lasers used at dusk or night. The values in this table are based on preliminary perceptions and accepted practice at the time that this document was published. Future research on visual interference effects may result in a modification of these levels.

†Measured (or calculated) irradiance levels must be multiplied by the photopic luminance efficiency coefficient obtained from Table 1 in order to correct for visual sensitivity of the human eye. The irradiance levels for the normal region are not corrected for visual effect using $V(\lambda)$ since these levels correspond to the MPE. The formula provides MPE values for exposure durations from 18 µs to 0.25 s. Whenever the irradiance exceeds the MPE, the MPE takes precedence even if the visual interference level is higher.

‡The normal region is limited by the MPE, which is not wavelength dependent in the visible spectrum. The MPE expressed as actual irradiance or radiant exposure is applicable for this region. The listed value for illuminance is only for a laser with a wavelength of 0.55 µm. The visual interference level for other wavelengths may be calculated by multiplying the provided value by $V(\lambda)$ from Table 1.

Table 6. Skin MPEs.*

Wavelength (µm)	Exposure Duration (s)	MPE	
		Pulsed $(J \cdot cm^{-2})$	CW $(W \cdot cm^{-2})$
0.180 to 0.314	10^{-9} to 3×10^{4}	Same as Table 2	Same as Table 2
0.315 to 0.400	10^{-9} to 10	$0.56 \times t^{0.25}$	$0.56 \times T_{max}^{-0.75}$
0.400 to 1.400	10^{-9} to 10^{-7}	$0.2 \times C_A \times 10^{-3}$	$1.1 \times C_A \times T_{max}^{-0.75}$
	10^{-7} to 10	$1.1 \times C_A \times t^{0.25}$	$0.2 \times C_A$
1.400 to 1.0×10^{3}	10	$2.0 \times C_A$	See Table 2
	10^{-9} to 10	See Table 2	

* Values are for selected wavelengths for exposure durations less than 10 s (except for UV).

35

Figure C-5: Visual Interference Levels

Table 8. Diffuse Reflection Hazard from Pulsed Lasers in Retinal Hazard Region.

Beam Diameter (mm)	Viewing Distance								
	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm	80 cm	90 cm	1 m
	Beam Energy (mJ)								
1	2	3	4	5	6	8	10	13	16
2	4	6	8	11	13	15	17	19	21
3	6	10	13	16	19	22	25	28	31
4	9	13	17	21	25	29	34	38	42
5	11	16	21	26	32	37	42	47	53
6	13	19	25	32	38	44	51	57	63
7	15	22	30	37	44	52	59	66	74
8	17	26	34	43	51	59	68	76	84
9	20	29	39	48	57	67	76	86	95
10	22	32	43	53	64	74	85	95	106
20	46	67	88	109	130	151	172	193	214
30	109	104	135	167	198	229	261	292	323
40	203	191	185	226	268	310	352	394	436
50	331	307	295	288	341	393	445	498	550
60	498	456	435	423	415	478	541	604	666
70	708	640	607	587	574	565	639	712	785
80	965	860	811	781	762	749	739	822	906
90	1272	1121	1049	1007	980	960	946	935	1029
100	1635	1425	1325	1266	1228	1202	1182	1166	1154

*Energy values listed in the table in mJ are those that will barely produce a diffuse hazard for Q-switched lasers at various viewing distances. Values listed are based on various beam diameters, at the point of impact on a white matte target, for wavelengths in retinal hazard region.

Notes:

1. For wavelengths between 0.7 μm and 1.4 μm, the above power values should be multiplied by factors of C_A and C_C as appropriate.

2. For wavelengths between 1.05 μm and 1.4 μm, the above values are multiplied by and additional factor of 2.

3. For repetitive-pulse lasers, the repetitive-pulse correction factor C_p should be applied.

37

Figure C-6: Diffuse Hazard intensity from a Pulsed Laser

VERTICAL BUFFER

HORIZONTAL BUFFER

TARGET AREA

HORIZONTAL BUFFER
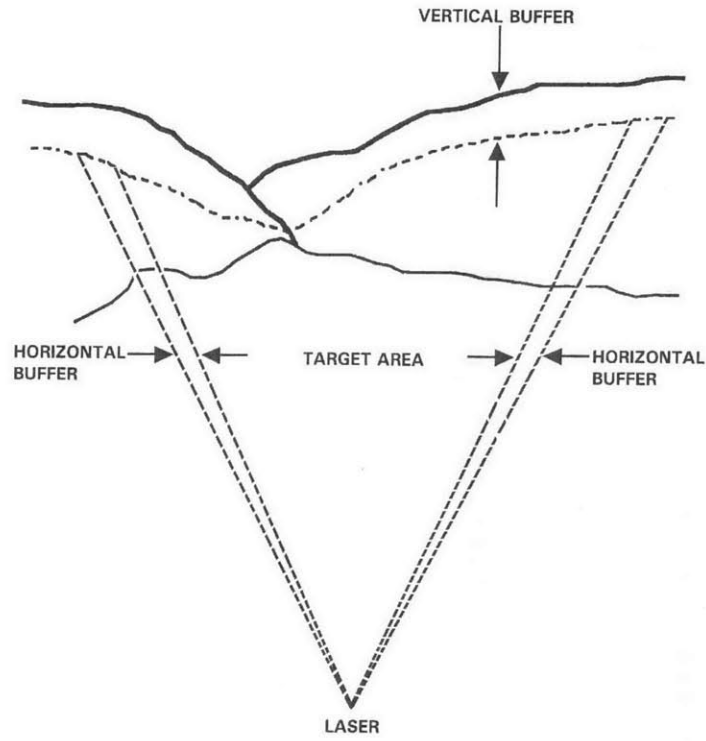
LASER

Figure 3. Laser Controlled Area on a Laser Range. Horizontal and vertical buffer areas are included. Natural terrain provides a backstop in the vertical buffer area.

40

Figure C-7: Example of Buffer Zone

Table 1. Photopic Luminous Efficiency Function V(λ).

Laser Wavelength (μm)	V(λ)	Laser Wavelength (μm)	V(λ)
0.380	0.00004	0.585	0.810
0.385	0.00007	0.590	0.758
0.390	0.00012	0.595	0.710
0.395	0.00018	0.600	0.633
0.400	0.00040	0.605	0.580
0.405	0.00058	0.610	0.503
0.410	0.0012	0.615	0.450
0.415	0.0020	0.620	0.382
0.420	0.0040	0.625	0.325
0.425	0.0065	0.630	0.265
0.430	0.0116	0.635	0.215
0.435	0.0170	0.640	0.175
0.440	0.0230	0.645	0.132
0.445	0.0300	0.650	0.107
0.450	0.0380	0.655	0.0750
0.455	0.0500	0.660	0.0610
0.460	0.0599	0.665	0.0435
0.465	0.0720	0.670	0.0321
0.470	0.0909	0.675	0.0225
0.475	0.105	0.680	0.0170
0.480	0.139	0.685	0.0106
0.485	0.162	0.690	0.0082
0.490	0.208	0.695	0.0059
0.495	0.250	0.700	0.0041
0.500	0.323	0.705	0.0030
0.505	0.400	0.710	0.0021
0.510	0.503	0.715	0.0014
0.515	0.620	0.720	0.0010
0.520	0.709	0.725	0.00077
0.525	0.800	0.730	0.00052
0.530	0.862	0.735	0.00035
0.535	0.925	0.740	0.00025
0.540	0.954	0.745	0.00018
0.545	0.980	0.750	0.00012
0.550	0.990	0.755	0.000085
0.555	1.000	0.760	0.000060
0.560	0.990	0.765	0.000042
0.565	0.970	0.770	0.000030
0.570	0.952	0.775	0.000020
0.575	0.910	0.780	0.000015
0.580	0.870		

*The listed CIE normalized photopic luminous efficiency function V(λ) is photopic for a standard observer. The illuminance (lm·cm²) is the measured irradiance multiplied by V(λ) and 683. The effective irradiance (W·cm²) is the actual (measured) irradiance multiplied by V(λ).

31

Figure C-8: Luminous Efficiency

Sample Notification Letter to FDA/CDRH

(This letter is an example of a notification letter to the FDA/CDRH once a variance has been granted. All names and places are intended to be fictitious, and any similarities are purely coincidental).

Date: 1/1/99

Office of Compliance (HFZ-342)   Ref: FDA/CDRH Docket No. 000-0000
Center for Devices and Radiological Health   Accession No.   0000000-0000
2098 Gaither Rd.   Date: 1/1/99
Rockville, MD 20850

This is a notice of the following laser light show:

EVENT:	Fourth of July Festivities
VENUE:	Seattle Fairgrounds
TIME(S) AND DATE(S):	7/4/99 - 8:00 p.m. to 10:00 p.m.
EFFECT(S) UTILIZED:	Beams into sky
DESCRIPTION OF SHOW:	Beams in an outdoor environment
EQUIPMENT UTILIZED:	Laser Model XXX 20 W System
LASER OPERATOR(S) IN CHARGE OF SHOW:	John Doe
AGENCIES NOTIFIED:	FDA/CDRH and FAA

DESCRIPTION OF SAFETY FACTORS: All pertinent safety factors will be adhered to: three-meter rule, barriers, beam blocks, and use of certified laser projector.

MISCELLANEOUS COMMENTS:

If you have any further questions or comments, please don't hesitate to call me at (000) 555-0000.

Sincerely,

John Doe
Office Manager

57

Figure C-9: Letter of Notification to the FDA

BLACK   RED BACKGROUND/WHITE LETTERS

DANGER

RED

Wavelength
BLACK   Ave Output Power: ANSI Class   Laser Product
LETTERS
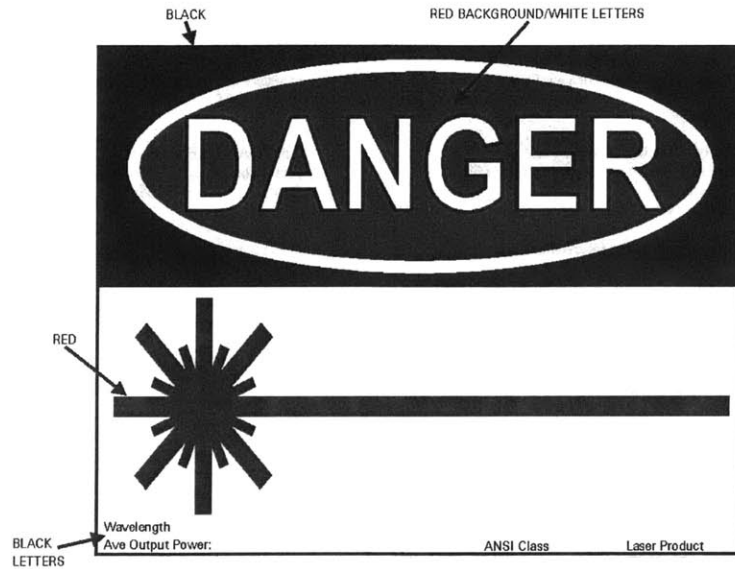
Figure 7c. Example of an Alternate Danger Label. Starburst is red; letters are black. Precautions including the NOHD would be placed above the tail of the starburst. The type of laser, including output power or pulse characteristics, placed below the starburst. If the output of the laser is invisible, the word "invisible" should be included below the tail of the starburst. The ANSI classification is placed in the lower right hand corner.

46

Figure C-10: Example Warning Sign

Please Type or Print on This Form

Form Approved OMB No. 2120-0662

Failure To Provide All Requested Information May Delay Processing of Your Notice

FOR FAA USE ONLY

U.S. Department of Transportation
Federal Aviation Administration

NOTICE OF PROPOSED OUTDOOR LASER OPERATION(S)

1. GENERAL INFORMATION

(a) To: *(FAA Regional Office)*	(b) From: *(Proponent)*

(c) Event or Facility	(d) Report Date:
(e) Customer	(f) Site address

2. DATE(S) AND TIME(S) OF LASER OPERATION

(a) Testing and alignment	(b) Operation

3. BRIEF DESCRIPTION OF OPERATION

4. ON-SITE OPERATION INFORMATION

(a) Operator(s)

(b) On-site phone #1	(c) On-site phone #2

5. FDS CDRH LASER LIGHT SHOW VARIANCE (if applicable)

(a) Variance #	(b) Accession #	(c) Expiration date

6. BRIEF DESCRIPTION OF CONTROL MEASURES

7. ATTACHMENTS

(a) Number of laser configurations [fill out one copy of page 2 of this notice ("Laser Configurations Worksheet") for each configuration]

(b) List Additional attachments *(including maps, diagrams, and details of control measures)*

8. DESIGNATED CONTACT PERSON *(if further information is needed)*

(a) Name	(b) Position
(c) Phone	(d) Fax	(e) E-mail

9. STATEMENT OF ACCURACY

To the best of my knowledge, the information provided in this Notice and attached worksheet(s) is accurate and correct.

(a) Name *(if different from contact person)*	(b) Position
(c) Signature	(d) Date

FAA Form 7140-1 (4-01) Local Reproduction Authorized 032500.111

Figure C-11: Application for Outdoor Laser Use, page 1

Form Approved OMB No. 2120-0662

Failure To Provide All Requested Information May Delay Processing of Your Notice

FOR FAA USE ONLY

U.S. Department of Transportation
Federal Aviation Administration

LASER CONFIGURATION WORKSHEET

1. CONFIGURATION INFORMATION	(b) Name of event/facility	(c) Report date:
(a) Configuration number _____ of _____		
(d) Brief Description of Configuration		

2. GEOGRAPHIC LOCATION	(d) Latitude _____ ° *(deg.)* _____ ` *(min.)* _____ `` *(sec.)*
(a) Site Elevation (ft. above Mean Sea Level)	(e) Longitude _____ ° *(deg.)* _____ ` *(min.)* _____ `` *(sec.)*
(b) Laser Height Above Site Elevation (ft.)	(f) Determined by: ☐ GPS ☐ Map *(Quad)* ☐ Other _____
(c) Overall Laser Elevation (a + b)	(g) Horizontal Datum: ☐ NAD 27 ☐ NAD 88
	(h) Vertical Datum: ☐ NGVD 29 ☐ NAVD 88

3. BEAM CHARACTERISTICS AND CALCULATIONS *(check one Mode of Operation only, and fill in only that column)*

Mode of Operation	☐ SINGLE PULSE	☐ CONTINUOUS WAVE	☐ REPETITIVELY PULSED
Laser Type *(lasing medium)*	*(not applicable)*		
Power *Watts (W)*		*maximum power*	*average power*
Pulse Energy *Joules (J)*		*(not applicable)*	
Pulse Width *Seconds (s)*	*(not applicable)*	*(not applicable)*	
Pulse Repetition Frequency *Hertz (Hz)*		*(not applicable)*	
Beam Diameter @ 1/e points *Centimeters (cm)*			
Beam Divergency 1/e @ full Angle Milliradians (mrad)			
Wavelength(s) *Nanometers (nm)*			

(a) MAXIMUM PERMISSIBLE EXPOSURE (MPE) CALCULATIONS *(will be used to calculate NOHD)*

MPE W/cm^2	*(not applicable)*		
MPE per pulse J/cm^2		*(not applicable)*	

(b) VISUAL EFFECT CALCULATIONS *(will be used only for visible lasers [400-700 nm] to calculate SZED, CZED, and LFED)*

Pre-Corrected Power *(PCP)* Watts *(W)*	*Pulse Energy (J) x 4*	*Maximum Power (from above)*	*Pulse Energy (J) x PRF (Hz) OR Average Power*
Visual Correction Factor *(VCF)* **(Enter "1.0" or use Table 5)**			
Visually corrected Power *PCP x VCF*			

4. BEAM DIRECTION(S)	Magnetic variation (degrees)		
Maximum elevation angle *(degrees)*	Azimuth ☐ True		☐ Magnetic
Minimum elevation angle *(degrees, where horizontal = 0°)*	*(degrees)* _____		

5. CALCULATED DISTANCES *(fill in all three columns)*	SLANT RANGE *(ft.)*	HORIZONTAL DISTANCE *(ft.)*	VERTICAL DISTANCE *(ft.)*
NOHD (based on MPE)			
*SZED *(for 100 µ W/cm^2 level)			
*CZED *(for 5 µ W/cm^2 level)			
*LFED *(for 50 n W/cm^2 level)			

*If the laser has no wavelengths in the visible range (400-700 nm), enter "N/A (non-visible laser)" in all blocks.
For visible lasers, if the calculated SZED, CZED, and/or LFED is less than the NOHD, enter "less than NOHD." than "NOHD."

6. CALCULATION METHOD	☐ Commercial software *(print product name)*
☐ Other *[describe method (spreadsheet, calculator, etc.)]*	

FAA Form 7140-1 (4-01)   Local Reproduction Authorized   032500.111

Figure C-12: Application for Outdoor Laser Use, page 2

Sample Letter from FAA
(This letter is an example. All names and places are intended to be fictitious, and any similarities are purely coincidental).

Mr. John Doe
Laser Coordinator
John Doe Laser Co.
0000 North St.
Seattle, WA 00000

Dear Mr. Doe:

This letter is in response to your proposals for a laser show schedules for July 4, 2000 at Seattle Fairgrounds, in Seattle, WA. The proposed site would be close to the nearby Seattle Airport. Unterminated beams would enter the "laser-free zone" described in FAA Order 7400.2D.

However, the FAA has no objection provided the laser beams are terminated on the grandstand building, as was stated in your letter. The termination area at the site must be large enough to stop the beams and allow for all pointing inaccuracies.

If you need further assistance, please contact me at (000) 555-0000.

Sincerely,

Tom Smith
Airspace and Procedures Manager

59

Figure C-13: Variance from the FAA

Appendix D

Police Procedures

D.1   Before Traffic Stop

When the officer has a target vehicle that needs to be pulled over, he flashes the police cruiser lights and siren. He follows the vehicle at close range until there is a safe shoulder or stop point for the vehicle to pull over. The vehicle and cruiser come to a complete stop before the officer exits the cruiser.

D.2   During Traffic Stop

The cruiser is cantered to the left between 10 and 45 degrees from the center of the lane. This allows the officer some protection in the event of a hostile driver/passenger, as the engine block can absorb incoming fire.

The officer shines a spot light directly into the rear window of the target vehicle, illuminating the interior. This allows the officer to observe the driver at all times, while preventing the driver from looking in the rear. The officer will either be at the forward doors of the vehicle, or sitting in the cruiser front seats using the dashboard computer for id checking, paperwork, and communication.

The officer will vary his approach to the car, either approaching the suspect on the

driver or passenger side. The officer crosses the rear of the cruiser when approaching on the passenger side or accessing equipment such as medical supplies, flares, and emergency signallers. The rear-facing radar provides audible feedback in the event of a speeding vehicle passing by.

D.3 Concerns

The officer crossing the rear of the cruiser is the largest safety hazard posed during normal operation. The officer will enter the projection zone of the laser scanner and the laser beam can be emitted at eye level. The primary beam is unattenuated by the reflection off the ground and is much brighter and can quickly cause ocular damage. An active laser is also inherently unsafe whenever the vehicle is in motion. Passing traffic currently cannot be warned or restricted from entering the NOHZ. The primary beam poses a large safety risk without additional active safeguards.

D.4 Images

Figure D-1: Rear of MSP Cruiser

Figure D-2: Cruiser Interior Computer

Figure D-3: Cruiser in a Traffic Stop

Appendix E

Formulas

E.1 Optics

E.1.1 Beam Expansion

Spherical Beam Expansion

Given input beam width W_i, and desired output width W_o magnification m is:

$$m = \frac{W_o}{W_i} = -\frac{f_2}{f_1} \qquad \text{(E.1)}$$

In the galilean beam expander, the length L of the beam expander is: $|f_1| - |f_2|$.

E.1.2 Divergence

The divergence Θ of a gaussian beam limited by its aperture is: $\Theta = lambda/(pi*W)$.

The narrowest segment of the laser beam is called the beam waist, denoted by width W.

Given input beam divergence D_i and beam magnification m, the output divergence D_o is:
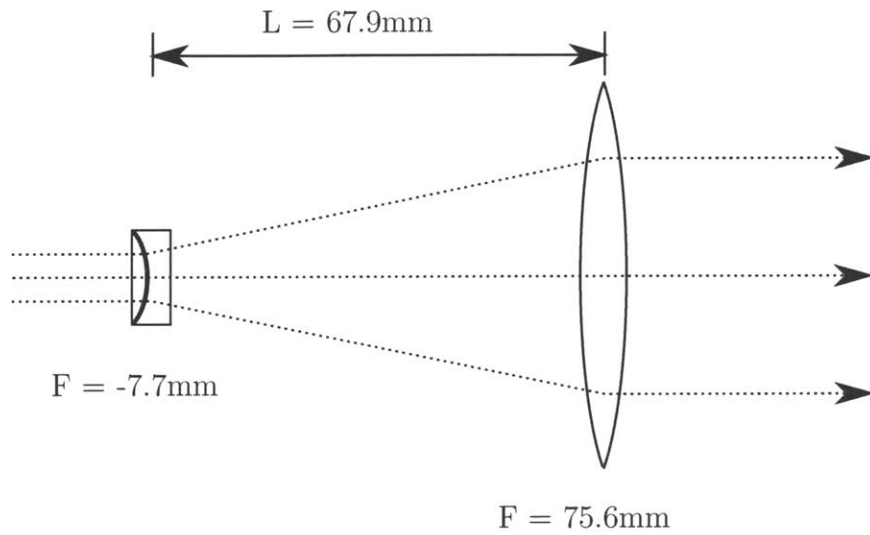
Figure E-1: Gaussian x10 Beam Expander
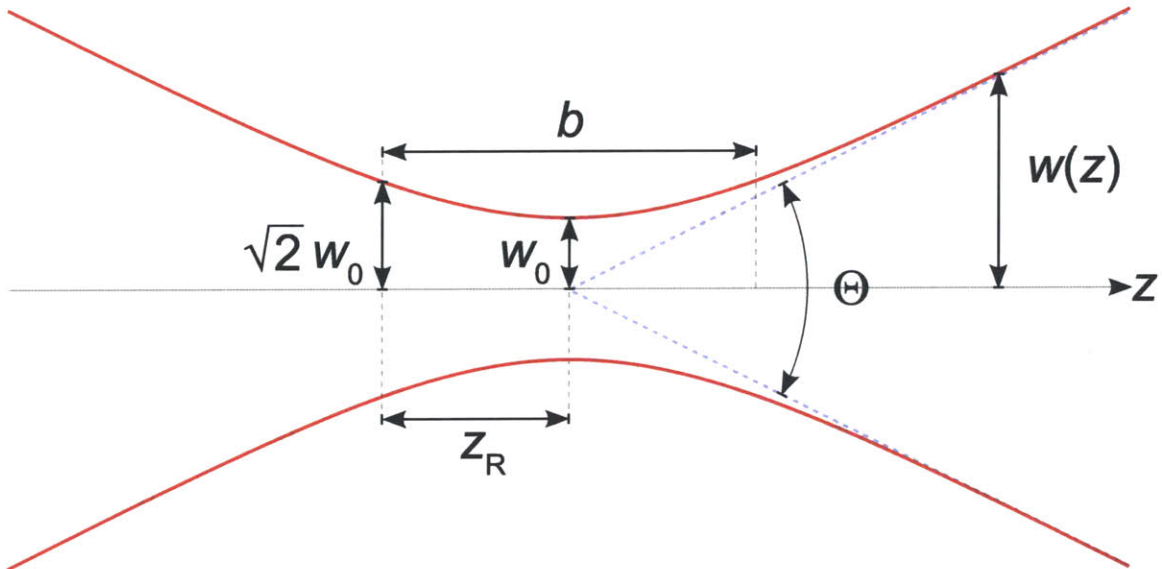
Figure E-2: Laser beam with minimum width W, divergance Θ; Source: Wikipedia
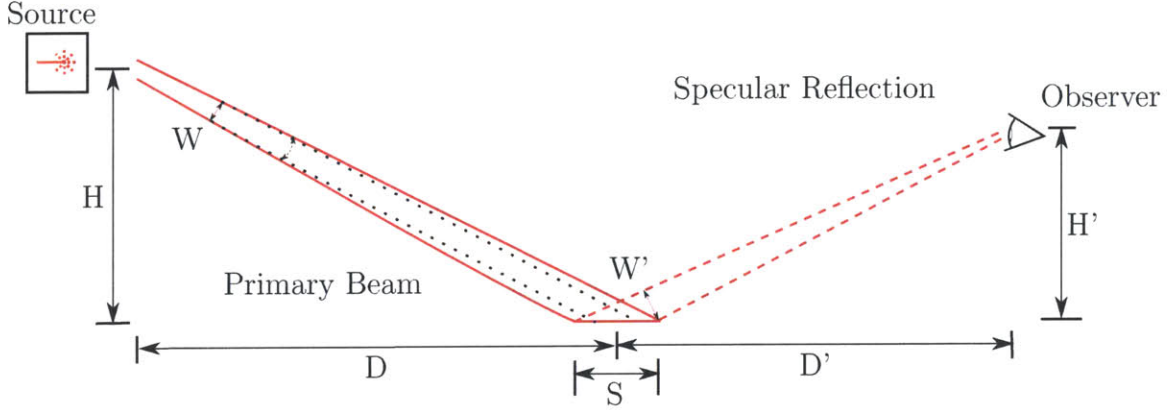
Figure E-3: Foreshortening and Reverse Foreshortening Effects

$$D_o = \frac{D_i}{m} \qquad (E.2)$$

Therefore a beam expander will reduce the divergance of the beam, while expanding it's size.

E.2 Laser Projection

E.2.1 Foreshortening Effect

(See figure E-3)For a laser at height H, output width W, divergence angle Θ projecting at point D distance away, the length of the spot on the pavement S is:

When $\frac{H}{D} << 1$, $\frac{H}{D} > \Theta$ and $\Theta << 1$, we can use the small angle approximation: $\arctan\left(\frac{H}{D}\right) \approx \frac{H}{D}$

$$S \approx \frac{W + \Theta \cdot D}{\frac{H}{D} - \frac{\Theta}{2}}$$

E.2.2 Reverse Foreshortening Effect

For a given observer at height H' located a distance D' from the edge of the laser spot, and distances $D' >> H', D' >> S$, we can use the small angle approximation

97

$\sin\left(\frac{H}{D}\right) \approx \frac{H}{D}$. The apparent width of the spot W' is:

$$W' \approx S \times \frac{H'}{D'}$$
$$W' \approx \frac{W + \Theta \cdot D}{\frac{H}{D} - \frac{\Theta}{2}} \times \frac{H'}{D'} \tag{E.3}$$

For oncoming drivers with parameters $H' \approx H$, $D' \approx D$, and $\frac{\Theta}{2} << \frac{H}{D}$:

$$W' \approx W + \Theta \cdot D$$

This is the spot size observed right at the projection, therefore the angular size is approximately $\frac{W'}{D'}$. For a laser with parameters of $W = 10\text{mm}$, $\Theta = 0.5\text{mrad}$; with a projection at $H = 1.5\text{mrad}$, $D = 100\text{m}$; and observed at: $H' = 1.2\text{m}$, $D' = 100\text{m}$:

$$S \approx \frac{10\text{mm} + 5 \cdot 10^{-4} * 100\text{m}}{\frac{1.5\text{m}}{100\text{m}} - \frac{5 \cdot 10^{-4}}{2}}$$
$$S \approx 4.07\text{m}$$
$$W' \approx 4.07\text{m} * \frac{1.2\text{m}}{100\text{m}}$$
$$W' \approx 4.8\text{cm}$$

The spot appears to only be 5cm tall, and viewed 100m away, has an angular size of 0.5 mrad.

E.3 Optical Safety

In the following examples we will also be deriving the safety qualities of an 'expected' usage of the laser projector.

The laser in this example is:

- 1W Peak

- 1.6KHz PWM

- 10% Duty

- 16μs to full power

- $\lambda = 655$nm

- $\theta_x = 5.6$mrad

- $\theta_y = 1.4$mrad

- Worst case distance to laser is 0.5m

- $W_x = 4.3$mm

- $W_y = 1$mm

The observer has:

- 7mm wide pupils

- 0.25s aversion response

Therefore in an exposure, we can expect 400 lasers pulses into the eye, each lasting 62.5μs. Since the time between pulses is greater than $t_{\min}(\lambda) = 18\mu$s, we count all the pulses as distinct.

E.3.1   Classification

The laser mentioned above is considered a Class 3b pulsed laser, however, Class 3b lasers cannot emit an average radiant power greater than 0.5W for more than 0.25s, or cannot produce radiant energy more than 0.125J within 0.25s, and cannot emit a radiant energy more than 0.03J per pulse. Therefore at 1.6KHz, the duty cycle cannot exceed 50%, as that would violate the first and second conditions. If the duty cycle exceed 50%, the laser is now a Class 4 Pulsed laser source.

E.3.2 Effective Divergence

Given a circular laser spot with radii r_x and r_y, and respective divergences θ_x and θ_y, the area of the spot at distance d is: $\pi * (r_x + d * \theta_x) * (r_y + d * \theta_y)$. If $d * \theta_x > r_x$ and $d * \theta_y > r_y$, we can aproximate the effective Divergence of the beam as $\sqrt{\theta_x \cdot \theta_y}$.

The effective divergance in our example laser is $\sqrt{5.6\text{mrad} \cdot 1.4\text{mrad}} = 2.8\text{mrad}$

E.3.3 Maximum Permissible Exposure

The Maximum Permissible Exposure is the limit of energy or power density on the eye before permanent damage can occur. Table 5a in (ANSI Z136.1-2000) gives us the MPE for our exposure limit (0.25s) and wavelength ($\lambda = 655nm$) at $1.8t^{0.75} \times 10^{-3}J \cdot cm^{-2}$. A pulsed correction factor C_p is needed due to the multiple pulses entering the eye before the observer can blink. $C_p = n^{-0.25}$.

Therefore the Maximum Permissible Exposure is:

$$MPE = 1.8t^{0.75} \times 10^{-3}\text{J} \cdot \text{cm}^{-2} \times n^{-0.25}$$

$$MPE = 1.8(0.25)^{0.75} \times 10^{-3}J \cdot cm^{-2} \times (400)^{-0.25}$$

$$MPE = 0.636\text{mJ} \cdot \text{cm}^{-2} \times .223 \tag{E.4}$$

$$MPE = 0.636\text{mJ} \cdot \text{cm}^{-2} \times .223$$

$$MPE = 0.141\text{mJ} \cdot \text{cm}^{-2}$$

E.3.4 Nominal Ocular Hazard Distance

Nominal ocular hazard distance r_{NOHZ} is the distance which the primary laser beam exceeds the MPE. Derived from ANSI Z136.1-2000 standard.

$$r_{\text{NOHZPrimary}} = \frac{1}{\phi} \left(\sqrt{\frac{1.27Q}{\text{MPE}} - A^2} \right)$$

- ϕ is the divergance of the primary beam

- Q is the Energy deposited in an exposure

- MPE is the maximum permissible exposure limit

- A is the beam diameter

With the example laser, $\phi = 2.8\text{mrad}$, $Q = 0.025\text{J}$, $MPE = 0.141\text{mJ} \times \text{cm}^{-2}$, $A^2 = 4.3\text{mm}^2$. Therefore the NOHZ is 53.6m.

When the laser is intersecting the road surface, it creates a lambertian diffuse reflection.

$$r_{\text{NOHZDiffuse}} = \left(\frac{\rho Q \cos \theta}{\pi \text{MPE}} \right)^{1/2}$$

Where θ is the observation angle, and ρ is the relflectivity of the pavement.

Using the Example laser, and worst-case viewing angle, and an asphalt reflectivity of 0.1 [Adrian and Jobanputra, 2005], and ignoring the large angular source factor:

$$r_{\text{NOHZDiffuse}} = \left(\frac{0.1 \times 0.025\text{J}}{\pi 0.141\text{mJ} \times \text{cm}^{-2} \times n^{-0.25}} \right)^{1/2}$$

(E.5)

$$r_{\text{NOHZDiffuse}} = 5\text{cm}$$

Diffuse reflections of asphalt have no significant NOHZ.

The Laser Range Nomogram (Figure C-4) can also be used to determine the minimum range given Energy output, radiant exposure, and beam divergence.

E.3.5   Interference Distances

Calculating the interference distancefor the primary beam is similar to calculating the NOHZ (Figure C-5).

$$r_{\text{NOHZPrimary}} = \frac{1}{\phi} \left(\sqrt{\frac{1.27Q}{\frac{EREL}{V(\lambda)} \times n^{-0.25}} - A^2} \right)$$

$$r_{\text{NOHZDiffuse}} = \left(\frac{\rho Q \cos\theta}{\pi \frac{EREL}{V(\lambda)} \times n^{-0.25}} \right)^{1/2} \tag{E.6}$$

We replace the MPE with the effective radiant exposure limit (EREL) (ANSI Z136.6-2000) divided by the photopic luminance efficiency coefficent, $V(\lambda)$. We still include the effect of multiple pulses though.

In the example, $V(\lambda = 655nm) = 0.075$.

For sensitive operations, the effective radiant exposure is 25×10^{-6}. Using the data in the example laser, sensitive operation range for the primary beam is 74 m. The sensitive operation range for diffuse reflections is 3.2 cm. Since the sensitive distance is less than the NOHZ, eye injury is more likely due to the lower sensitivity of the eye to this particular wavelength.

For critical operations, such as driving, the effective radiant exposure is 1.25×10^{-6}. Using the data in the example laser, the critical interference range for the primary beam is 325 m. The critical interference range for the diffuse reflection is 15 cm.

For laser-free operations, such as airport runways, the effective radiant exposure is 12.5×10^{-9}. Using the data in the example laser, the laser-free distance for the primary beam is 3.4 Km. The laser-free distance for the diffuse reflection is 150 cm.

Thus the main hazard is the primary beam and not the diffuse reflection.

Appendix F

Code Examples

```python
lc = lcm.LCM(ttl=1)
subscription = lc.subscribe("GALVO_CONTROLS", my_handler)
persist = True
while persist:
    try:
        valid_ports = checkPorts()
        GS = GalvoSerial(port=valid_ports[0], timeout=0.1,
            baudrate=9600, bytesize=EIGHTBITS, parity=
            PARITY_NONE, stopbits=STOPBITS_ONE)  #Establish
            Communications with port
        print(GS.enableGalvo())
        print("Galvo_Enabled")
        persist=False
    except KeyboardInterrupt:
        print('Cancelling_Port_detection_and_quitting')
        persist=False
    except Exception as e:
        print("Error_%s,_failure_to_open_stream,_retrying" %
            e)

print("LCM_started,_press_CTRL-C_to_terminate")

try:
    while True:
        lc.handle()
```

```
except KeyboardInterrupt:
    print("User_Keyboard_exit")
```

Listing F.2: LCM Package Handler

```
def my_handler(channel, data):
    intensity_factor = 0.01;
    msg = galvo_controls_t.decode(data)
    print("Received_message_on_channel_\"%s\"" % channel)
    for i in range(msg.size):
        print("____(time,_intensity,_theta1,_theta2)_____=_(%s
            ,_%s,_%s,_%s)" % (str(msg.angle_data[i][0]), str(
            msg.angle_data[i][1]), str(msg.angle_data[i][2]),
            str(msg.angle_data[i][3])))
    #print("Message Received")
        time_delay = msg.angle_data[i][0]
        intensity = msg.angle_data[i][1] * intensity_factor
        theta1 = msg.angle_data[i][2]
        theta2 = msg.angle_data[i][3]

    if(msg.size == 0):
        return
    elif(msg.size==1):
        print(GS.singleShot(theta1, theta2, intensity,
            time_delay))
    else:
        # Tell the microcontroller how large the data set is
        GS.stopOutputSequence();
        GS.setSequenceLength(msg.size)
        # Load X data
        X = column(msg.angle_data, 2)
        GS.loadData('X', X)
        # Load Y data
        Y = column(msg.angle_data, 3)
        GS.loadData('Y', Y)
        # Load I data
        I = column(msg.angle_data, 1)
        GS.loadData('INT', I)
        # Load T data
        T = column(msg.angle_data, 0)
        GS.loadData('T', T)
        # Start
        GS.startOutputSequence()
        GS.enableLaser()
    time.sleep(time_delay)
```

```
#define MAX_LENGTH 100
#define MAX_SPI_COM_LENGTH 5
#define T_GRANULE 100 // each bit of T corresponds to a wait
   time of 100 microseconds, max wait time of 6 seconds
#define LASER_LIMIT 28000    //The limit is defined as (
   Maximum current/ [2.3 Ampere/Volt])/ Peak Voltage * 2^16

uint16_t EEMEM X_Table[MAX_LENGTH], Y_Table[MAX_LENGTH],
   I_Table[MAX_LENGTH], T_Table[MAX_LENGTH];
uint16_t EEMEM table_length = 0, X_Single = 0, Y_Single = 0,
   I_Single=0, T_Single=0;        //internal memory

unsigned char debug = 1; // handshaking debugging allowed
volatile unsigned int eeprom_w1 = 0, eeprom_w2 = 0, eeprom_w3
   = 0, eeprom_w4 = 0;
volatile uint8_t run_state = 0, in_drawing_pattern = 0; //Run
   State
volatile RUN_STATE_T    run_state_enum  = E_STATE_STANDBY;
volatile uint16_t table_index = 0;

int main(void)
{
  DDRA = 0xFF;      //All pins are output by default
  DDRC = 0xFF;      //Enable !Sync line and !EN Line
  PORTC = 0xFF;
  SET(PORTA, PORTA4); // debug
  SET(PORTA, PORTA2); //debug
  wdt_init();       // Disable watchdog so it does not shut
     down the board;
  uart0_init();     //start USART
  USART_INT_ENABLE;        //enable interrupt vector on incoming
      character
  //SET(PCICR, PCIE0);  //A change on the enabled pins on
     PCINT 0-7 will trigger an interrupt
  //RTS means that the 232 is ready to receive signals from
     the controller
  //CTS_DISABLE;  CTS is the controller able to accept inputs

  spi_init();//Define SPI_PIN Outputs &START SPI
  sei();  //enable interrupts
  OE_DISABLE; // Disable the OE line
  LASER_DISABLE;
  //transmitByte('0');  //Chip is alive and communicating
```

```
while(1)
  {
    //Main Loop...
```

Listing F.4: Routine for Plotting a Point in a Series of Points

```
if (run_state_enum == E_STATE_SEQ_P_FIX_T || run_state_enum
    ==E_STATE_SEQ_P_VAR_T)     //If Run is not in the Halt
    State
        {
            USART_INT_DISABLE;  //Disable the interrupt
                vector while loading the data
            eeprom_w1 = eeprom_read_word(&X_Table[table_index
                ]);
            eeprom_w2 = eeprom_read_word(&Y_Table[table_index
                ]);
        eeprom_w3 = eeprom_read_word(&I_Table[table_index]);
        eeprom_w4 = eeprom_read_word(&T_Table[table_index]);
        USART_INT_ENABLE;

            DAC_writeBuffer(dac0_a, eeprom_w1);
            _delay_us(10);

            DAC_writeBufferUpdateAll(dac0_b, eeprom_w2);   //
                write Y
            _delay_us(10);

            //write I and update
            //not implemented in this test, parameters for I
                keep changing

        if(run_state_enum == E_STATE_SEQ_P_FIX_T){
          _delay_ms(1);
          SET(PORTA, PORTA7);
          _delay_ms(1);
          CLEAR(PORTA, PORTA7);
        }
        else if(run_state_enum == E_STATE_SEQ_P_VAR_T){
          for(uint16_t i = 0; i < eeprom_w4;i++){
            _delay_us(T_GRANULE);
          }
        }

        table_index++;
```

106

```
            if ( table_index >= eeprom_read_word(&table_length )
                )
            {
                table_index=0;
            }
```

Listing F.5: Serial Interrupt Routine

```
ISR(USART0_RX_vect)  /*If we get a message*/
{
    USART_INT_DISABLE;                  //disable USART INterrupt
        Vector
  DIAG_TOGGLE;
  //RTS_INT_DISABLE;                    /*Disable RTS external
    interrupt vector*/
    unsigned char verify = receiveByte(); //get verification
        character
unsigned char com_verify = 0;     //Command verify byte
//laser_enabled = false;            // disable laser as default
     ;
                        //send command to dim laser
    if (verify == '*')
    {
    transmitByte('V');   //Respond that correct command is
        received
        // if it matches the special character [ascii value
            of 0x2A], then do command split
        unsigned char command = receiveByte();

        //unsigned char c1, c2;
        switch(command)
        {
        case 0x00:     //Disable Outputs on DACs
        {
    transmitByte(command);     //send that command has been
        received
            DAC_stop();

    com_verify = '0';
            break;
        }
        case 0x01:     //Enable Outputs on DACs
        {
    transmitByte(command);     //send that command has been
        received
```

```c
                DAC_init () ;

    com_verify = '1';
            break;
        }
        case 0x02:      //Stop outputting data
        {
    transmitByte (command);      //send that command has been
        received
            run_state_enum=E_STATE_STANDBY;

    com_verify = '2';
            break;
        }

        case 0x03:      //Start outputting data to DACs
            sequentially, fixed time
        {
    transmitByte (command);      //send that command has been
        received
                run_state_enum=E_STATE_SEQ_P_FIX_T;

    com_verify = '3';
            break;
        }
        case 0x04:      //Start outputting data to DACs
            sequentially, variable time, intensity
        {
    transmitByte (command);      //send that command has been
        received
            run_state_enum=E_STATE_SEQ_P_VAR_T;

    com_verify = '4';
            break;
        }
case 0x05:      //Start outputting data to DACs
    sequentially, line segements, variable time/intensity
{
    transmitByte (command);      //send that command has been
        received
    run_state_enum=E_STATE_SEQ_TRACE;

    com_verify = '5';
    break;
}
```

```
case 0x0B:      //Set laser power source
{
  transmitByte(command);     //send that command has been
      received
  //unimlemented
  com_verify = 'S';
  break;
}
case 0x0C:      //flag allow laser
{
  transmitByte(command);     //send that command has been
      received
  //laser_enabled = true;
  LASER_ENABLE;
  com_verify = 'L';
  break;
}

case 0x0D:        //flag disable laser
{
  transmitByte(command);     //send that command has been
      received
  //laser_enabled = false;
  LASER_DISABLE;
  com_verify = 'O';
  break;
}

case 0x0F:        //reset controller
{
  transmitByte(command);     //send that command has been
      received
  run_state_enum = ESTATE_SHUTDOWN;
  com_verify = 'R';
  break;
}


//
// Block 0x1X concerns setting internal data
//

    case 0x10:     //set Table Length
```

```
{
transmitByte(command);        //send that command has been
    received
        unsigned int length = (unsigned int) receiveByte
            ();
        eeprom_update_word(&table_length, length);
        com_verify = 'A';
        break;
}


    case 0x11:        //Load table variables X, Y, Z, T
    {
transmitByte(command);        //send that command has been
    received
//transmitByte('C');
        uint16_t len = eeprom_read_word(&table_length);
unsigned char table = receiveByte();
transmitByte(table);
        for(uint16_t i = 0; i< len; i++)
        {
    eeprom_busy_wait();
            unsigned int temp = getIntFromSerial(debug);
    switch(table){
      case 0:
        eeprom_update_word(&X_Table[i], temp);
        break;
      case 1:
        eeprom_update_word(&Y_Table[i], temp);
        break;
      case 2:
        eeprom_update_word(&I_Table[i], temp);
        break;
      case 3:
        eeprom_update_word(&T_Table[i], temp);
        break;
      _delay_us(100);
    }
        }
table_index = 0;
in_drawing_pattern = 0;
com_verify = 'B'+table; //return that the table is
    completed
        break;
    }
```

```c
case 0x12:        //  Single  Shot ,  X, Y,  I ,  T
    {
    transmitByte(command);      //send  that  command  has  been
        received
    run_state_enum  =  E_STATE_SINGLE_P_VAR_T;
    //transmitByte ( 'D');
    unsigned int temp= 0;

    temp  =  getIntFromSerial(debug);
    eeprom_update_word(&X_Single ,  temp);

    temp  =  getIntFromSerial(debug);
    eeprom_update_word(&Y_Single ,  temp);

    temp  =  getIntFromSerial(debug);
    eeprom_update_word(&I_Single ,  temp);

    temp  =  getIntFromSerial(debug);
    eeprom_update_word(&T_Single ,  temp);

    com_verify  =  'T';
    break;
}
case 0x13:      //Clear  table  length
{
    transmitByte(command);      //send  that  command  has  been
        received
    eeprom_update_word(&table_length ,  0);
    run_state_enum  =  E_STATE_STANDBY;
    com_verify  =  'C';

}
case 0x14:      //Clear  all  data  from  tables  and  single
    shot  register
{
    transmitByte(command);      //send  that  command  has  been
        received
    for(int  i=0;  i< MAX_LENGTH;  i++)
    {
        eeprom_update_word(&X_Table[ i ] ,  0);
        eeprom_update_word(&Y_Table[ i ] ,  0);
        eeprom_update_word(&I_Table[ i ] ,  0);
        eeprom_update_word(&T_Table[ i ] ,  0);
    }
    eeprom_update_word(&X_Single ,  0);
```

```
    eeprom_update_word(&Y_Single , 0);
    eeprom_update_word(&I_Single , 0);
    eeprom_update_word(&T_Single , 0);
    run_state_enum=E_STATE_STANDBY;
    com_verify = 'C';
    break;
}


//
// Block 0x3X concerns returning state data , the driver
    will get the data on length and message
//


case 0x30:      //return state
{
    transmitByte(command);      //send that command has been
        received
    transmitByte(1); // how long the data is
    transmitByte(run_state);
    transmitByte('S');
    break;
}
case 0x31:      // Get table length
{
    transmitByte(command);      //send that command has been
        received
    transmitByte(1); // how long the data is
    uint16_t len = eeprom_read_word(&table_length);
    transmitByte((unsigned char) len&0xFF );
    com_verify = 'L';
    break;
}

case 0x32:      //read table data
{
    transmitByte(command);      //send that command has been
        received
    unsigned char table = receiveByte();
    uint16_t len = eeprom_read_word(&table_length);
    unsigned char t1 = (unsigned char) len & 0xFF;
    t1 <<= 1; //multiply table by 2
    transmitByte(t1); //We are ready to send packet size t1
        , the computer should be robust enough to get all of
```

112

```c
          the data
    uint16_t temp= 0;
    for(uint16_t i = 0; i< len; i++)
    {
      temp=0;
      switch(table)
      {
        case 0x00:      //xtable
        temp = eeprom_read_word(&X_Table[i]);
        break;

        case 0x01:      //ytable
        temp = eeprom_read_word(&Y_Table[i]);
        break;

        case 0x02:      //Itable
        temp = eeprom_read_word(&I_Table[i]);
        break;

        case 0x03:      //T table
        temp = eeprom_read_word(&T_Table[i]);
        break;
      }
      transmitByte((unsigned char) (temp>>8));
      transmitByte((unsigned char) (temp&0xFF));
    }
    com_verify = 'D';
    break;
}


//
// Block 0x4X concerns diagnostics
//


case 0x40:    // Echo data back, this needs to work
{
  transmitByte(command);      //send that command has been
        received
  unsigned char temp = requestByte();
  com_verify = temp;
  break;
}
```

```
//
// Un-allocated commands are errors!
//

     default:
         {
       transmitByte(command);        //send that command has been
           received
               com_verify = 'Z';  //FAILED COMMAND
               break;
         }
         }
     transmitByte(com_verify);  //Reply that the command was
         successful, final sync block
     }
     else
     {
         //if it fails, reply that the sending of code failed
         transmitByte('Z');  //FAILED COMMAND
     }

   //RTS_INT_ENABLE; //enable RTS interrupt vector

     USART_INT_ENABLE; //enable USART interrupt vector
}
```

Listing F.6: Serial Handler

```
from serial import Serial
import math
class GalvoSerial(Serial):
    '''

    classdocs
    '''

    channel_x = 0
    channel_y = 1
    channel_i = 2
    channel_t = 3
    verify = '*'
    verify_response = 'V';
    MAXLENGTH=100
    angular_scale=2.0
    peak_voltage=5.0
    bits=16
    turn_on_current=1.9
```

114

```python
watts_amp = 0.81        #Laser Wattage per amp of current RED
    LASER FC COUPLED
amps_volt = 2.3         #Current to Laser based on input
    voltage
watts_volt = watts_amp * amps_volt
max_watt = 0.1          # Maximum power allowed
REVERSE_X = True;
REVERSE_Y = False;


def sendMessage(self, message, response=False, debug=
    False, handshake=False):
    buffer =[]
    self.write(self.verify.encode(encoding='utf_8'))
    if self.read() == self.verify_response:
        for word in message:
            self.write(bytearray([word]))
            if debug:
                print(word)
            if handshake:
                print(self.read())
        if response:
            try:
                length = ord(self.read())        #get the
                    length of the response message
                if debug:
                    print(length)
                for i in range(length):
                    buffer.append(ord(self.read()))
            except:
                return buffer
            buffer.append(self.read())    #read the final
                termination byte
        return buffer

def disableGalvo(self):
    return self.sendMessage([0x00])


def enableGalvo(self):
    return self.sendMessage([0x01])


def startOutputSequence(self, var_time = False):
    message = [0x03] if not var_time else [0x04]
    return self.sendMessage(message)


def stopOutputSequence(self):
```

```python
        return self.sendMessage([0x02])




    def setSequenceLength(self, length):
        length = min(max(1, length), self.MAXLENGTH)
        return self.sendMessage([0x10, (length>>8)&0xFF,
            length])


    def loadSequence(self, channel, sequence, d=False):
        message = [0x11, channel]
        for item in sequence:
            message.append((item>>8) & 0xFF)
            message.append(item & 0xFF)
        print(str(message))
        return self.sendMessage(message, debug=d, handshake=
            True)


    def loadData(self, channel, sequence, d=False):
        if channel=='x' or channel=='X' or channel==self.
            channel_x:
            if self.REVERSE_X:
                sequence = [-1.0*i for i in sequence]
            self.loadSequence(self.channel_x, [self.
                angle_to_binary(x) for x in sequence], d)
        elif channel=='y' or channel == 'Y' or channel==self.
            channel_y:
            if self.REVERSE_Y:
                sequence = [-1.0*i for i in sequence]
            self.loadSequence(self.channel_y, [self.
                angle_to_binary(y) for y in sequence], d)
        elif channel=='Z' or channel == 'I' or channel=='INT'
            or channel=='Intensity' or channel==self.
            channel_i:
            self.loadSequence(self.channel_i, [self.
                intensity_to_binary(i) for i in sequence], d)
        elif channel=='T' or channel == 'Time':
            self.loadSequence(self.channel_t, [self.
                time_to_binary(t) for t in sequence], d)
        else:
            print('Undefined channel!')
            return 0
        return 1
    def setCoordinates(self, x_angle, y_angle):
        x_bin = int(2**(self.bits-1) * (x_angle/(2.0*self.
```

```
            angular_scale*self.peak_voltage) + 1))
        x_bin = min(max(x_bin, 0), 2**self.bits-1)

        y_bin = int(2**(self.bits-1) * (y_angle/(2.0*self.
            angular_scale*self.peak_voltage) + 1))
        y_bin = min(max(y_bin, 0), 2**self.bits-1)
        message= [0x12] + self.byte_chunk(x_bin, self.bits) +
            self.byte_chunk(y_bin, self.bits)
        return self.sendMessage(message, handshake=True)

    def setIntensity(self, intensity_watt):
        i_bin = int(2**self.bits * (min(intensity_watt, self.
            max_watt)/self.watts_amp + self.turn_on_current)/
            (self.amps_volt*self.peak_voltage))
        message = [0x13]
        message = message + self.byte_chunk(i_bin, self.bits)
        return self.sendMessage(message, long_response=False,
            handshake=True)




    def enableLaser(self):
        return self.sendMessage([0x0C])

    def disableLaser(self):
        return self.sendMessage([0x0D])


    def singleShot(self, x_angle, y_angle, intensity_watt,
        duration):
        if self.REVERSE_X:
            x_angle = -1.0*x_angle
        if self.REVERSE_Y:
            y_angle = -1.0*y_angle
        x_bin = int(2**(self.bits-1) * (x_angle/(2.0*self.
            angular_scale*self.peak_voltage) + 1))
        x_bin = min(max(x_bin, 0), 2**self.bits-1)
        print("X_binary_=_%s" % x_bin)
        y_bin = int(2**(self.bits-1) * (y_angle/(2.0*self.
            angular_scale*self.peak_voltage) + 1))
        y_bin = min(max(y_bin, 0), 2**self.bits-1)
        print("Y_binary_=_%s" % y_bin)
        i_bin = int(2**self.bits * (min(intensity_watt, self.
            max_watt)/self.watts_amp + self.turn_on_current)/
```

```python
            (self.amps_volt*self.peak_voltage))
        print("Intensity_binary_=_%s" % i_bin)
        t_bin = min(max(int(duration * 2000),0), 2**self.bits
            -1) #500 useconds per digitial unit
        print('Time_binary_=_%s' % t_bin)
        message= [0x12] + self.byte_chunk(x_bin, self.bits) +
            self.byte_chunk(y_bin, self.bits) + self.
            byte_chunk(i_bin, self.bits) + self.byte_chunk(
            t_bin, self.bits)
        return self.sendMessage(message, handshake=True)
        pass


    def getState(self):
        return self.sendMessage([0x30], response=True)

    def getSequenceLength(self):
        return self.sendMessage([0x31], response=True)

    def getSequence(self, channel):
        return self.sendMessage([0x10, channel], response=
            True)

    def echo(self, letter):
        return self.sendMessage([0x40, ord(letter)], response
            =False)           #the Verify byte is the letter sent
            , not considered a response since it does not read
            internal state

    def byte_chunk(self, num, length, byte_length=8):
        output = []
        mask = 2**byte_length-1
        chunks = int(math.ceil(length / (byte_length * 1.0)))
        for segment in range(chunks):
            shift_mask = mask<<(byte_length*(chunks-segment
                -1))
            data = shift_mask & num
            data = data>>(byte_length*(chunks-segment-1))
            output.append(data)
        return output

    def angle_to_binary(self, angle):
        ang_bin = int(2**(self.bits-1) * (angle/(2.0*self.
            angular_scale*self.peak_voltage) + 1))
        ang_bin = min(max(ang_bin, 0), 2**self.bits-1)
```

```python
        return ang_bin

    def intensity_to_binary(self, intensity): #Assumes linear
        mapping between intensity and binary code
        i_bin = int(2**self.bits * (min(intensity, self.
            max_watt)/self.watts_amp + self.turn_on_current)/
            (self.amps_volt*self.peak_voltage))
        i_bin = min(max(i_bin, 0), 2**self.bits -1)
        print("Intensity binary = %s" % i_bin)
        return i_bin

    def time_to_binary(self, time):
        t_bin = min(max(int(time * 10000),0), 2**self.bits -1)
            #500 useconds per digitial unit
        return t_bin
    def limit(self, num, lower=0, upper=2**bits -1):
        return min(max(num, lower), upper)

    def purge(self):
        return self.write(bytes([0xFF]))
```

Listener

```
Find Serial Port
        ↓
Connect to Projector
        ↓
LCM Package Received?  ─────┐
        ↓                   │
Parse LCM package           │
        ↓                   │
Set State=STANDBY           │
        ↓                   │
Set Table Length            │
        ↓                   │
Write X Table               │
        ↓                   │
Write Y Table               │
        ↓                   │
Write I Table               │
        ↓                   │
Write T Table               │
        ↓                   │
Set State =                 │
SCAN_POINTS  ───────────────┘
```
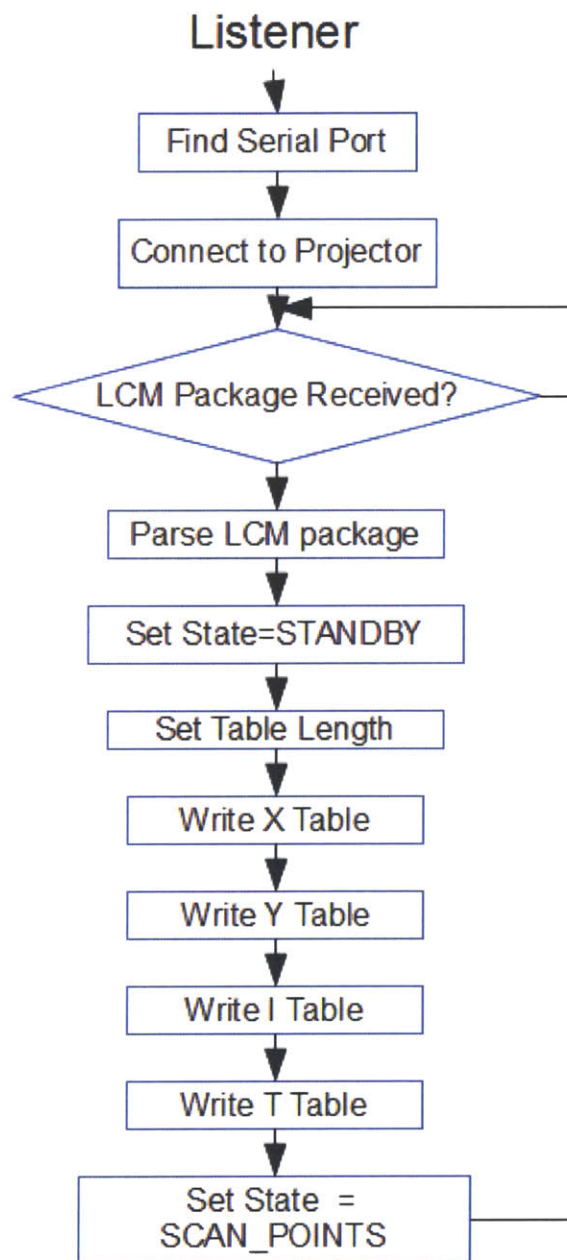
Figure F-1: Listener Program Flow

Project Next Point

```
                    ┌─────────────────┐
                    │ Table length > 0?│──── No ────┐
                    └─────────────────┘             │
                            │                        │
                           Yes                       │
                    ┌─────────────────┐             │
                    │ Disable Interrupts│            │
                    └─────────────────┘             │
                            │                        │
        ┌──────────────────────────────────────┐   │
        │ Get Point Data <X[i],Y[i],I[i],T[i]>  │   │
        │ from EEPROM Tables                     │   │
        └──────────────────────────────────────┘   │
                            │                        │
                    ┌─────────────────┐             │
                    │ Enable Interrupts │            │
                    └─────────────────┘             │
                            │                        │
                ┌──────────────────────┐            │
                │ Write X[i] and Y[i] to DAC│        │
                └──────────────────────┘            │
                            │                        │
                    ┌─────────────────┐             │
                    │ Enable Laser     │             │
                    └─────────────────┘             │
                            │                        │
                    ┌─────────────────┐             │
                    │ Wait T[i]*100us  │             │
                    └─────────────────┘             │
                            │                        │
                    ┌─────────────────┐             │
                    │ Disable Laser    │             │
                    └─────────────────┘             │
                            │                        │
                    ┌─────────────────┐             │
                    │ Get next index i │             │
                    └─────────────────┘             │
                            │                        │
                    ┌─────────────────┐             │
                    │     Return       │◄────────────┘
                    └─────────────────┘
```
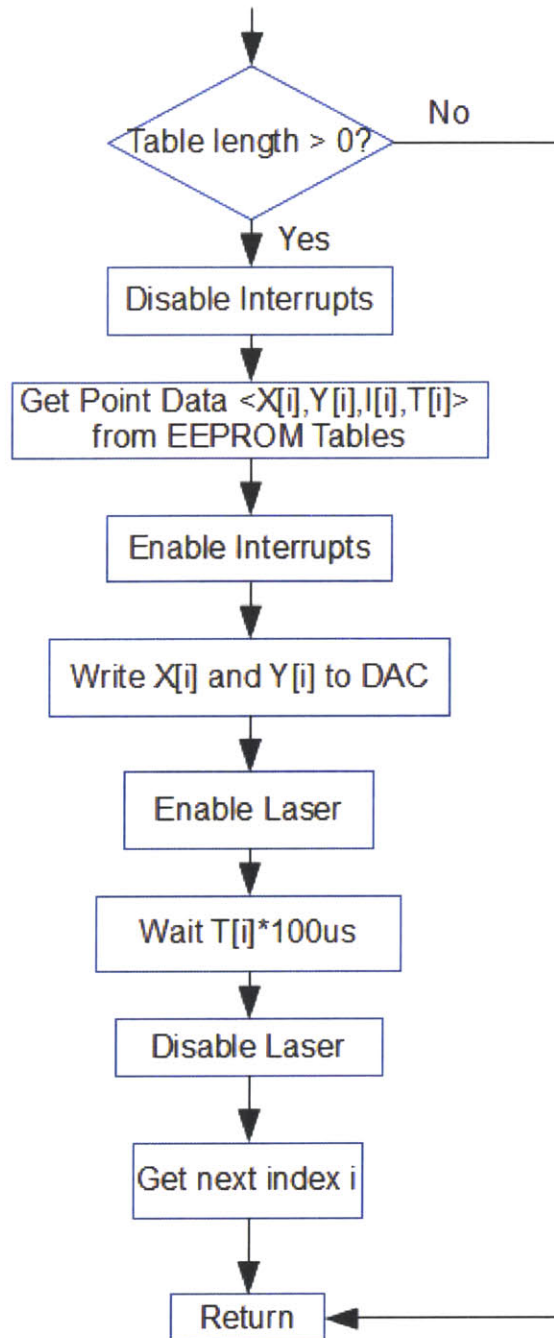
Figure F-2: Scanning Sequential Points Program Flow
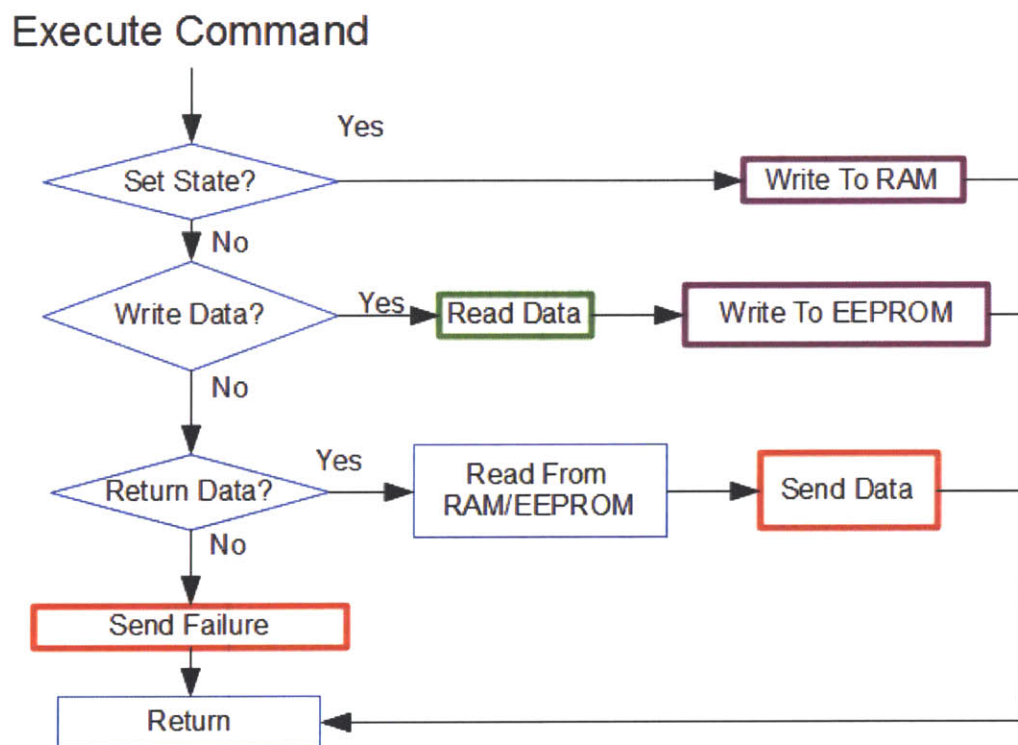
Figure F-3: Command Parser Flow

Internal Operation

```
┌──────────┐
│   Boot   │
│ Sequence │
└────┬─────┘
     │
  ┌──▼───────┐
  │ Main Loop│
  └──────────┘
```

Boot Sequence

```
┌─────────────────────┐
│  State = STANDBY     │
└──────────┬──────────┘
           ▼
┌─────────────────────┐
│ Send X, Y Galvos to 0,0│
└──────────┬──────────┘
           ▼
┌─────────────────────┐
│ Scan Table Length = 0│
└──────────┬──────────┘
           ▼
┌─────────────────────┐
│ Initialize Serial Port│
└──────────┬──────────┘
           ▼
┌─────────────────────┐
│ Enable Serial Interrupt│
└──────────┬──────────┘
           ▼
      ┌────────┐
      │ Return │
      └────────┘
```

Main Loop

State = STANDBY? — Yes → Set Galvos to 0,0 / Wait 100 us

No ↓

State = SEQ_POINTS? — Yes → Project Next Point

No ↓

State = LINE_SEG? — Yes → Project Next Line Segment

No ↓

State = STANDBY → Return
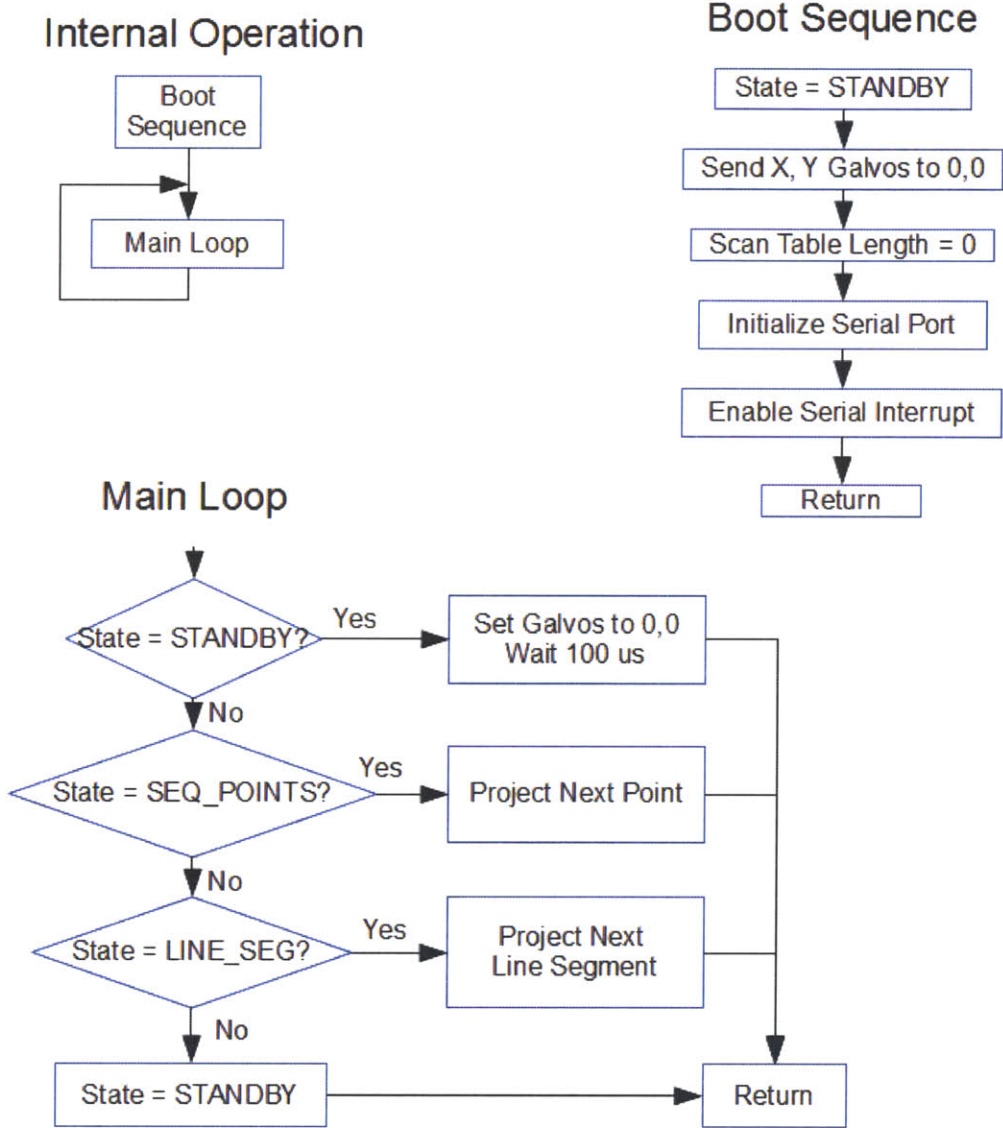
Figure F-4: Controller Program Flow

Byte Received

```
┌──────────────────┐
│ Serial Interrupt │
│     Process      │
└──────────────────┘
         │
         ▼
┌──────────────────┐
│     Resume       │
│  Main Process    │
└──────────────────┘
```

Serial Interrupt Process

```
┌──────────────────┐
│     Disable      │
│ Serial Interrupt │
└──────────────────┘
         │
         ▼
┌──────────────────┐
│  Disable Laser   │
└──────────────────┘
         │
         ▼
┌──────────────────┐
│    Read Byte     │
└──────────────────┘
         │
         ▼
      ╱Byte =╲            No
    ╱ Validation Byte? ╲────────────┐
      ╲            ╱                 │
         │ Yes                       │
         ▼                           │
┌──────────────────┐                 │
│ Send Validation  │                 │
└──────────────────┘                 │
         │                           │
         ▼                           │
┌──────────────────┐                 │
│ Read Command Byte│                 │
└──────────────────┘                 │
         │                           │
         ▼                           │
   ╱Command Byte valid?╲   No         │
    ╲                 ╱───────────────┤
         │ Yes                        │
         ▼                            ▼
┌──────────────────┐          ┌──────────────────┐
│ Send Command Byte│          │   Send Failure   │
└──────────────────┘          └──────────────────┘
         │                            │
         ▼                            │
┌──────────────────┐                  │
│ Execute Command  │                  │
└──────────────────┘                  │
         │                            │
         ▼                            │
┌──────────────────┐                  │
│      Send        │                  │
│ Termination Byte │                  │
└──────────────────┘                  │
         │                            │
         ▼                            │
┌──────────────────┐                  │
│     Enable       │◄─────────────────┘
│ Serial Interrupt │
└──────────────────┘
```
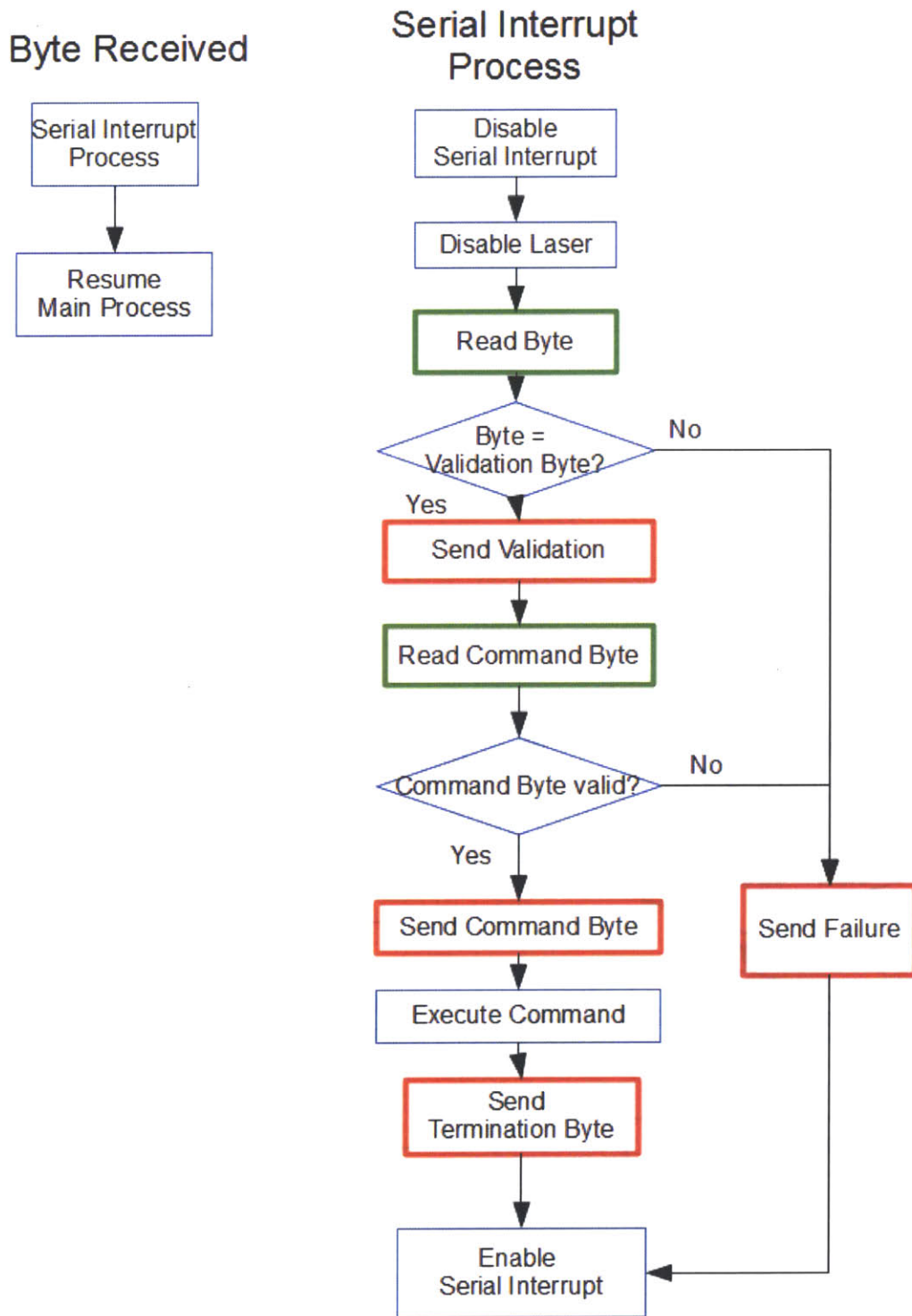
Figure F-5: Interrupt Routine Flow

124

Bibliography

W. Adrian and R. Jobanputra. Influence of pavement reflectance on lighting for parking lots. *PCA R&D Serial 2458*, 2005.

Kenneth R. Agent and Jerry G. Pigman. Accidents involving vehicles parked on shoulders of limited access highways. *Transportation Research Record*, 1270:3–11, 1990.

American National Standards Institution. American national standard for safe use of lasers. Technical report, Laser Institute of America, Orlando, FL, 2000a.

American National Standards Institution. American national standard for safe use of lasers outdoors. Technical report, Laser Institute of America, Orlando, FL, 2000b.

K. Barat. *Laser Safety Management*. CRC Press, Boca Raton, FL, 2006.

J. Berkhout. Information transfer characteristics of moving light signals. *Human Factors*, 21(4):445–455, 1979.

J. D. Bullough, M. S. Rea, R. M. Pysar, H. K. Nakhla, and D.E. Amsler. Paper #14, rear lighting configurations for winter maintenance vehicles. In *Proc. Illuminating Engineering Society of North America Annual Conference*, pages 87–94, August 2001a.

J. D. Bullough, J. Van Derlofske, and H. Yan. Evaluation of automotive stop lamps using incadescent and sweeping neon and led sources. In *Lighting Technology Developments for Automobiles, SP-1595*, pages 87–94, Warrendale, PA, March 2001b. Society of Automotive Engineers.

J. D. Bullough, H. Yan, and J. Van Derlofske. Effects of sweeping, color and luminance distribution on response to automotive stop lamps (reprint of SAE paper 2002-01-0911). *Society of Automotive Engineers Transactions Journal of Passenger Cars - Mechanical Systems*, 111(6):1294–1298, January 2002.

Michael T. Charles, John Crank, and David N. Falcone. *A Search for Evidence of the Fascination Phenomenon in Roadside Accidents*. AAA Foundation for Traffic Safety, 1990.

B. Clark, M. A. Nicholson, and A. Graybiel. Fascination: A cause of pilot error. *Aviation Medicine*, pages 429–440, October 1953.

T. A. Croft. Failure of visual estimation of motion under strobe. *Nature*, 231(302): 397, June 1971.

Food and Drug Administration Center for Devices and Radiological Health. Fda 21 cfr 1040.10 - laser products. `http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=1040.10`, April 2012.

A.K Ganguly. *Optoelectroniic Devices and Circuits*. Alpha Science International Ltd, Oxford, UK, 2007.

Martin Helander. Drivers' steering behavior during traffic events: A case of perceptual tropism? *Human Factors*, 6(20):681–690, 1978.

K. Jiang, K. Yu, and Y. Zhao. Investigations of the dynamics of road pavement reflectance. *Chinese Optics Letters*, 10(4), April 2012.

F. Kitamura, K. Matsunaga, and I. Nagao. Influence of looking at hazard lights on car-driving performance. *Perceptual and Motor Skills*, 78(3 part 2):1059–1065, 1994. ISSN 0031-5125.

Kustom Signals. Police Lidar & Radar, Video Surveillance, Speed Monitoring & Detection Devices. `http://www.kustomsignals.com/product\_body2.asp?product\_id=89\&cat\_id=8\&strpagename=fixedmount`, 2011.

W. J. Marshall. Laser reflections from relatively flat specular surfaces. In D. H. Sliney, editor, *Selected Papers on Laser Safety*, volume MS117 of *SPIE Milestone Series*, Bellingham, WA, 1995. SPIE, SPIE Optical Engineering Press.

Massachusetts Department of Public Health. 105 cmr 121 - to control the radiation hazards of lasers, laser systems and optical fiber communication systems utilizing laser diode or light emitting diode sources. `http://www.lawlib.state.ma.us/source/mass/cmr/cmrtext/105CMR121.pdf`, 1997.

R. G. Mortimer. Requirements for automotive exterior lighting. *Visual Factors in Transportation Systems*, 1969.

Occupational Safety and Health Administration. Osha 29 cfr 1926.54 - nonionizing radiation. `http://www.osha.gov/pls/oshaweb/owadisp.show\_document?p\_id=10627\&p\_table=STANDARDS`, 1993.

P. L. Olson. *Vision and perception*. Taylor and Francis, London, 1993.

Wilson O. Readinger, Astros Chatziastros, Douglas W. Cunningham, Heinrich H. Bulthoff, and James E. Cutting. Gaze-eccentricity effects on road position and steering. *Journal of Experimental Psychology: Applied*, 8:247–258, 2002.

Matthew R. Smith, John M. Flach, Scott M. Dittman, and Terry Stanard. Monocular optical constraints on collision control. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2):395–419, April 2001.

Stephen S. Solomon and George L. Ellis. *Emergency vehicle accidents: Prevention and reconstruction.* Lawyers and Judges Press, Tucson, AZ, 1999.

U.S. Department of Justice, Federal Bureau of Investigation, Criminal Justice Information Services Divison. Law Enforcement Officers Killed and Assualted (Table 61: Law Enforcement Officers Accidentally Killed; Circumstance at Scene of Incident, 2000–2009). `http://www2.fbi.gov/ucr/killed/2009/data/table\_61.html`, 2009.

U.S. Department of Transportation Federal Avaiation Administration. Faa order 7400.2h - outdoor laser operations. `http://www.faa.gov/air_traffic/publications/atpubs/AIR/air2901.html`, February 2012a. Last updated 3/7/13.

U.S. Department of Transportation Federal Avaiation Administration. Notice of proposed outdoor laser use. `http://www.faa.gov/documentLibrary/media/form/faa7140-1.pdf`, February 2012b.