A Low-Cost Laser Positioning Apparatus and UUV for Ship Hull Analysis

By

Hunter Crenshaw Brown

Bachelor of Science
Applied Mathematics
North Carolina State University
2003

A thesis submitted to
Florida Institute of Technology
in partial fulfillment of the requirements
for the degree of

Master of Science
in Ocean Engineering

Melbourne, Florida
August, 2006
We the undersigned committee hereby approve the attached thesis

A Low-Cost Laser Positioning Apparatus and UUV for Ship Hull Analysis

by
Hunter Crenshaw Brown

George A. Maul, Ph.D.
Professor
DMES
Department Head

Stephen Wood, Ph.D., P.E.
Assistant Professor
Ocean Engineering
Committee Chair

Geoffrey Swain, Ph.D.
Professor
Ocean Engineering

Hector Gutierrez, Ph.D., P.E.
Associate Professor
Mechanical Engineering
Abstract

Title:
A Low-Cost Laser Positioning Apparatus and UUV for Ship Hull Analysis

Author:
Hunter Crenshaw Brown

Principle Advisor:
Stephen Wood, Ph.D.

In the maritime shipping, cruise, and naval industries, vast expenditures are made in fuel costs that could be saved by implementing more efficient ship-husbandry techniques. A system that allows a quick, accurate, and low-cost quantitative and qualitative analysis of the condition of a vessel’s hull has been designed to promote better decisions resulting in time and financial savings.

New underwater vehicles have flooded the commercial markets, but there is a distinct dearth of vehicles that include both forward-looking and side-looking cameras combined with the necessary equipment to perform visual ship hull analysis. Several systems are available that include vehicles that cling to the hull and use a stylus to record roughness, but there are very few that can perform quick visual scans.

The Center for Corrosion and Biofouling Control (CCBC) at the Florida Institute of
Technology (FIT) is currently testing various biocide and antifouling hull coatings, while also building an image database for hull condition quantization. The Underwater Technologies Laboratory (UTL) at FIT is in an excellent position to provide the means for acquiring real-world images of hull conditions through the development of a new ROV/AUV and thereby extend the work of the CCBC. The vehicle for accomplishing this was designed using state-of-the-art CAD software, new microcontrollers and circuitry, and a new laser distance and orientation apparatus.

A low-cost (under $5,000) ROV/AUV was designed with side-looking capabilities and a new laser distance-and-orientation apparatus. The laser device was created to be very low cost (under $70) and versatile so it can be used for other tasks such as normal video recording.

This work describes the design and creation of the laser distance-and-orientation apparatus and a vehicle, the SVK-1 ("Scout"), that provides such images. The vehicle will also serve the Department of Marine and Environmental Systems (DMES) by generating interest in marine technology and marine environments, and by providing new, unique teaching capabilities through field usage on the Delphinus. The low-cost laser distance-and-orientation sensor includes proof-of-concept software and will serve as a baseline for future research.
5.5.6 SVK-0007-Shell .................................................. 84
5.5.7 SVK-0008-Sled .................................................. 85
5.5.8 SVK-0009-Sled Wheels ........................................ 85
5.5.9 SVK-0010-Sled Wheel Support Rail ......................... 86
5.5.10 SVK-0011-Camera Tilt Mount ............................... 86
5.5.11 SVK-0012-End Cap Mounting Flange ....................... 87
5.6 Chapter References ............................................... 88

6 Conclusions .......................................................... 90
  6.1 Laser Apparatus .................................................. 90
  6.2 Image Processing ............................................... 92
  6.3 Vehicle and Tether ............................................. 92
  6.4 Software ....................................................... 93

7 Future Work ......................................................... 95
  7.1 Laser Apparatus .................................................. 95
  7.2 Image Processing ............................................... 96
  7.3 Vehicle and Tether ............................................. 96
  7.4 Simulation ..................................................... 97
  7.5 Control .......................................................... 97

References ........................................................... 98

Appendices ........................................................... 101
  A ROV User Notes .................................................. 102
    A.1 Setup ......................................................... 102
    A.2 Testing ...................................................... 102
    A.3 Maintenance ............................................... 103
  B Definitions and Explanations .................................. 103
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1 RS-232 Communication</td>
<td>103</td>
</tr>
<tr>
<td>B.2 Fiber-Optic Communication</td>
<td>104</td>
</tr>
<tr>
<td>C Code</td>
<td>104</td>
</tr>
<tr>
<td>C.1 Simple Linear Least-Squares Regression</td>
<td>104</td>
</tr>
<tr>
<td>C.2 Multiple Linear Least-Squares Regression</td>
<td>107</td>
</tr>
<tr>
<td>C.3 Simple Linear Least Squares for Parabola Matching</td>
<td>109</td>
</tr>
<tr>
<td>D Mechanical Drawings</td>
<td>111</td>
</tr>
<tr>
<td>E Circuits</td>
<td>127</td>
</tr>
<tr>
<td>F Least-Squares Estimation</td>
<td>131</td>
</tr>
<tr>
<td>G Software Tools</td>
<td>132</td>
</tr>
<tr>
<td>H Appendix References</td>
<td>133</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Scout Vehicle K-1 .................................................. 4

2.1 Laser Apparatus ...................................................... 7
2.2 Laser Attachment Bracket ........................................ 8
2.3 CCD Camera .......................................................... 9
2.4 Comparison of 2nd degree and 3rd degree LSE .............. 20
2.5 Residuals for Actual LSE .......................................... 21
2.6 Comparison of Distance Techniques ............................ 23
2.7 Results of Remapped Comparison ............................... 26
2.8 Point and Cubic Function ........................................... 30
2.9 Laser Spot & Cloud Size .......................................... 35
2.10 Laser Estimation Model .......................................... 38
2.11 Hough - Original .................................................. 42
2.12 Hough - Edge Finding ............................................. 44
2.13 Hough - Average .................................................. 46
2.14 Hough - Edge Finding ............................................. 47
2.15 Hough - Hough Transform ....................................... 48
2.16 Hough - Results .................................................. 50
2.17 Technique #1 (left) and Technique #2 (right) results for 36in image. 55
2.18 Laser Reflection Points ........................................... 56
3.1 Gemini Joystick .................................................. 60
3.2 Universal Control System ....................................... 61
3.3 Control Suite Screenshot ......................................... 63
3.4 Master Control .................................................... 65
3.5 Joystick Control .................................................. 66
3.6 Communication Window .......................................... 67
3.7 Sensor Display ................................................... 68
3.8 Joystick Setup .................................................... 69

4.1 Tether Termination ............................................... 72
4.2 Tether .............................................................. 74

5.1 SVK-1 Main Body .................................................. 77

1  SVK-0001 - Main Pressure Housing ............................ 113
2  SVK-0002 - Clear Viewport ..................................... 114
3  SVK-0003 - Removable End Cap ................................. 115
4  SVK-0004 - Side Motor Attachment Bracket .................. 116
5  SVK-0005 - Rear Motor Attachment Bracket .................. 117
6  SVK-0006 - Shell Bracket ........................................ 118
7  SVK-0007 - Protective Shell ...................................... 119
8  SVK-0008 - Internal Electronics Sled .......................... 120
9  SVK-0009 - Sled Wheel ........................................... 121
10 SVK-0010 - Sled Rail Support ................................... 122
11 SVK-0011 - Side-Looking Camera Mount ...................... 123
12 SVK-0012 - End-Cap Mounting Flange ......................... 124
13 Internal Sled Assembly ............................................ 125
14 SVK-1 Assembly .................................................... 126
15 UCS Circuit Diagram .............................................. 127
16 Com Board Schematic ........................................ 128
17 Sensor Board Schematic ........................................ 129
18 Video Motor Board Schematic ................................. 130
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Math Engine Least-Squares Check Dataset</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Math Engine Least-Squares Check Results</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>Residuals from Two-Calibration Image Set</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>Residuals from Three-Calibration Image Set</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>Residuals from Three-Calibration Image Set</td>
<td>14</td>
</tr>
<tr>
<td>2.6</td>
<td>Residuals from Three-Calibration Image Set</td>
<td>14</td>
</tr>
<tr>
<td>2.7</td>
<td>Residuals from Four-Calibration Image Set</td>
<td>14</td>
</tr>
<tr>
<td>2.8</td>
<td>Residuals from Four-Calibration Image Set</td>
<td>15</td>
</tr>
<tr>
<td>2.9</td>
<td>Residuals from Five-Calibration Image Set</td>
<td>15</td>
</tr>
<tr>
<td>2.10</td>
<td>Residuals from Six-Calibration Image Set</td>
<td>15</td>
</tr>
<tr>
<td>2.11</td>
<td>Residuals from Seven-Calibration Image Set</td>
<td>15</td>
</tr>
<tr>
<td>2.12</td>
<td>Residuals from Eight-Calibration Image Set</td>
<td>16</td>
</tr>
<tr>
<td>2.13</td>
<td>Average Results for 2nd Degree LSE on 3-Image Sets</td>
<td>17</td>
</tr>
<tr>
<td>2.14</td>
<td>Average Results for 3rd Degree LSE on 3-Image Sets</td>
<td>17</td>
</tr>
<tr>
<td>2.15</td>
<td>Average Results for 3rd Degree LSE on 4-Image Sets</td>
<td>17</td>
</tr>
<tr>
<td>2.16</td>
<td>Average Results for 3rd Degree LSE on 5-Image Sets</td>
<td>18</td>
</tr>
<tr>
<td>2.17</td>
<td>Average Results for 3rd Degree LSE on 6-Image Sets</td>
<td>18</td>
</tr>
<tr>
<td>2.18</td>
<td>Average Results for 3rd Degree LSE on 7-Image Sets</td>
<td>18</td>
</tr>
<tr>
<td>2.19</td>
<td>Average Results for 3rd Degree LSE on 8-Image Sets</td>
<td>18</td>
</tr>
<tr>
<td>2.20</td>
<td>Average Results for 3rd Degree LSE on 9-Image Sets</td>
<td>18</td>
</tr>
</tbody>
</table>
2.21 Average Results for 3rd Degree LSE on 10-Image Set .......................... 19
2.22 Distance Estimation Comparison ...................................................... 22
2.23 ANOVA of Three Laser Location Methods ........................................... 27
2.24 ANOVA of Three Laser Location Methods ........................................... 27

4.1 Cable Drag Constants ........................................................................... 73

5.1 Construction Notes ............................................................................... 83
5.2 Parts List .............................................................................................. 87

6.1 Laser RangeFinder Comparison ............................................................ 91
List of Keywords

Autonomous Underwater Vehicle
AUV
Camera
Department of Marine and Environmental Systems
Distance
Florida Institute of Technology
Hull Inspection
Laser
Rangefinder
Remotely Operated Vehicle
ROV
Simulation
Submersible
Submarine
Underwater Technologies Laboratory
Underwater Robotics
Underwater Vehicle
List of Abbreviations

ABS - American Bureau of Shipping
ASME - American Society of Mechanical Engineers
AUV - Autonomous Underwater Vehicle
CAD - Computer Aided Design
CAN - Controller Area Network
CCBC - Center for Corrosion and Biofouling Control
CCD - Charge-Coupled Device (Camera)
CTD - Conductivity, Temperature, Depth
DMES - Department of Marine and Environmental Systems
FIT - Florida Institute of Technology
FOV - Field of View
FS (F.S.) - Factor of Safety
GUI - Graphical User Interface
IC - Integrated Circuit
LNG - Liquid Natural Gas
NTSC - National Television Standards Committee
PCB - Printed Circuit Board
PIC - Microchip PicMicro Microcontroller
PMMA - Polymethyl Methacrylate
RCA - Radio Corporation of America
ROV - Remotely Operated Vehicle
TTL - Transistor-Transistor Logic
UCS - Universal Control System
USB - Universal Serial Bus
USN - United States Navy
UTL - Underwater Technologies Lab
UUV - Unmanned Underwater Vehicle
VB - Visual Basic
List of Symbols and Units

A - Amp(s)
cm - Centimeter(s)
dpi - Dot(s) per inch
f - Farrad(s)
fps - Frames per second
fsw - Feet of salt water
ft - Foot/Feet
g - Gram(s)
Hz - Hertz
in - Inch(es)
kgs - Kilogram(s)
ksi - Kilo-pounds per square inch
lbf - Pound force(s)
lbs - Pound(s)
m - Meter(s)
mm - Millimeter(s)
msw - Meter(s) of salt water
nm - Nanometer(s)
µF - MicroFarrad(s)
Ω - Ohm(s)
oz - Ounce(s) psi - Pound(s) per square inch
psf - Pound(s) per square foot
v - Volt(s)
yd - Yard(s)
Acknowledgements

Dr. Stephen Wood, Ocean Engineering
Dr. Hector Gutierrez, Mechanical Engineering
Dr. Geoffrey Swain, Ocean Engineering
Dr. Eric Thosteson, Ocean Engineering
Dr. Eraldo Ribeiro, Computer Vision
Mikhail Dembicki, Electronics
John Lee, Machinist
Bill Bailey, Welding and Fabricating
Steven Martyr, Machining
Glenn Guzik, Machining
Bill Battin, Systems Support
Fraser Dalgleish, Optics and Revisions
Dedication

For

my Father, Barry,
who always managed to find the space in the wheel for the wrench,

my Mother, Barbara,
who always encouraged me to fix that space,

and my Brother, Trevor,
who eagerly provided the wrench.
Chapter 1

Introduction

Errare humanum est; aedificare, divinum.

"The development of submarine vessels has been one of the slowest in the history of modern inventions.” Or so claimed Henry Williams in 1919 [23]. With the advent of computers and microcontrollers, however, that evolution has been accelerated. While traditional submersibles and submarines still require years of planning and huge financial reserves for construction, small, nimble, ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles) are beginning to become more commonplace in the world’s oceans.

Each year enormous financial coffers are drained to cover losses due to the operation of ocean-going vessels with biological fouling on the hulls. It has been estimated that the US Navy (USN) expends up to $700 million on fuel each year [19] alone. Much
of this expenditure is used generating the power necessary to overcome the increased
hydrodynamic drag of up to 60%, created by fouling [5]. Most large shipping and
cruise companies, as well as the USN, subject their vessels to time-dependant cleaning
regimens. Many factors, such as the geographic region to which the ship is exposed,
water temperatures and water quality, influence the type and growth of organisms on
the hull. In winter months in the mid-latitudes, for example, relatively few examples
of common foulings will appear. During summer months, however, fouling growth
will be accelerated. Instead of subjecting vessels to costly, time-dictated cleanings, a
system to quantify and analyze the hull condition to determine the extent of fouling
and hull roughness in order to more accurately assess the need of cleaning would
greatly reduce both the associated costs and cleaning cycles.

An image-processing group here at Florida Institute of Technology is building a sys-
tem to quantify hull-condition characteristics based solely on image mosaics of the
hull. Research by Dr. Eraldo Ribeiro has shown that even given images out of rota-
tional orientation, it is possible to rebuild the view of the plane image [16][17]. This
research, in combination with the image-based hull-condition analysis software, lends
itself perfectly for use by an ROV/AUV system. Instead of sending teams of divers
to photograph the hull of a vessel, survey team could release an AUV into the sur-
rounding waters and have it return with a complete mosaic. If special circumstances
were encountered, the vehicle could be reconfigured for manual control and operated
as an ROV system completely under human guidance. Adding to the vehicle the laser
apparatus described in Chapter 2 would provide even more information to users and
help to increase the speed of the hull-analysis software.

As port and harbor security concerns grow with the transfer of control to foreign
nations, the SVK-1 is the perfect platform to conduct underwater surveillance, mine
sweeps, contraband searches, and more. The forward-looking camera in conjunction with the side-looking camera provide an optimal setup for inspection devices and packages surreptitiously stowed outside the hull of a vessel.

The Florida Institute of Technology will also benefit from such a vehicle through its use in several course disciplines, such as oceanography, biology, and engineering. The real-time video cameras on board and the capability of the vehicle to sample such water characteristics as temperature, chlorinity, turbidity, and depth, make this an ideal platform for ocean studies.

One of the most basic problems affecting visual ship hull analysis is accurately positioning the survey vehicle in relation to the hull. The vehicle position must provide a reference for each image acquired so that the image is mapped to the correct area of the true ship hull. To accomplish this positioning, depth, orientation, and vehicle-ship separation must be carefully maintained. A low-cost three-laser apparatus was designed to provide accurate distance and orientation information. Experimentation with the image processing techniques applied to the acquired images yielded excellent project scope cost-benefit relations.

Several vehicles have been designed, such as the Navy’s Automated Hull Maintenance Vehicle (AHMV), that crawl along the hull while to make assessments. Lynn and Bohlander [13] have shown a method of recording hull condition through paint thickness, but the method uses a paint thickness probe that is in direct contact with the ship hull for all readings. In this paper, only visual assessment is discussed. As image processing software progresses and CCD cameras improve, visual inspections of ship hulls will provide much faster means of analysis than physical contact methods. The method described by Lynn and Bohlander measured 2500-3000 data points on a
Nimitz class aircraft carrier. At the maximum number of data points, this translates to around 2.5 hours per survey. Utilizing state of the art image processing and a new hull inspection vehicle, a visual assessment could be made, potentially, in well under a single hour.

Figure 1.1: Scout Vehicle K-1
Chapter 2

Laser System

2.1 Overview

In missions involving underwater vehicles, or UUVs, localization is critical. Knowledge about the vehicles position in relation to its environment is especially significant when surveying vessels through visual means. Current methods for vehicle localization utilize high-cost long-baseline (LBL), short-baseline (SBL), or ultra-short-baseline (USBL) acoustic transceivers, which function with remote ping-generators. These systems are extremely costly, and also unwieldy due to the necessity of placing and calibrating the multiple remote pingers. The current price for a typical installation of these acoustic positioning systems is around $100,000.

In an attempt to present a low-cost solution to this problem, a special apparatus was constructed to utilize three independent laser sources for range and orientation data. Image processing software was written for use with the apparatus and is used to find the relative orientation of the camera to the surface in the visible area of the image. By comparing the position of the reflected laser point to a calibration image database, it is shown that range and orientation data can be interpreted from
images with no laser alignment calibration. Above-water testing of the device was performed in order to assess the validity of the design. Once range information is garnered, trilateration can provide an accurate description of the vehicles’ position relative to the ship-hull. This method returns two dimensional position (depth and hull displacement) and does not obtain vehicle position relative to the bow or stern of the vessel to be inspected.

A simple water clarity experiment was conducted on July 15, 2006 at Port Canaveral, FL using a Secchi Disk. By recording the depth at which the disk is visible, it is possible to map the clarity of water throughout the port. As was expected, the further into the port the measurements were taken, the lower the visibility. Readings nearest the docking area of the cruise ships indicates a visual range of around four ft (see 4).

2.2 Laser Apparatus

Traditional laser-range devices are both expensive and time-consuming for laser calibration and setup (1,2). The premise behind this apparatus was to construct a laser-range and orientation device that was low cost, required little to no calibration, and produced accurate results (± 1 in) over a typical range of hull inspection (1ft to 10ft).
Figure 2.1: Laser Range/Orientation Apparatus
Three off-the-shelf keychain lasers were purchased on Ebay at a cost of $.99 each. These are 650nm class 3a lasers with an output rated at less than 5mW. Hose clamps from a local hardware store were then used to attach the lasers to a clear acrylic mounting plate (fabricated from free plastic scraps and cut on a benchtop bandsaw). It is possible to cut the base and three laser mounting pieces from a single 7in by 7in sheet of plastic. For this particular device, the sheet was slightly under $3\frac{3}{16}$ in thickness, measuring 0.177in in thickness. The small, quarter-circle plastic mounting brackets attached to the lasers were originally intended to allow the return of the laser to a particular angle. After the software was created to allow any angle for the range and orientation information, this feature was withdrawn from use.

![Figure 2.2: Laser Attachment Bracket](image-url)
A Sharp 1/3” CCD CCTV Dome Camera was installed in the base bracket just below the battery pack and is used to capture input video and images. The camera has a 3.6mm auto-iris lens, which functions at 0.7 lux off of a supply of 12 volts and produces 412 lines of TV resolution. The images acquired from the camera are 480 pixels in height and 640 pixels in width with a 96dpi resolution.

Figure 2.3: CCD Dome Camera (Without Dome)
2.3 Test Procedure

A test procedure was identified to measure the accuracy of the system described above. This test procedure was conducted in an enclosed and protected room on dry land.

1. Acquire ten (10) calibration images following the procedures below:

   (a) Position the clear pane perpendicular to a flat, non-reflective surface at a measured distance at the ultimate range of application (for this experiment, the distance was 90in).

   (b) Acquire images at 6in. intervals over the range of 36in to 90in.

   (c) Before relocating the apparatus, measure and record the distance from the clear pane to the surface, and the distances between each laser.

2. Subject the calibration images to the modified Hough Transform algorithm to determine the locations of the laser points within each image.

3. Choose the number of calibration images in the set (trial set) and randomly choose that number of images from the original 10.

4. Run a 3rd degree linear least-squares regression analysis on the location data from the trial set images to obtain estimation coefficients for both coordinates of each laser over the set of calibration images.

5. Subject the coordinates from all 10 images to the estimation equation produced by the least-squares estimation.

6. Compare the estimated distance to the actual distance to obtain residue.
2.4 Results

2.4.1 Mathematics Checks

After acquiring the initial calibration images and determining the laser positions in the image, the software runs a least-squares analysis for each laser’s X and Y coordinates. To check this least-squares regression, Matlab was utilized to perform the same computation on the same dataset. The results are given in the table 2.4.1.

Table 2.1: Math Engine Least-Squares Check Dataset

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th></th>
<th>L2</th>
<th></th>
<th>L3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>y</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>316</td>
<td>313</td>
<td>241</td>
<td>263</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>318</td>
<td>316</td>
<td>239</td>
<td>258</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>323</td>
<td>328</td>
<td>229</td>
<td>240</td>
<td>223</td>
</tr>
</tbody>
</table>

Table 2.2: Math Engine Least-Squares Check Results

<table>
<thead>
<tr>
<th></th>
<th>L1-X</th>
<th></th>
<th>L2-X</th>
<th></th>
<th>L3-X</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HB-VB</td>
<td>Matlab</td>
<td>HB-VB</td>
<td>Matlab</td>
<td>HB-VB</td>
<td>Matlab</td>
</tr>
<tr>
<td></td>
<td>72818.06</td>
<td>72818.06358</td>
<td>35593.33</td>
<td>35593.3329</td>
<td>7118.086</td>
<td>7118.086958</td>
</tr>
<tr>
<td></td>
<td>-446.742</td>
<td>-446.7428973</td>
<td>-217.666</td>
<td>-217.666664</td>
<td>-58.6259</td>
<td>-58.626087</td>
</tr>
<tr>
<td></td>
<td>0.6857</td>
<td>0.685714349</td>
<td>0.3333</td>
<td>0.33333333</td>
<td>0.1217</td>
<td>0.12173913</td>
</tr>
<tr>
<td></td>
<td>L1-Y</td>
<td></td>
<td>L2-Y</td>
<td></td>
<td>L3-Y</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HB-VB</td>
<td>Matlab</td>
<td>HB-VB</td>
<td>Matlab</td>
<td>HB-VB</td>
<td>Matlab</td>
</tr>
<tr>
<td></td>
<td>10886.4</td>
<td>10886.4</td>
<td>37547.3</td>
<td>37547.3</td>
<td>3538.8</td>
<td>3538.800061</td>
</tr>
<tr>
<td></td>
<td>-72.6085</td>
<td>-72.60869568</td>
<td>-324</td>
<td>-324</td>
<td>-37.9</td>
<td>-37.9000005</td>
</tr>
<tr>
<td></td>
<td>0.1217</td>
<td>0.12173913</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
<td>0.10000001</td>
</tr>
</tbody>
</table>
2.4.2 Timing

In order to more carefully compare the various functions tested for laser-localization, the time involved in each subsection of each function was recorded. This also emphasizes the algorithms that need further optimization.

The table below shows the normal timings of the individual functions involved in the modified Hough Transform algorithm. These functions have not been optimized for onboard (the vehicle) computation and include windows functions that are very slow for time-critical applications such as real-time processing. The algorithm presented here is a proof-of-concept type study, which shows results after each step and is not intended for a critical mission, but can be used in a real-time setting until more focus has been placed on optimization. It should be easy to port this code to C\C++ or even VB without the graphics capabilities for much higher speeds.

<table>
<thead>
<tr>
<th>Function</th>
<th>Duration (s):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge</td>
<td>0.125</td>
</tr>
<tr>
<td>Average</td>
<td>0.039063</td>
</tr>
<tr>
<td>Edge</td>
<td>0.117188</td>
</tr>
<tr>
<td>Hough</td>
<td>0.078125</td>
</tr>
<tr>
<td>Locate</td>
<td>0.054688</td>
</tr>
<tr>
<td>Misc</td>
<td>0.078125</td>
</tr>
<tr>
<td>Total Time</td>
<td>0.492188</td>
</tr>
</tbody>
</table>

Regular Average Time 0.490625

The timing of the other techniques, such as technique #3 (see 2.7.1), is slightly slower and with lower accuracy. While the modified Hough Transform method locates the laser in each image, the other algorithms have higher rates of errors. The average
timing for technique #3 was 0.88s, but this system returned inaccurate results for one out of ten images.

2.4.3 Degree of Least-Squares Test

The least-squares test was devised to determine the best order of least-squares computation to use for the distance estimation. First through fourth degree least-squares analyses were performed on the same data sets in order to compare residual magnitudes.

The tables shown below display the results of comparing 2-, 3-, 4-, and 5-degree linear least-squares regression fits to the noted calibration set. The result of applying the regression is a distance estimation, which is then compared to the original distance. The sum of the residuals is shown for comparison purposes.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>36.0000</td>
<td>2799.1562</td>
<td>-72.0165</td>
<td>-91.2311</td>
</tr>
<tr>
<td>42</td>
<td>49.2478</td>
<td>2812.0689</td>
<td>-64.6922</td>
<td>-71.7178</td>
</tr>
<tr>
<td>48</td>
<td>58.6900</td>
<td>2820.3319</td>
<td>-58.8147</td>
<td>-57.7098</td>
</tr>
<tr>
<td>54</td>
<td>66.4230</td>
<td>2827.0016</td>
<td>-54.4711</td>
<td>-45.9865</td>
</tr>
<tr>
<td>60</td>
<td>72.3970</td>
<td>2831.9459</td>
<td>-51.0204</td>
<td>-35.9248</td>
</tr>
<tr>
<td>72</td>
<td>80.9485</td>
<td>2838.9543</td>
<td>-45.0792</td>
<td>-22.4419</td>
</tr>
<tr>
<td>78</td>
<td>85.1853</td>
<td>2842.2844</td>
<td>-42.4373</td>
<td>-16.4540</td>
</tr>
<tr>
<td>84</td>
<td>87.8225</td>
<td>2844.2064</td>
<td>-41.4996</td>
<td>-10.9753</td>
</tr>
<tr>
<td>90</td>
<td>90.0000</td>
<td>2846.0293</td>
<td>-39.3851</td>
<td>-7.9013</td>
</tr>
<tr>
<td>Σ Residue</td>
<td><strong>73.5574</strong></td>
<td>27567.176</td>
<td>1147.89464</td>
<td>1019.0857</td>
</tr>
</tbody>
</table>
### Table 2.4: Residuals from Three-Calibration Image Set 1

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>32.5058</td>
<td>9.4492</td>
<td>32.5058</td>
<td>9.4492</td>
</tr>
<tr>
<td>48</td>
<td>41.1347</td>
<td>3.6853</td>
<td>3.6853</td>
<td>41.1347</td>
</tr>
<tr>
<td>54</td>
<td>53.9879</td>
<td>0.0121</td>
<td>53.9879</td>
<td>0.0121</td>
</tr>
<tr>
<td>60</td>
<td>61.0960</td>
<td>1.0906</td>
<td>61.0960</td>
<td>1.0906</td>
</tr>
<tr>
<td>66</td>
<td>66.4804</td>
<td>0.4804</td>
<td>66.4804</td>
<td>0.4804</td>
</tr>
<tr>
<td>72</td>
<td>71.5317</td>
<td>0.4683</td>
<td>71.5317</td>
<td>0.4683</td>
</tr>
<tr>
<td>78</td>
<td>77.1106</td>
<td>0.8894</td>
<td>77.1106</td>
<td>0.8894</td>
</tr>
<tr>
<td>84</td>
<td>80.3135</td>
<td>3.6865</td>
<td>80.3135</td>
<td>3.6865</td>
</tr>
<tr>
<td>90</td>
<td>82.8749</td>
<td>7.1521</td>
<td>82.8749</td>
<td>7.1521</td>
</tr>
</tbody>
</table>

**Σ Residue:** 46.8733

**25.3405**

**361.6580**

**2657.276**

### Table 2.5: Residuals from Three-Calibration Image Set 2

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>9.4725</td>
<td>10.9725</td>
<td>9.4725</td>
<td>10.9725</td>
</tr>
<tr>
<td>42</td>
<td>45.1780</td>
<td>3.4780</td>
<td>39.5974</td>
<td>2.4026</td>
</tr>
<tr>
<td>48</td>
<td>52.6299</td>
<td>4.6299</td>
<td>45.6935</td>
<td>2.3065</td>
</tr>
<tr>
<td>54</td>
<td>58.5196</td>
<td>4.5196</td>
<td>53.0866</td>
<td>0.9134</td>
</tr>
<tr>
<td>60</td>
<td>63.0040</td>
<td>3.0400</td>
<td>60.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>66</td>
<td>66.9676</td>
<td>0.9676</td>
<td>66.0415</td>
<td>0.0145</td>
</tr>
<tr>
<td>72</td>
<td>69.5262</td>
<td>2.4674</td>
<td>72.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>78</td>
<td>72.7070</td>
<td>5.2300</td>
<td>79.1746</td>
<td>1.1746</td>
</tr>
<tr>
<td>84</td>
<td>74.7695</td>
<td>9.2305</td>
<td>83.9137</td>
<td>0.8683</td>
</tr>
<tr>
<td>90</td>
<td>76.4276</td>
<td>13.5724</td>
<td>87.6666</td>
<td>2.3934</td>
</tr>
</tbody>
</table>

**Σ Residue:** 47.1371

**9.3183**

**56.7969**

**10124.1016**

### Table 2.6: Residuals from Three-Calibration Image Set 3

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>3.3416</td>
<td>32.5844</td>
<td>63.3603</td>
<td>27.3863</td>
</tr>
<tr>
<td>42</td>
<td>23.7287</td>
<td>18.2713</td>
<td>52.8192</td>
<td>10.8192</td>
</tr>
<tr>
<td>48</td>
<td>38.5746</td>
<td>9.4254</td>
<td>49.7965</td>
<td>1.7965</td>
</tr>
<tr>
<td>54</td>
<td>50.9345</td>
<td>3.6665</td>
<td>54.8762</td>
<td>0.8762</td>
</tr>
<tr>
<td>60</td>
<td>59.6628</td>
<td>0.3072</td>
<td>60.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>66</td>
<td>66.6302</td>
<td>0.6302</td>
<td>65.7145</td>
<td>0.2855</td>
</tr>
<tr>
<td>72</td>
<td>72.9598</td>
<td>9.9598</td>
<td>72.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>78</td>
<td>79.4287</td>
<td>1.4287</td>
<td>79.7146</td>
<td>1.7146</td>
</tr>
<tr>
<td>84</td>
<td>83.3473</td>
<td>0.6527</td>
<td>84.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>90</td>
<td>86.8396</td>
<td>3.1664</td>
<td>87.8599</td>
<td>0.2691</td>
</tr>
</tbody>
</table>

**Σ Residue:** 71.1055

**43.0640**

**908494.6476**

**5027.3590**

### Table 2.7: Residuals from Four-Calibration Image Set 1

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>31.5652</td>
<td>4.9468</td>
<td>36.2648</td>
<td>0.2648</td>
</tr>
<tr>
<td>42</td>
<td>44.8230</td>
<td>2.8230</td>
<td>40.6070</td>
<td>1.3930</td>
</tr>
<tr>
<td>48</td>
<td>53.5966</td>
<td>5.9966</td>
<td>47.6087</td>
<td>0.9313</td>
</tr>
<tr>
<td>54</td>
<td>61.5204</td>
<td>7.5204</td>
<td>54.5459</td>
<td>0.5459</td>
</tr>
<tr>
<td>60</td>
<td>67.3153</td>
<td>7.3153</td>
<td>61.5978</td>
<td>1.5978</td>
</tr>
<tr>
<td>66</td>
<td>71.6272</td>
<td>5.6272</td>
<td>67.6801</td>
<td>1.6801</td>
</tr>
<tr>
<td>72</td>
<td>75.6320</td>
<td>3.6320</td>
<td>73.7109</td>
<td>1.7109</td>
</tr>
<tr>
<td>78</td>
<td>79.7560</td>
<td>1.7560</td>
<td>80.5335</td>
<td>2.5335</td>
</tr>
<tr>
<td>84</td>
<td>82.3183</td>
<td>1.6817</td>
<td>85.0439</td>
<td>1.0439</td>
</tr>
<tr>
<td>90</td>
<td>84.4332</td>
<td>5.5668</td>
<td>88.9556</td>
<td>1.4444</td>
</tr>
</tbody>
</table>

**Σ Residue:** 45.9588

**12.7456**

**4.0178**

**12143.9734**
### Table 2.8: Residuals from Four-Calibration Image Set 2

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>16.7879</td>
<td>11.9128</td>
<td>3.9174</td>
<td>26.8705</td>
</tr>
<tr>
<td>42</td>
<td>43.5060</td>
<td>4.9490</td>
<td>4.3133</td>
<td>28.4249</td>
</tr>
<tr>
<td>48</td>
<td>45.9484</td>
<td>2.4052</td>
<td>1.4042</td>
<td>10.9384</td>
</tr>
<tr>
<td>54</td>
<td>55.3013</td>
<td>1.3013</td>
<td>0.9436</td>
<td>12.1115</td>
</tr>
<tr>
<td>60</td>
<td>62.8541</td>
<td>2.8541</td>
<td>0.9743</td>
<td>27.5747</td>
</tr>
<tr>
<td>66</td>
<td>68.4751</td>
<td>2.4751</td>
<td>0.4751</td>
<td>27.5747</td>
</tr>
<tr>
<td>72</td>
<td>73.7164</td>
<td>1.7164</td>
<td>0.1640</td>
<td>27.9460</td>
</tr>
<tr>
<td>78</td>
<td>79.0583</td>
<td>1.0583</td>
<td>0.0583</td>
<td>28.5447</td>
</tr>
</tbody>
</table>

}\[ Σ Residue \]

### Table 2.9: Residuals from Five-Calibration Image Set

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>33.5060</td>
<td>8.4940</td>
<td>4.5133</td>
<td>28.4249</td>
</tr>
<tr>
<td>42</td>
<td>43.5060</td>
<td>8.4940</td>
<td>4.3133</td>
<td>28.4249</td>
</tr>
<tr>
<td>48</td>
<td>45.9484</td>
<td>2.4052</td>
<td>1.4042</td>
<td>10.9384</td>
</tr>
<tr>
<td>54</td>
<td>55.3013</td>
<td>1.3013</td>
<td>0.9436</td>
<td>12.1115</td>
</tr>
<tr>
<td>60</td>
<td>62.8541</td>
<td>2.8541</td>
<td>0.9743</td>
<td>27.5747</td>
</tr>
<tr>
<td>66</td>
<td>68.4751</td>
<td>2.4751</td>
<td>0.4751</td>
<td>27.5747</td>
</tr>
<tr>
<td>72</td>
<td>73.7164</td>
<td>1.7164</td>
<td>0.1640</td>
<td>27.9460</td>
</tr>
<tr>
<td>78</td>
<td>79.0583</td>
<td>1.0583</td>
<td>0.0583</td>
<td>28.5447</td>
</tr>
</tbody>
</table>

}\[ Σ Residue \]

### Table 2.10: Residuals from Six-Calibration Image Set

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>31.8507</td>
<td>4.1493</td>
<td>0.0920</td>
<td>27.5747</td>
</tr>
<tr>
<td>42</td>
<td>43.5060</td>
<td>8.4940</td>
<td>4.5133</td>
<td>28.4249</td>
</tr>
<tr>
<td>48</td>
<td>45.9484</td>
<td>2.4052</td>
<td>1.4042</td>
<td>10.9384</td>
</tr>
<tr>
<td>54</td>
<td>55.3013</td>
<td>1.3013</td>
<td>0.9436</td>
<td>12.1115</td>
</tr>
<tr>
<td>60</td>
<td>62.8541</td>
<td>2.8541</td>
<td>0.9743</td>
<td>27.5747</td>
</tr>
<tr>
<td>66</td>
<td>68.4751</td>
<td>2.4751</td>
<td>0.4751</td>
<td>27.5747</td>
</tr>
<tr>
<td>72</td>
<td>73.7164</td>
<td>1.7164</td>
<td>0.1640</td>
<td>27.9460</td>
</tr>
<tr>
<td>78</td>
<td>79.0583</td>
<td>1.0583</td>
<td>0.0583</td>
<td>28.5447</td>
</tr>
</tbody>
</table>

}\[ Σ Residue \]

### Table 2.11: Residuals from Seven-Calibration Image Set

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>30.7676</td>
<td>5.2324</td>
<td>0.0920</td>
<td>27.5747</td>
</tr>
<tr>
<td>42</td>
<td>43.5060</td>
<td>8.4940</td>
<td>4.5133</td>
<td>28.4249</td>
</tr>
<tr>
<td>48</td>
<td>45.9484</td>
<td>2.4052</td>
<td>1.4042</td>
<td>10.9384</td>
</tr>
<tr>
<td>54</td>
<td>55.3013</td>
<td>1.3013</td>
<td>0.9436</td>
<td>12.1115</td>
</tr>
<tr>
<td>60</td>
<td>62.8541</td>
<td>2.8541</td>
<td>0.9743</td>
<td>27.5747</td>
</tr>
<tr>
<td>66</td>
<td>68.4751</td>
<td>2.4751</td>
<td>0.4751</td>
<td>27.5747</td>
</tr>
<tr>
<td>72</td>
<td>73.7164</td>
<td>1.7164</td>
<td>0.1640</td>
<td>27.9460</td>
</tr>
<tr>
<td>78</td>
<td>79.0583</td>
<td>1.0583</td>
<td>0.0583</td>
<td>28.5447</td>
</tr>
</tbody>
</table>

}\[ Σ Residue \]
Table 2.12: Residuals from Eight-Calibration Image Set

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deg. 1 Residual</th>
<th>Deg. 2 Residual</th>
<th>Deg. 3 Residual</th>
<th>Deg. 4 Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>30.5439</td>
<td>30.5439</td>
<td>30.5439</td>
<td>30.5439</td>
</tr>
<tr>
<td>42</td>
<td>43.3372</td>
<td>40.2833</td>
<td>42.7608</td>
<td>72.2158</td>
</tr>
<tr>
<td>48</td>
<td>52.4569</td>
<td>46.4734</td>
<td>48.0992</td>
<td>77.5205</td>
</tr>
<tr>
<td>54</td>
<td>59.0222</td>
<td>53.7291</td>
<td>54.1361</td>
<td>83.6074</td>
</tr>
<tr>
<td>60</td>
<td>65.6935</td>
<td>60.6949</td>
<td>60.1375</td>
<td>89.5895</td>
</tr>
<tr>
<td>66</td>
<td>69.9780</td>
<td>66.7325</td>
<td>65.8485</td>
<td>95.3563</td>
</tr>
<tr>
<td>72</td>
<td>73.9637</td>
<td>72.6944</td>
<td>71.8992</td>
<td>101.1508</td>
</tr>
<tr>
<td>78</td>
<td>78.0552</td>
<td>79.3630</td>
<td>79.0545</td>
<td>108.3075</td>
</tr>
<tr>
<td>84</td>
<td>80.5943</td>
<td>83.8692</td>
<td>84.1948</td>
<td>113.5416</td>
</tr>
<tr>
<td>90</td>
<td>82.7145</td>
<td>87.7735</td>
<td>88.7745</td>
<td>118.0172</td>
</tr>
<tr>
<td>Σ Residue</td>
<td>39.5541</td>
<td>9.7555</td>
<td>3.8728</td>
<td>294.9516</td>
</tr>
</tbody>
</table>
2.4.4 Distance Estimation Results

In order to determine the optimal number of calibration images for the best accuracy, average errors, with respect to increasing numbers of calibration-images per sets, were recorded.

The tables below show the average error results for the calibration trial sets composed of three to ten images. The overall average is in bold face in the lower right-hand corner of each table. Note that as the number of calibration images per set increases from three to ten, the overall average residual decreases from 2.26in to less than 0.36in.

Table 2.13: Average Error Results for 2nd Degree LSE on 3-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Avg</td>
<td>1.7298</td>
<td>3.0648</td>
<td>0.9318</td>
<td>1.9808</td>
<td>4.3064</td>
<td>2.4043</td>
<td>1.1608</td>
<td>2.5341</td>
<td>2.2641</td>
</tr>
</tbody>
</table>

Table 2.14: Average Error Results for 3rd Degree LSE on 3-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>6.1362</td>
<td>466.2536</td>
<td>11.3676</td>
<td>297.0824</td>
<td>104188.1488</td>
<td>65.2448</td>
<td>42.0741</td>
<td>43.4083</td>
<td>13140.3520</td>
</tr>
<tr>
<td>Min</td>
<td>2.8055</td>
<td>431.1632</td>
<td>1.1544</td>
<td>259.9599</td>
<td>83131.7349</td>
<td>54.1055</td>
<td>32.6085</td>
<td>31.8358</td>
<td>10493.1709</td>
</tr>
<tr>
<td>Avg</td>
<td>4.3285</td>
<td>458.2059</td>
<td>5.6797</td>
<td>280.6623</td>
<td>90859.4648</td>
<td>56.5848</td>
<td>37.6918</td>
<td>36.1658</td>
<td>11467.3479</td>
</tr>
</tbody>
</table>

Table 2.15: Average Error Results for 3rd Degree LSE on 4-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>799.9592</td>
<td>2.9085</td>
<td>4.9099</td>
<td>1.2685</td>
<td>2.1542</td>
<td>1.8324</td>
<td>1.6822</td>
<td>19.5564</td>
<td>101.1052</td>
</tr>
<tr>
<td>Min</td>
<td>284.3605</td>
<td>0.0091</td>
<td>0.0273</td>
<td>0.0463</td>
<td>0.0041</td>
<td>0.0217</td>
<td>0.1247</td>
<td>1.0131</td>
<td>35.7005</td>
</tr>
<tr>
<td>Avg</td>
<td>361.8433</td>
<td>0.6754</td>
<td>1.0507</td>
<td>0.4758</td>
<td>0.5444</td>
<td>0.4316</td>
<td>0.5409</td>
<td>10.5977</td>
<td>47.0200</td>
</tr>
</tbody>
</table>

17
Table 2.16: Average Error Results for 3rd Degree LSE on 5-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.35,6,7</td>
<td>1.25,7,9</td>
<td>1.3,7,8,10</td>
<td>1.4,5,6,9</td>
<td>2.6,7,8,10</td>
<td>1.2,3,4,6</td>
<td>1.2,4,8,9</td>
<td>2.3,4,8,10</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>0.0026</td>
<td>0.0028</td>
<td>0.0150</td>
<td>0.0002</td>
<td>0.0098</td>
<td>0.0254</td>
<td>0.0228</td>
<td>0.1135</td>
<td>0.0240</td>
</tr>
<tr>
<td>Avg</td>
<td>0.4937</td>
<td>0.3592</td>
<td>0.4822</td>
<td>0.5114</td>
<td>3.3926</td>
<td>0.9160</td>
<td>0.5511</td>
<td>1.8065</td>
<td><strong>1.0641</strong></td>
</tr>
</tbody>
</table>

Table 2.17: Average Error Results for 3rd Degree LSE on 6-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>2.6,7,8,10</td>
<td>1.2,3,4,6</td>
<td>1.2,4,8,9</td>
<td>2.3,4,8,10</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2.6854</td>
<td>2.7532</td>
<td>21.2051</td>
<td>2.7768</td>
<td>5.7529</td>
<td>3.7699</td>
<td>1.8585</td>
<td>2.4587</td>
<td>5.4076</td>
</tr>
<tr>
<td>Min</td>
<td>0.0288</td>
<td>0.0160</td>
<td>0.0856</td>
<td>0.0048</td>
<td>0.0384</td>
<td>0.0084</td>
<td>0.0121</td>
<td>0.0109</td>
<td>0.0246</td>
</tr>
<tr>
<td>Avg</td>
<td>0.8113</td>
<td>0.5370</td>
<td>3.9989</td>
<td>0.4889</td>
<td>0.9584</td>
<td>0.7243</td>
<td>0.4273</td>
<td>0.6025</td>
<td>0.6109</td>
</tr>
</tbody>
</table>

Table 2.18: Average Error Results for 3rd Degree LSE on 7-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>1.25,7,9</td>
<td>2.6,7,8,10</td>
<td>1.2,3,4,6</td>
<td>1.2,4,8,9</td>
<td>2.3,4,8,10</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>1.2505</td>
<td>1.8031</td>
<td>1.1671</td>
<td>4.0494</td>
<td>4.9655</td>
<td>7.1551</td>
<td>1.2156</td>
<td>1.1753</td>
<td>2.8477</td>
</tr>
<tr>
<td>Min</td>
<td>0.0169</td>
<td>0.0310</td>
<td>0.0908</td>
<td>0.0011</td>
<td>0.0063</td>
<td>0.0102</td>
<td>0.0152</td>
<td>0.0109</td>
<td>0.0228</td>
</tr>
<tr>
<td>Avg</td>
<td>0.3506</td>
<td>0.4315</td>
<td>0.4180</td>
<td>0.7106</td>
<td>0.8325</td>
<td>1.3329</td>
<td>0.3968</td>
<td>0.3942</td>
<td>0.6109</td>
</tr>
</tbody>
</table>

Table 2.19: Average Error Results for 3rd Degree LSE on 8-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3,5,6</td>
<td>1.3,7,9</td>
<td>1.3,7,8,10</td>
<td>1.3,7,8,10</td>
<td>5.8,10,6,7,10</td>
<td>8.9,10,6,7,10</td>
<td>8.9,10,6,7,10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2.6314</td>
<td>1.1148</td>
<td>2.463</td>
<td>1.249</td>
<td>1.7865</td>
<td>1.2239</td>
<td>1.6067</td>
<td>1.5427</td>
<td>1.6827</td>
</tr>
<tr>
<td>Min</td>
<td>0.0152</td>
<td>0.0225</td>
<td>0.0163</td>
<td>0.0013</td>
<td>0.0535</td>
<td>0.0126</td>
<td>0.0084</td>
<td>0.0044</td>
<td>0.0158</td>
</tr>
<tr>
<td>Avg</td>
<td>0.5176</td>
<td>0.4614</td>
<td>0.5577</td>
<td>0.3914</td>
<td>0.4282</td>
<td>0.4242</td>
<td>0.3882</td>
<td>0.3941</td>
<td>0.4454</td>
</tr>
</tbody>
</table>

Table 2.20: Average Error Results for 3rd Degree LSE on 9-Image Sets A through H

<table>
<thead>
<tr>
<th>Images</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3,5,6</td>
<td>1.3,7,9</td>
<td>1.3,7,8,10</td>
<td>1.3,7,8,10</td>
<td>5.8,10,6,7,10</td>
<td>8.9,10,6,7,10</td>
<td>8.9,10,6,7,10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>1.4893</td>
<td>1.3250</td>
<td>1.3139</td>
<td>1.9027</td>
<td>4.1694</td>
<td>1.1577</td>
<td>1.2195</td>
<td>1.2595</td>
<td>1.6641</td>
</tr>
<tr>
<td>Min</td>
<td>0.0125</td>
<td>0.0234</td>
<td>0.0554</td>
<td>0.0644</td>
<td>0.0225</td>
<td>0.0041</td>
<td>0.0074</td>
<td>0.0266</td>
<td>0.0270</td>
</tr>
<tr>
<td>Avg</td>
<td>0.3886</td>
<td>0.3753</td>
<td>0.3543</td>
<td>0.3710</td>
<td>0.7358</td>
<td>0.3865</td>
<td>0.4050</td>
<td>0.3455</td>
<td><strong>0.4172</strong></td>
</tr>
</tbody>
</table>
Table 2.21: Average Error Results for 3rd Degree LSE on 10-Image Set

<table>
<thead>
<tr>
<th>Images</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>1.3111</td>
</tr>
<tr>
<td>Min</td>
<td>0.0055</td>
</tr>
<tr>
<td>Avg</td>
<td>0.3537</td>
</tr>
</tbody>
</table>
Figure 2.4: Comparison of 2nd degree and 3rd degree LSE
Figure 2.5: Residuals for Actual LSE
2.4.5 Distance Estimation Technique Comparison

Three methods of distance estimation were considered using identical laser-location coordinate sets from the Modified-Hough method. The simple linear least-squares regression and parabola-matching scheme produced very similar results, although the parabola-matching scheme is much more computationally intensive. The simple multiple regression technique produced poor results.

The table below shows the average error for each trial and method. Although the parabola/cubic matching scheme does perform better for two of the trials, as the number of calibration images increases, the simple linear least-squares regression becomes the obvious choice for accuracy. Due to the complexity of the parabola matching scheme, the less intensive simple regression scheme was chosen for the distance calculations.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Lin. Regr.</td>
<td>3.2255</td>
<td>2.7739</td>
<td>0.8449</td>
<td>0.3861</td>
<td>0.0366</td>
<td>0.3610</td>
</tr>
<tr>
<td>Multiple Regr.</td>
<td>11.2095</td>
<td>7.0444</td>
<td>3.0445</td>
<td>0.9813</td>
<td>1.7755</td>
<td>1.1981</td>
</tr>
<tr>
<td>Parabola Matching</td>
<td>3.1600</td>
<td>3.9417</td>
<td>0.8244</td>
<td>0.4628</td>
<td>0.1236</td>
<td>0.5172</td>
</tr>
</tbody>
</table>

Table 2.22: Distance Estimation Technique Comparison
Figure 2.6: Comparison of Distance Techniques
2.5 Discussion

2.5.1 Mathematical Checks

This section used the least-squares technique discussed in section (2.6.2), and more thoroughly in Appendix F, to compare results between Matlab and the project code. The distances were used for the Y matrix while the coordinate locations were used as the X matrix. Estimation-coefficients were determined for each coordinate. These coefficients return one distance estimate based on the x coordinate and one distance estimation for the y coordinate of every laser point location. These two distance estimates are then averaged to find the final distance estimate for the laser point. To ensure that the least-squares code functioned properly, the formula \( b = (X'X)^{-1}X'Y \) was computed in both the newly-written functions and Matlab as a check. This test involves matrix multiplication, matrix inverses, and matrix transforms. The results from Matlab, while more precise, agreed with those found with the equivalent functions written in VB for the 2nd degree least-squares results. The 3rd degree least-squares does not agree due to the limits of VB to handle large floating point numbers. The problem lies in the matrix inverse step of the least-squares calculation, \( X' \). These calculations were performed in Matlab by manually entering laser locations into an M-file script.

2.5.2 Timing

Typically, movie cameras record at about 24fps (full frames, not the 48, or more, half fields), and the human eye can capture around 20fps according to the Internet Movie Database (3). To achieve a useful information stream from the vehicle relating distance and orientation data, all image processing must be accomplished in \( \frac{1}{3} \) to \( \frac{1}{2} \) of a second. This creates an information transmission frequency of about 2-3
Hertz (the maximum number of data items an operator can accept per second, \([24]\)). While a human would be able to accept this information if the only focus were the distance/orientation, operators have other tasks to which to attend. Corren, Ward, and Enns (1999) suggest that the minimum interval between data groups is at least 200ms for near 100\% recognition \([7]\). Distance information is stored along with all other data so operators can return for analysis at a later time in case a mission history must be reviewed. Currently, the modified Hough Transform algorithm runs in the 0.4-0.5s range and the intensity-only based algorithm runs in the 0.8-1.0s range. Manual intervention is extremely slow and should not be attempted for real-time use. The speed of the modified Hough algorithm places this algorithm within the dictated information transmission rate.

The maximum vehicle speed is recommended at 6 knots or 3.06 m/s (10.13 ft/s) (see section 5.2.1). With a data acquisition speed of 3 Hz, one distance/orientation sample is collected for every meter (three feet) of motion. At a vehicle speed of 3 knots (1.53 m/s, 5.06 ft/s), a distance/orientation measurement is collected every 0.51m or 1.69ft. The faster the data acquisition is relative to the absolute translation of vehicle position, the better association between vehicle position and acquired images will be.

### 2.5.3 Degree of Least-Squares

The experimental setup seems to lend itself very well to a multiple linear regression model, but when similar computations were compared to the simple linear regression technique used, distance estimates were over 920\% greater in average error. The multiple linear regression technique led to an average of 3.25in of error, while the simple linear regression technique described here yields 0.35in of average residual.
2.5.4 Laser Location Method

After testing the effects of remapping the original fisheye image to a rectilinear image and performing the same laser location process to the resultant images, there was no statistically significant difference in locations. This was shown by the relatively small magnitude of F when compared to the critical value of F. The recommended Modified Hough Transform was used to process fisheye and converted rectilinear images in order to determine if the conversion is necessary. A slower, original Hough method (not described) was also tested as a third group in the ANOVA report. In the second ANOVA, only the fisheye and rectilinear results are compared.

Figure 2.7: Results of Remapped Comparison
Table 2.23: ANOVA of Three Laser Location Methods

Anova: Single Factor

<table>
<thead>
<tr>
<th></th>
<th>Count</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Hough</td>
<td>10</td>
<td>4.6144</td>
<td>0.46144</td>
<td>0.451017</td>
</tr>
<tr>
<td>Current Hough</td>
<td>10</td>
<td>3.199</td>
<td>0.3199</td>
<td>0.18335</td>
</tr>
<tr>
<td>Remapped</td>
<td>10</td>
<td>3.8569</td>
<td>0.38569</td>
<td>0.05347</td>
</tr>
</tbody>
</table>

ANOVA

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>0.100333194</td>
<td>2</td>
<td>0.050166597</td>
<td>0.218801</td>
<td>0.804892</td>
<td>3.354131</td>
</tr>
<tr>
<td>Within Groups</td>
<td>6.190536493</td>
<td>27</td>
<td>0.229279129</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.290869687</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.24: ANOVA of Two Laser Location Methods

Anova: Single Factor

<table>
<thead>
<tr>
<th></th>
<th>Count</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Hough</td>
<td>10</td>
<td>3.199</td>
<td>0.3199</td>
<td>0.18335</td>
</tr>
<tr>
<td>Remapped</td>
<td>10</td>
<td>3.8569</td>
<td>0.38569</td>
<td>0.05347</td>
</tr>
</tbody>
</table>

ANOVA

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>0.021642</td>
<td>1</td>
<td>0.021642</td>
<td>0.182768</td>
<td>0.674076</td>
<td>4.413863</td>
</tr>
<tr>
<td>Within Groups</td>
<td>2.131384</td>
<td>18</td>
<td>0.11841</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.153026</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.5.5 Distance Estimation

Simple Linear Least-Squares Regression

As is evident by the results shown above, the simple linear least-squares regression technique returns the best estimated distance for each image. Matlab code, which uses 6 calibration images to perform this technique, is supplied in Appendix C.1.

Multiple Linear Least-Squares Regression

The first regression scheme that comes to mind when two variables interact to result in a third (x,y coordinates yield a distance) is the multiple linear least-squares regression. It turns out (see error tables) that this resulted in the worst of the distance estimation schemes. This occurs due to the interaction between the relatively large x and y coordinate values and the relatively small distance values with few cases (up to 6 in this particular example) to build the regression upon. Matlab code is shown in Appendix C.2.

Maple Parabola/Cubic Function Matching

The following text forms a Maple worksheet that was used during the testing of the parabola-matching/cubic-matching distance estimation technique. The results of a simple linear least-squares regression on the x coordinates and y coordinates of the three lasers (code given in Appendix C.3 are entered into the Maple worksheet, along with the original laser location. (Each laser is run in a unique worksheet.) The worksheet then matches the located laser point with the closest point on the least-squares curve-fit to the original data points.
This Maple worksheet calculates the point on a cubic function closest to a particular point given the coefficients of the cubic function and the point \((x,y)\).

```maple
restart;
with(plots,display):
origCubic := \(a + bx + cx^2 + dx^3\);

The function below, \(f\), is the distance from a point \((\hat{x}, \hat{y})\) to the origCubic function.

\[
f := \text{expand}\left((x - \hat{x})^2 + (a + bx + cx^2 + dx^3 - \hat{y})^2\right);
\]

\[
f := x^2 - 2x\hat{x} + \hat{x}^2 + 2bx^3c - 2a\hat{y} + b^2x^2 + c^2x^4 + d^2x^6 + \hat{y}^2 + 2adx^3 - 2bx\hat{y} - 2cx^2\hat{y} - 2dx^3\hat{y} + 2acx^2 + 2abx + 2cx^5d + 2bx^4d + a^2
\]

Minimize the original distance function by taking the derivative and solving for zero.

```maple
> f2 := diff(f(1/2), x);
```

```maple
f2 := 1/2 \* (2*x - 2*xh + 6*b*x^2 + 2*b^2*x + 4*c^2*x^3 + 6*d^2*x^5 + 6*a*d*x^2 - 2*b*yh - 4*c*x*yh - 6*d*x^2*yh + 4*a*c*x + 2*a*b + 10*c*x^4*d + 8*b*x^3*d)/(x^2 - 2*x*xh + xh^2 + 2*b*x^3 + c - 2*a*yh + b^2*x^2 + c^2*x^4 + d^2*x^6 + yh^2 + 2*a*d*x^3 - 2*b*x*yh - 2*c*x^2*yh - 2*d*x^3*yh + 2*a*c*x^2 + 2*a*b*x + 2*c*x^5 + d + 2*b*x^4 + d + a^2 \)^(1/2)
```

```maple
> a := -146830.24609375;
> b := 1290.71127319336;
> c := -3.77808880805969;
> d := 0.00369158014655113;
> xh := 345; # Image
> yh := 367;

29
> plot(f2x, x = 180..350);
> myPara := plot(origCubic, x = 315..360);
> myDots := PLOT(POINTS([xh,yh],SYMBOL(DIAMOND))):
> display([myPara, myDots]);

Figure 2.8: Point and Cubic Function
We solve for zero here, and take the real root as the x coordinate of the point on the cubic function.

\[
\begin{align*}
\text{ans} &:= [\text{solve}(f2 = 0, x)]; \\
\end{align*}
\]

\[
\begin{align*}
> \text{origCubic} &= -146830.24609375 + 1290.71127319336 \times x - 3.77808880805969 \times x^2 + .369158014655113e - 2 \times x^3
\end{align*}
\]

Simply plugging the root back into the original cubic function yields the y coordinate of the point on the cubic function.

\[
\begin{align*}
> x &:= 344.8024393 : \\
> \text{printf ("Closest point on cubic: (x,y) = ( %g, %g) \\

n",x,\text{origCubic});} \\
> \text{printf ("Distance between is: %g", \text{sqrt((x-h)^2+(y-\text{origCubic})^2))});}
\end{align*}
\]

Closest point on cubic: (x,y) = ( 344.802439, 367.3920 )
Distance between is: .43897

The point ( 344.802439, 367.3920 ) is now substituted into the formula with the original regression coefficients, and a distance estimation is made.

2.5.6 Calibration

1. Situate the apparatus in a dimly lit room with little clutter and few glossy objects within the field of view.
2. Place the apparatus at an equal distance from the calibration surface as the maximum expected distance to a target surface during the mission.

3. Orient the apparatus such that the clear pane is parallel to a large, flat calibration surface.

4. Use a carpenter’s level or other device to level the apparatus and ensure proper alignment.

5. Turn on the lasers.

6. Acquire an image at equal spacing over the entire range of the expected target distances.

7. For example, if the mission dealt with flying an ROV near a ship hull at a distance of 3 to 5 feet, the apparatus would first be positioned at five feet from the surface. After the initial image was acquired, the apparatus would be moved closer by, say, six inches, and the image acquisition procedure repeated. This process is repeated until the apparatus is 3 feet from the wall or surface and the last image is acquired.

The range to the flat surface should be near the intended range of use for best results. A minimum of two images can be used for calibration, but more images over a larger range of distances will give the best results and most accurate estimation. The results section shows that using a calibration set of at least 8 to 9 images per 4ft. produces the best estimation.

Taking initial calibration images with the addition of a clear acrylic or plastic pane in front of the lasers and camera is highly recommended. All measurements are then relative from this pane to the surface using either a laser range finder or tape measure. This ensures that minute differences in the laser positions and camera position do not
factor into the distance and orientation estimations. The larger the angle between
the laser and the surface, the better the distance approximation. This effect occurs
due to the larger change of laser position per change in distance (making it easier
for the camera to distinguish minute changes in distance). Arranging the lasers to
accommodate the larger angle is recommended with the added caution to ensure the
laser point remains within the camera’s field of view when located at the maximum
distance of interest. To guarantee the lasers remain in the field of view, set the ap-
paratus up with the first calibration image being at the minimum distance from the
surface over which the vehicle should estimate planar orientation and distance. From
this point, obtain the other calibration images by moving the laser apparatus further
from the surface for each image.

It is important to remember to accommodate for the distance between the clear pane
and the camera lens when incorporating the test apparatus into a vehicle. The best
method by which to achieve such a setup is to measure the offset between the camera
lens and the pane before disassembling the apparatus and then comparing that dis-
tance to the distance between the camera lens and the housing in which the apparatus
will be installed.

2.5.7 Error

As is evident by figure 2.5, the greater the number of calibration images, the better
the distance estimation and hence the better plane estimation. Error is necessarily
introduced at each stage of calibration and computation; but due to the statistical
nature of this project, it is possible to negate many of the common factors of such
error.
The first source of error begins in the calibration stage. The laser apparatus (translucent pane) must be situated as close to parallel to a surface as possible. A tracked device, such as the 80-20 Inc. T-Slotted framing system, which could maintain the parallel orientation while varying the distance would greatly reduce or possibly eliminate positioning error, and speed the calibration process. This system would, however, increase the cost of the system.

Another source of error at this, and every other stage, is the focusing ability of the laser. Due to the incredibly low cost and thus, low quality, of the laser emitters chosen for this experiment, very little focusing could be accomplished; and the size of the laser spot grew to larger than $\frac{1}{4} \text{in}$ at a distance of 8ft. The laser cloud, the surrounding area which also receives some of the emitted light, increased to almost 2in. in diameter at the same distance (see Figure 2.9). This large cloud diameter contributes significantly to the centroid location determined by the localization algorithms. A higher quality laser with better focusing abilities will decrease the point and cloud sizes and allow a more accurate spot position to be determined from input images.

The resolution of the video camera used to acquire images is vital to the distance estimation process. The current resolution of 640 pixels in width and 480 pixels in height (420 tv lines run through a USB tv tuner card) is close to the minimum necessary for an accurate estimation. A higher resolution image-input system would allow finer changes in position to be registered and tracked, leading to less residual after computing the estimated distance.

An alternative to this could be to change the lens of the camera to a smaller angle of view. Using the standard orthogonal projection formula for fish-eye lenses yields the best approximation to the field of view of the current lens.
Figure 2.9: Laser Spot & Cloud Size vs. Distance

\[ FOV_{ortho} = 4 \times \tan^{-1}\left(\frac{\text{FrameSize}}{4 \times \text{FocalLength}}\right) \]

FrameSize refers to the dimension of the frame in the direction of interest. For the 1/3” CCD, the standard frame size is 4.8mm (H) by 3.6mm (V). FocalLength refers to the fixed focal length of the lens. In this case, the focal length of the lens is 3.6mm.

The calculated horizontal viewing angle was 75.25° while the measure horizontal viewing angle was 75.56°. The vertical viewing angle was calculated to be 60.00°, while the measured angle was 53.26°. The difference is probably due to the low-cost (and hence lower quality) lens not conforming to lens specifications. If a lens’ viewing angle were matched to the largest divergence of the lasers, the resolution would be much greater within the area of the image containing the lasers. The tradeoff would be losing visual information outside of the laser bounded region.
Another source of error derived from the video camera is lens distortion. Due to the slightly "fisheye" nature of the lens, light rays entering the lens away from the center of the field of view appear distorted when viewed in a rectilinear images. The process of correcting for this type of distortion is called remapping an image. Remapping an image, for fisheye to rectilinear, consists of determining four control parameters (physical properties of the lens) and subjecting the image to a mapping function. The function to remap the polar-style coordinate system of a fisheye lens to a Cartesian coordinate system of a rectilinear image is as follows:

\[
\text{radius}_{\text{new}} = a(\text{radius}_{\text{old}})^4 + b(\text{radius}_{\text{old}})^3 + c(\text{radius}_{\text{old}})^2 + d(\text{radius}_{\text{old}})
\]

Parameters a, b, c, and d, are adjusted based on the physical properties of the lens and are determined experimentally. When dataset images were remapped to rectilinear images before processing by laser-location and distance estimation algorithms, the results were slightly less accurate, and slightly more precise (see section 2.5.4).

Each algorithm was calibrated with an 8-image set and run on all eight images for distance comparison. The minimum error, maximum error, and average error were plotted for each algorithm set. The original Hough algorithm used original, non-optimized, parameters for laser locations. The updated Hough algorithm shifted the code into a freestanding VB class module and utilized better parameters. The remapped algorithm utilized the same class module but with remapped images. Although it does appear that precision is increased by utilizing the remapping function, the benefits gained are small compared to the computational time for remapping each image before processing. Perhaps with a faster algorithms to accomplish this remapping, the scheme can be both more accurate and more precise.
In an underwater setting, thermoclines and pycnoclines will influence the path of light traveling through them. The main use of the Scout is for ship-hull surveying, which will generally not be affected by these types of environments. On scientific missions, video may be captured from above a thermocline of a surface below the change in water properties. In addition to shifting the laser points, thus skewing distance estimates, the thermocline will blur images to the extent of a non-usable form. If the vehicle is operating near a thermocline, acquisition of images either above or below the boundary layer is recommended to reduce errors created by the refraction of light in the thermocline.

Operation of this system in the underwater environment will present new hurdles for investigators. There exists a potential for biological interference such as plant and animal marine life to interrupt the laser projection. In this case, though, it is doubtful images would be included in the hull inspection since the object occluding the laser will also hide the hull surface. Turbidity will also play a role in detracting from optimal usage of the system. The higher the turbidity of the water, the more backscatter from the lasers. Again, these images may be ill-suited for use in the final inspection due to occlusion of the hull. For best results, water with low turbidity and low vertical mixing with a minimum of water layers should be sought for operation of the laser distance and orientation system.

2.6 Theory

2.6.1 System Setup

The laser apparatus described above serves to produce an image of known size describing the position of the incident points of three lasers on some unknown surface.
If the three lasers are situated such that the reflected point lies within the field of view of the CCD camera, and no laser is parallel to the orthogonal projection from the center of the camera lens to the surface, then range information can be extracted from each laser by analyzing the two-dimensional location of the reflected point in the image plane. Combining multiple sets of these ranges results in the ability to infer the plane that passes through all three ranges and best approximates the surface the camera is viewing.

Figure 2.10: Example Surface for Laser Estimation
2.6.2 Linear Least-Squares

The calibration set of images provides the reference for all future image comparisons. After the calibration images are acquired and fed to the modified Hough Transform algorithm, a list is created of the laser point locations in each image. From these locations, it is possible, using the least-squares estimation technique (LSE), to calculate a correlation function between laser point location and distance each laser lies from the surface. When a new image is considered, the position of the laser point is fed into the equation formulated by the LSE and a distance estimation is returned. When all three ranges are established, it is simple to determine the equation of the plane that passes through all three locations. See Appendix F for the details of computing the least-squares coefficients. The least-squares coefficients take the form, \( \hat{\mu}_{y|x} = b_0 + b_1 x + b_2 x^2 + \cdots + b_n x^n \) where \( b_0, b_1, \ldots \) signify the coefficients and \( \hat{\mu} \) signifies the estimated distance from the target surface. It was shown in section (2.4.3) that the optimal linear least-squares regression curve was quadratic. Although a linear pattern created from the calibration set would produce the best results with a second-degree regression, small deviations from a true linear pattern in the calibration set force the regression to take on a slight curvature, described best by the quadratic equation generated by a third-degree regression.

After the estimator \( b = [b_0, b_1, \ldots, b_k] \) has been calculated for each coordinate (two for each \((x,y)\) pair), distance estimations are calculated for every coordinate. This yields a total of two distance estimations per laser and six for the entire image. The distance estimates shown in Tables 2.3 through Table 2.21 are the average distance for the six estimates. This is a valid estimator since the calibration images are theoretically taken with the camera lens parallel to the viewable surface. Once the camera departs from the parallel position, each pair of laser distance-estimations must be grouped into pairs to accurately assess each distance properly.
2.6.3 Plane Estimation

The real world is three-dimensional. To describe a point in the real world, one three-dimensional coordinate must be known. To describe a line in that same real world, at least two (collinear if more than two) points must be known. To describe a plane, at least three coordinates must be known. The goal of this project was to determine those three points using lasers to infer the relative orientation of the surface which the CCD camera is viewing.

If a laser is parallel to the orthogonal projection from the center of the camera lens to the surface, then the range information will be unavailable for inclusion; and only a linear estimation is available. This occurs due to the fact that the reflected laser point will not change its relative location in the image plane and hence will not yield a distance estimation. When no range information is obtained, the first-order linear-regression estimation for that point will result in a slope of zero for both the X coordinate and the Y coordinate. If the lasers are positioned away from this critical orientation, the situation will never arise.

The equation of a plane takes the form, \( Ax + By + Cz + D = 0 \), where A,B,C, and D are given by the determinants,

\[
A = \begin{vmatrix} 1 & y_1 & z_1 \\ 1 & y_2 & z_2 \\ 1 & y_3 & z_3 \end{vmatrix}, \quad B = \begin{vmatrix} x_1 & 1 & z_1 \\ x_2 & 1 & z_2 \\ x_3 & 1 & z_3 \end{vmatrix}, \quad C = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}, \quad D = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}
\]

The X and Y coordinates are calculated by combining knowledge of the camera lens with the distance estimations to compute a parallel size grid of known dimensions.
The angle of view of the camera lens used in this project was 75.56° in the horizontal plane and 53.26° in the vertical plane. Using simple trigonometry, and the distance information, it is possible to determine the actual height and width in inches of the field of view (FOV). Once the field of view is known, X and Y dimensions within the FOV space can be computed by mapping the pixel coordinate to the actual grid coordinate.

2.7 Image Processing

The image processing routines employed in the project seek to accurately and quickly locate the laser points within an image, establish a distance estimation to each point (based on previously acquired images), and determine the relative orientation of the surface plane in the image.

2.7.1 Laser Location

As described in the previous section, the first processing that occurs on an image is laser location. This routine attempts to accurately and quickly return the location of each laser point within an image. Several methods of accomplishing this localization have been investigated and compared in the following sections.

Technique #1 - Modified Hough Transform

The Modified Hough Transform method is completely autonomous and functions over a wide range of environments. Thresholds for each internal algorithm must be carefully tailored, however, for best results. This method utilizes an edge-detection scheme, averaging, and finally a circular Hough transform to locate the laser location.
The first step is to subject the image to the edge-detection routine. A bounding box is created from the calibration image closest to the surface. This is the image which shows the greatest separation between laser points. All other images’ laser points will fall within the bounding box around the points in this image.

Pseudocode of the routine follows a picture of the original image.

Figure 2.11: Original Image
threshold = 20
LeftBound = left coordinate (X) of bounding box
RightBound = right coordinate (x) of bounding box
UpperBound = upper coordinate (y) of bounding box
LowerBound = lower coordinate (y) of bounding box

for $i = \text{LeftBound}$ to $\text{RightBound}$ do
  for $j = \text{UpperBound}$ to $\text{LowerBound}$ do
    if intensityDifference(pixel($i,j$),pixel($i+1,j$)) or intensityDifference(pixel($i,j$),pixel($i,j+1$)) $>$ threshold then
      Color(pixel($i,j$), black)
    else
      Color(pixel($i,j$), white)
    end if
  end for
end for
Figure 2.12: Hough Transform Edge Find #1
After initial edge-detection has been undertaken, the resulting image must be averaged. The averaging function simply uses a growing threshold to expand the image. Pseudocode of the routine is as follows:

\[
\text{threshold} = 1 \\
\text{for } i = \text{LeftBound} \text{ to } \text{RightBound} \text{ do} \\
\quad \text{for } j = \text{UpperBound} \text{ to } \text{LowerBound} \text{ do} \\
\quad \quad \text{if pixel}(i,j) \text{ is neighboring threshold black pixels then} \\
\quad \quad \quad \text{Color(TempPixel}(i,j)\text{, black}) \\
\quad \quad \text{else} \\
\quad \quad \quad \text{Color(TempPixel}(i,j)\text{, white}) \\
\quad \quad \text{end if} \\
\quad \text{end for} \\
\text{end for} \\
\text{Redraw image using TempPixels as data}
\]
Figure 2.13: Hough Transform Average
Following the initial averaging, the edge detection scheme is used again to reduce the number of pixels on which the Hough Transform must operate.

Figure 2.14: Hough Transform Edge Find #2
The next algorithm applied to the resulting image is the actual circular Hough transform. This transformation maps the Cartesian coordinates of image pixels to an accumulator matrix, which is then used to determine laser point centers. Pseudocode is as follow:

\[\text{Radius} = 7;\]
\[\text{for } i = \text{LeftBound} \text{ to } \text{RightBound} \text{ do}\]
\[\quad \text{for } j = \text{UpperBound} \text{ to } \text{LowerBound} \text{ do}\]
\[\quad \quad \text{if } \text{pixel}(i,j) = \text{black} \text{ then}\]
\[\quad \quad \quad \text{in an accumulator matrix, add 1 to each cell at an integer radius of 7 away from cell}(i,j)\]
\[\quad \quad \text{end if}\]
\[\quad \text{end for}\]
\[\text{end for}\]

Figure 2.15: Hough Transform
This image shows the results of the laser point locating results from the modified Hough Transform algorithm presented for this project. The position is located by code such as the following:

```plaintext
threshold = 120;
distanceThreshold = 20;
for i = LeftBound to RightBound do
  for j = UpperBound to LowerBound do
    if accumulator(i,j) > threshold then
      sort coordinates into clusters of locations by finding the distance between
      the points and using the distanceThreshold value to sort.
    end if
  end for
end for
Find the centroid (the center of each laser point) of each cluster.
```
Figure 2.16: Hough Transform Results
Technique #2 - Assisted Autonomous

This method is very similar to the manual method (#4), with the exception that the software still determines the center of the specified laser point. After an image is acquired, the first step with this method is to manually draw a filled circle of a known color over the laser point in each image. After this step been completed for each image in the dataset, software searches the images for the known color, uses a four-direction (or possibly eight-direction) floodfill algorithm to determine sizes and locations of each color-blob, and then calculates the centroid of each blob to determine the laser centers. Due to manual intervention, this method is not an option for in-mission calculations.

Technique #3 - Intensity Based Autonomous

The image processing involved in autonomously determining the location of the reflected laser points takes place in four distinct phases. The first phase, segmentation, attempts to decide whether or not a pixel in the image is a possible laser reflection based on intensity. The average intensity ranges for indoor test images were from 145-161 out of a scale of 0-255. The average pixel intensity of the laser points was in the range of 220-240 out of 255. These images were acquired in open air with the laser situated perpendicular to a solid backdrop surface. The automatic processing of each image is described below. Pseudocode of the routine is as follows:

```python
threshold = 220
if intensity(pixel) > threshold then
    color pixel white
else
    color pixel black
```
end if

The second phase consists of two averaging passes over the segmented image. This step serves to eliminate noise and enhance the possible laser points. The pseudocode of this phase is as follows:

create copy of segmented image in memory
thresholdCount = 3
for i = 1 to 2 do
    for each pixel in segmented image do
        count number of white pixels in 3x3 area around pixel
        if count > thresholdCount then
            color pixel white in memory copy
        end if
    end for
end for
overwrite original image with memory image
end for

The next phase attempts to use a sweeping algorithm to locate the laser points. Since the lasers should appear near the center of the image, the search extends in a circular pattern originating at the center. After each a 360deg rotational sweep, the radius length of the search is extended by one pixel. In images where the surface is no closer than five ft. to the camera, the search radius length must extend at least through 90 pixels to ensure the laser points are located. A proximity requirement was set arbitrarily through experimentation such that possible laser points were ignored if they are too close to another point. The threshold distance was set to 40 pixels. This
phase finds the three nearest pixels of white color which are at least 40 pixels distant from each other. Pseudocode is as follows:

```plaintext
for radius = 1 to 90 do
    for angle = 1 to 360 do
        if point (r,angle) is white then
            check for proximity
            if too close to another pixel then
                ignore
            else
                save in list of pixels
            end if
        end if
    end for
end for
```

After the locations of the three white pixels nearest to the center of the image are determined, the next phase is to determine the center and size of the white blob at that location. A blob in image processing refers to a cluster of pixels of similar color. The software recognizes this blob by using a standard four direction floodfill algorithm that simply looks to the northern, southern, eastern, and western neighbors of a pixel and recursively steps through the list of pixels whose color matches the particular color of interest. If the initial pixel is set at the locations determined in the previous step, the floodfill algorithm can return number of pixels of similar color in the blob as well as the boundaries of the blob for a centroid estimation. Pseudocode is as follows:
for each pixel in sweeps list do
    floodfill the region of similar color beginning with pixel
    record min X, max X, min Y, and max Y values
    record size (in pixels) of filled region
end for

At this point, we know the center location of each laser point and the size of the reflected spot. The recorded size is a good indicator of whether or not the true laser point was detected. If a point was incorrectly identified, then the size of the spot will differ from the others by being either being much larger or much smaller. If the recorded size falls into this category, it is possible to return to the sweeping algorithm and ignore the errant location.

**Technique #4 - Manual**

The last technique is accomplished by manually entering the coordinates for the centers of the lasers in each image. This option allows for manual testing and calibration but is not suited for field use. Mouse sensitivity and screen resolution play a large role in the accuracy of manual selection and in tests; results using this technique were less accurate than those obtained with autonomous localization methods.

**2.7.2 Comparison**

While both manual and autonomous methods yield coordinates close to the actual location of each laser, the tradeoffs between time and accuracy must be decided by the user. If distance information and planar estimation are not needed during the mission, the use of the most accurate method should be employed due to the lack
of time constraint. If it is highly important to have an estimation of distance and orientation during the mission at the expense of accuracy, a faster method should be chosen with the realization that the results may contain much larger errors.

2.8 Underwater Usage

When utilizing this laser distance/orientation system in an underwater environment, modifications to the various threshold values must be made for proper laser reflection identification to occur. Underwater, the infrared component of the lasers will be filtered naturally; and the camera will not have that extra component to interfere with the image. The overall intensity, though, will be decreased.
Figure 2.18: Example Laser Point Locations with Respect to Surface Distance
The code for this project was written using Microsoft’s Visual Basic 6.0 (VB) to utilize the quick GUI tools and ease of programming. Visual Basic has historically been slow when compared to C++; but with VB5 and newer versions, the interpreted executables were changed to compiled executables, an upgrade which helped the speed tremendously. The average computational time per image with the VB code was 0.49 seconds. This is within the speed range necessary for real-time application. While the image-input system can input from 20-30 fps, distance and orientation information retrieval at a rate of 2 Hz is quite good for normal operation. A higher analysis frame rate could be foreseeable if the code were rewritten in C++ with optimization in mind. For this project, the speeds are real-time and fast enough for demonstration.

2.9 Chapter References


   http://www.sick.com/de/products/categories/auto/

   laser_measurement_systems___robotics/1mi400/en.html


Chapter 3

User Interface and Control System

3.1 Overview

A prime focus of the design of this vehicle is the ease of use. To this end, a simple Windows software package was written to provide pilots a quick and intuitive interface for flying the vehicle. This interface is customizable and contains a number of unique features, such as programmable input-output matching, dynamic function positioning, and the use of standard Plug & Play game controllers. Most features can be adjusted to suit a particular mission’s needs, and the settings can be saved to a file for use if a similar mission arises.

3.1.1 Traditional Control Systems

As the field of commercially available ROVs has grown, so, too has the number of unique solutions to the user interface between the vehicle and the operator. Many companies choose to build custom control boxes with various assortments of knobs, displays, and switches that are predefined to perform certain tasks. Once such control system includes two 1.5cf interface boxes, plus an oversized, uncomfortable joystick,
and an external keyboard (4). This type of human-computer-interface (HCI) is extremely rigid and often is inefficient for particular tasks [24]. A Universal Control System (UCS) centered around current laptop PC technology eliminates the wide variability amongst competitors and allows the creation of custom configurations to suit a special mission. In addition, the same control system can be used to direct several different vehicles from different manufacturers.

3.1.2 Universal Control System

The premise behind the Universal Control System (UCS) is that an operator should have complete control over how the system works. The UCS is composed of three separate components, each of which can easily be tailored to suit a particular application. The joystick, the software package, and the UCS interface component work together to provide a seamless system for operating an ROV. With control commands that are 100% customizable, a method to save and restore custom setups, and the ability to accept any joystick or gamepad that the operating system recognizes, the UCS promises to quickly take over the ROV HCI market.

3.2 Hardware

3.2.1 Joystick

The UCS accomplishes a high level of interoperability by accepting any standard Plug & Play joystick for use as the controller of the ROV system. In this project, a Gemini Industries Inc. Recoil Retractable USB joystick was used. The device has two two-axis sticks, a point of view hat, and 12 buttons, and also features force feedback that can be implemented in future versions of the software control package.
The Gemini joystick was chosen as a representative model of what is readily available and commonly used for video game systems. As larger percentages of the population become exposed to video game systems, the learning curve associated with standard type joysticks decreases. The joystick operation, thus, is quite intuitive; and even novices can learn the system with ease.

By utilizing the software function mapper, it is possible to program the various buttons on the gamepad to send user-defined ASCII messages through RS-232 (included in the UCS Interface) communication scheme to the vehicle. If a pilot would prefer the right button on the gamepad send a ”lights on” command than a ”camera up” command, he could simply redefine the button through the software.
### 3.2.2 UCS Interface

The UCS interface is the electrical interface between the actual ROV and the computer software. The software translates joystick commands to instructions that are sent via the interface to the ROV. Most vehicles on the commercial market are controlled by either RS-232 or RS-485 signals transmitted through a long, reinforced wire or fiber-optic cable to the ROV (1,2,3). The RS-232 standard has long been included in personal computers right off the shelf and has become one of the most widely-used device-communication standards in existence (5). Since most computers are shipped with standard DB9 serial port connectors, it is very inexpensive (around $4 USD) to purchase or build an RS-232 to TTL adapter for PC-to-microcontroller communication. See Appendix B.1 for more details on RS-232 communication. For computers without the DB9 connection, DB9 to USB cables are available at most electronics stores.

The UCS interface accepts a standard DB9 connector from the computer and uses a MAX232 RS-232 line driver to convert the incoming RS-232 signals to microcontroller-acceptable TTL signals. The TTL signals are sent through fiber-optic communication lines to the vehicle. The vehicle has the matching pair of transmitter and receiver fiber-optic devices. See Appendix B.2 and Chapter 4 for the fiber-optic communication details. (See Appendix 15 for circuit diagram)

---

![Diagram of Universal Control System](image)  

**Figure 3.2:** Universal Control System
3.2.3 Computer

The computer can be any laptop computer running Microsoft Windows 98/2000/XP that has at least one serial port (DB9), a USB port for video, and a USB port for the joystick. Dual monitor setups lend themselves to this task extremely well since sensor and video data can be displayed on one monitor, while control system information can be displayed on the other.

3.2.4 Dazzle D90 TV Tuner

A Dazzle D90 TV Tuner was used to incorporate video input into the UCS software. This device receives the standard NTSC output from a video camera located on the vehicle and sends the output through a USB 2.0 interface to the computer. This device receives power through the computer via the USB cable.

3.3 Software

3.3.1 Overview

The software package for the UCS is the information center when operating the Scout vehicle. Written in Microsoft’s Visual Basic, the software provides an easy-to-use graphical user interface (GUI) that relays pertinent information to an operator through a traditional-looking display. The GUI is customizable and also can display video if the video line from the ROV is connected to a PC tuner card. The various display components designed for the UCS conform to guidelines set forth in [24]. The software aims to allow the computer to become the information hub that all data travels through, so as to minimize complexity and the number of necessary compo-
nents.

After a compliant joystick has been connected and recognized by the computer, a custom function map can be created that allows users to configure the joystick in a manner which is efficient, comfortable, and easy to learn and remember. A standard configuration file is also included for several common joysticks. The flexibility of this arrangement offsets the increased setup time required if a custom interface is desired. After receiving an input command from the joystick, the software matches the command to the configuration file and determines the appropriate instruction to send to the UCS interface. Using the serial port and an RS-232 (Appendix 5) communication scheme, the instruction is then transmitted to the ROV.

Figure 3.3: Control Suite Screenshot
3.3.2 Manual

The control software suite is organized in a Multiple Document Interface (MDI). Within this architecture, systems can be organized into moveable windows that can be positioned to the pilot’s liking. If a pilot prefers the video window in a particular location, it is possible to simply drag and drop the window in that position without affecting any other windows. All system windows are available under the View menu item in the Menu area of the window. Under this menu, the systems available are Controls, Joystick, Communications, Sensors, Video, and Control Setup.
The Controls menu item opens the main systems-power control window shown in (3.4). Using this window, systems may be powered on and off for testing or for emergency situations to give the pilot more control over power usage onboard the vehicle.

![Figure 3.4: Master Controls](image)

Figure 3.4: Master Controls
The Joystick menu item opens the main joystick interface windows shown in (3.5). This window allows pilots to modify button style (momentary vs. toggle) and check the response of the system to a particular joystick.

Figure 3.5: Joystick Control
The Communications menu item opens the window that is used to control vehicle communication. Through this window, the serial port is assigned, opened, and controlled. Direct messages can be sent to the vehicle from this window, and all received messages from the vehicle will be displayed in this window. This window is critical for mission control, system diagnostics, and troubleshooting.

Figure 3.6: Communication Window
The Sensors menu item opens the sensor display window, which presents sensor data in a graphical manner similar to the dashboard of an automobile (3.7). Currently, two analog-gauge style data displays are available. It is easy to add more controls programmatically to display more information.

Figure 3.7: Sensor Display
The Control Setup menu item opens the joystick control setup window, which is used to assign messages to each button of the joystick. It is possible to assign specific messages to both button-down events and button-up events for the use of buttons as toggle switches. Special messages can also be assigned to the axis sticks on certain joysticks. The settings are saved and updated upon the window’s closing and are restored each time the program is run.

Figure 3.8: Joystick Control Setup
Once the control setup has been created, the serial port settings entered, and the com port opened for communication, messages can be sent directly to the vehicle from joystick input, or by keyboard/mouse through the Control window, or through the direct message entry frame in the communication window. As data is returned from the vehicle, the displays will be updated as close to real-time as the communication scheme allows.

### 3.4 Chapter References

   
   http://www.argus-rs.no/

   

   
   http://www.seaeye.com/cougar.html

   
   http://www.seaeye.com/falcon.html

   
Chapter 4

Communications Tether

4.1 Overview

The communications tether is the lifeline of the vehicle during manually-controlled missions. The tether includes a 97ft. split-loom tube shield, two fiber-optic communications lines and two 2-conductor video lines. Main power for the vehicle is onboard, so no power transmission lines need to be included. Through the use of epoxy filled bulkhead penetrations, the tether can be safely attached to the underwater vehicle. On the surface, the tether is simply run through a mechanical strain relief and connected directly to the interface box, described in 3.2.2, connected to a PC via USB and serial ports. The connection to the interface box is situated for quick release in emergency situations. In the event of the tether being caught in a propeller, the cable will disconnect from the topside equipment, potentially saving thousands of dollars of computer technology from an early watery demise. The optimal tether would utilize state-of-the-art multiplexers to allow broadcasts of both video transmissions to travel through a single fiber-optic cable, in addition to the serial communications. The equipment necessary for this scheme is, however, financially prohibitive for this project. A protective shell or coating is necessary, however, due to possible mechan-
ical wear against underwater obstacles and ship hulls. The design of the test tether is explained below.

The specific components used in this tether are:

- 9.52mm diam. polyethylene split Loom Tubing (Shielding)
- 1mm diam. HFBR-RUS100 Agilent/HP Polyethylene Fiber Optic Cable (TX)
- 1mm diam. HFBR-RUS100 Agilent/HP Polyethylene Fiber Optic Cable (RX)
- 2.1mm diam. standard coax component video cable (Video 1)
- 2.1mm diam. standard coax component video cable (Video 2)

Figure 4.1: Tether Termination
4.2 Mechanical

As with all tethered vehicles, the ROV tether must be designed such that sufficient data flow through the internal cables can be achieved while minimizing hydrodynamic drag. The test tether for this project is constructed to allow for bidirectional fiber-optic communication and two shielded-and-isolated video lines. While the multiple video lines increases the complexity of the tether system, it reduces the number of onboard electronic components (video multiplexers, etc.) and allows simultaneous viewing and recording of both video transmission lines.

- Cable drag: Cable drag was computed using the following constants,

<table>
<thead>
<tr>
<th>Table 4.1: Cable Drag Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater Density at (10(^{\text{deg}C})): 1026 (\frac{kg}{m^3}) (2) ([8])</td>
</tr>
<tr>
<td>Seawater Dynamic Viscosity: 1.4(\times10^{-3}) (\frac{Ns}{m^2})</td>
</tr>
<tr>
<td>Cable Diameter: 0.9525cm</td>
</tr>
<tr>
<td>Cable Length: 29.565m</td>
</tr>
<tr>
<td>Speed: 1.5433(\frac{m}{s}) (3 knots)</td>
</tr>
</tbody>
</table>

The results of the hydrodynamic analysis are as follows:

\[
Re: \quad 1.08\times10^4 \\
Cd: \quad 1.02 \\
Fd: \quad 351.15N
\]

For the speed of 1.029 \(\frac{m}{s}\) (2 knots) a drag force of 157.04N (35.30lbf) was found; and similarly, for a speed of 0.5144 \(\frac{m}{s}\) (1 knot), the drag force was calculated to be 39.9N (8.96lbf).

The Reynolds number was calculated using the formula, \(Re = \frac{V_0d\rho}{\mu}\) \([8]\) Ex.
11.1). The coefficient of drag was calculated using the formula, $C_d = 1 + 10 \times Re^{-\frac{1}{2}}$ ([21], Eq. 3-268). This formula covers the range of Reynold’s numbers from $1$ to $10^5$. The drag force was then calculated using the formula, $F_d = \frac{C_d A_p V_0^2}{2}$ ([8], Eq. 11.5). More information can be found in [1].

- **Strength**: The tether should not be used to support loads [4] other than incurred hydrodynamic drag [8]. The maximum tensile strength of the fiber-optic cabling is $50\text{N}$ (11.24lbf), and the long-term tensile limit is $1\text{N}$ (0.22lbf), according to (1). However, field tests of the cabling suggests much higher strengths.

- **Minimum bend radius**: The split loom tubing is a non-strength member and only serves to protect the inner cabling from mechanical wear damage. The minimum bend radius of the most critical inner cable, the fiber-optic cabling, is $35\text{mm}$ (1.38in) (1), although laboratory tests indicate the cable can withstand brief bending radii of much less than the $35\text{mm}$ specified.

![Figure 4.2: Tether](image)
4.3 Chapter References


Chapter 5

ROV System

5.1 Overview

As technology advances, new, autonomous solutions to ship-hull analysis are beginning to gain in popularity. Most systems currently in use utilize divers or vehicles that crawl along the surface of the hull and photograph interesting sections. This process can take up to several days to assess the hull of a cruise ship or other ocean liner sized vessel. In order to minimize the duration of this process, a new ROV/AUV system has been designed that incorporates forward and side-looking cameras in addition to the standard compliment of ocean monitoring sensors. By utilizing forward and side-looking cameras, image processing software can both guide the vehicle along a pre-programmed hull path and create a photomosaic of the hull. This photo-mosaic can then be submitted to an automatic categorizing algorithm by matching conditions to a pre-compiled database of qualitatively annotated images. Sections of the vessel hull that are matched to high-priority images in the database can be flagged for attention of a human operator.

The design concept of the SVK-1 (Scout) was to create a modular system in which
components could be replaced with ease and efficiency. To this end, the internal
circuits are situated on a sliding mechanism to provide quick access to the boards.
The modular design of the electrical system, in addition to onboard batteries, allows
boards to be modified or replaced without interfering with other components. If new
types of sensors are integrated into the vehicle, the sensor board is easily modified
to accept such additions. This type of design is ideal for the university setting where
student projects will upgrade the vehicle each semester. The overall aim of the vehi-
cle, however, would still be focused on autonomous hull-analysis.
5.2 Design

5.2.1 Requirements

Perhaps the foremost requirement, other than the desirable water-tight hull, is the depth rating. This depth was determined by the nature of the missions in which the vehicle will be involved. For ship hull inspection, a general rating of 50ft (15.2m) will typically allow the vehicle to inspect most cruise liners, naval vessels, and LNG carriers. Academic use, such as gathering pelagic samples, CTD data, or other water column measurements, demands a greater depth rating than the hull inspection. A depth rating of 30.5m (100ft) allows the vehicle to be much more useful to other academic pursuits, while meeting the requirements of the hull inspection missions. At this depth, ambient pressure is around 0.414MPa (60psi).

Carnival Cruise Lines: Legend, Draft 7.8m (25ft, 7in) (1)
Carnival Cruise Lines: Elation, Draft 7.8m (25ft, 9in) (2)
Carnival Cruise Lines: Destiny, Draft 8.2m (27ft) (3)
Carnival Cruise Lines: Celebration, Draft 7.5m (24ft, 6in) (4)
Carnival Cruise Lines: Valor, Draft 8.2m (26ft, 11in) (5)
Celebrity Cruises: Galaxy, Draft 7.9m (26ft) (6)
Costa Cruises: Costa Atlantica, Draft 8.2m (26ft, 10in) (8)
Disney Cruise Line: Magic/Wonder, Draft 7.7m (25ft, 4in) (7)
Holland America Line: Amsterdam, Draft 7.8m (25ft, 7in) (11)
Orient Lines: Marco Polo, Draft 8.2m (26ft, 11in) (9)
Princess Cruises: Diamond Princess, Draft 8.5m (28ft) (13)
Queen Mary 2, Draft 9.95m (32ft, 7in) (12)
Royal Caribbean Intlrl. Cruise Lines: Adventure of the Seas, Draft 8.8m (29ft)[10]
Typical LNG Tanker, Draft 11-12m (36-39ft)(14)
United States Navy: USS Nimitz (CVN 68), Draft 11.5m (41ft) (15)

The vehicle speed must overcome the currents found both at depth and at the surface in ports and harbors, in addition to the drag introduced by the tether in ROV mode. The vehicle must also be able to remain stable enough for digitization of the hull using digital photographic techniques. A maximum speed of six knots has been identified to overcome three knot currents within ports or harbors.

The Scout must also be small enough for two normal students to be able to deploy the vehicle, while also being easily packaged for ground transport to and from deployment vessels. According to Woodson, [24], a total vehicle weight of around 45kg (100lbs) is a maximum weight limit for two adult males of average strength or 28kg (62lbs) for two adult females to lift from the floor to knuckle height and carry a short distance.

The vehicle must also contain two video cameras, which serve as virtual reverse periscopes, or as Corbin states it in [6], ”the eye of the submerged vessel.” These cameras relay what is occurring in the immediate environment around the vehicle to observers above the water line, instead of the more traditional role of a periscope, which gave submariners inside the submarine a view of the events above water.

5.3 Mechanical

As was stated in the previous section, the ambient pressure at 30.5msw (100fsw) is around 0.414Mpa (60psi). Standard Schedule 40 PVC pipe, with a 15.24cm (6in) diameter, has a critical collapse pressure of 0.579MPa (84psi) according to the Harvel Clear PVC datasheet(16). This results in a factor of safety of 1.4. For the relatively
shallow mission environment of the Scout, the F.S. of 1.4 is adequate. The nominal weight, according to (16) is 1.60kg (3.535lbs) per .3048m (1ft) which results in a total weight of 4.56kg (10.6lbs). The other members are smaller than the main body tube, and the total combined vehicle weight will be under 60 to 70lbs.

The acrylic end cap factor of safety was calculated according to the formula presented in [10] and based upon a 0.3175cm (0.125in) thickness, outer radius of 8.38cm (3.3in), and modulus of elasticity of 2.93GPa(425,000psi). This results in an F.S. of 6.35. The standard density for molded Polymethyl Methacrylate (PMMA or Acrylic) is 1.15-1.19 g/cc (0.0415-0.0430 lb/in^3) and results in a weight of 0.25kg (0.55lbs).

5.3.1 Buoyancy

In order to properly maintain vehicle position during missions, it is critically important to control for buoyancy. The total volume of exterior parts, excluding motors and kort nozzles, is 6292.63 cm^3 (384 in^3 or 0.2222 ft^3). This results in approximately 6.28 liters (1.66 gallons) of water displacement at 1026 kg/m^3 (64.05 lb/ft^3) for a total water displacement weight of 6.46kg (14.23lbs).

The total weight of structural components is currently 13.79kg (30.4lbs), which does not include motors, electronics, or batteries. The batteries will add 2.7kg to 4.5kg (6 to 10lbs) to the total mass. If we subtract the buoyant force of the displaced water, we still have around 11.89kg (26.2lbs) of negative buoyancy. Through the use of syntactic foam, this can be negated to create a neutrally buoyant vehicle. Common syntactic foams have a density near 448.5kb/m^3 (28lb/ft^3). To account for the current configuration with onboard batteries, a volume of 0.027 m^3 (0.94 ft^3) of syntactic foam is necessary. This can be mounted between the main body tube and the outer shell for
best results. Only through experimentation will proper placement be guaranteed.

5.4 Electrical

The Scout is based on a +12v system. Onboard batteries provide power for the onboard computers, sensors, and motors. When in ROV mode, the commands from a topside computer are passed through the onboard computer and directly to the motor control board. Sensor data is sent directly back to the topside computer. In AUV mode, the onboard computer handles all communication with peripherals and also performs data storage. The system was developed such that each function resides on a single board and can be substituted with ease. The electrical system is composed of a communication circuit board, a motor control board, a sensor board, a video camera board, and a tool board. This allows future upgrades to be made painlessly. Communication protocols between boards are discussed in the appendices. The system is designed to house a PC104-based computer system; but until such a system can be purchased, the alternative is to use microcontroller-based boards of similar footprints. Although these boards could be combined into one or two PC104-sized boards, the modularity of the design allows for quick and easy updates to one set of functions, such as motor control, or sensor controls, without having to redesign and rebuild the remaining functionality.

5.4.1 Communication Board

The Communication Board handles all incoming and outgoing messages to and from the vehicle. This board contains the fiber-optic transmitter and receiver in addition to two MicroChip PicMicrocontrollers. These chips interface directly with all other
boards in the vehicle. See (16) for the circuit schematic.

5.4.2 Motor Control Board

The Motor Control Board houses the JFETs and control circuitry for motor control and sensing. This board is currently in development by Larry Buist, Electronics Technician, College of Engineering at FIT. The new design incorporates surface mount technology, and will help regulate board temperature and current limiting.

5.4.3 Sensor Control Board

The Sensor Control Board manages the output from the various sensors that may be included in the SVK-1 design. This board serves as the digital and analog acquisition site for incoming data and passes the information to the communication board for dissemination to the surface. See (17) for the circuit schematic.

5.4.4 Video Control Board

The Video Control Board manages the vertical tilt of the camera based on RS-232 commands sent by the external or internal PC or microcontroller. This board advances and retreats a small stepper motor connected to a worm gear reduction system that smoothly adjusts the tilt of the video camera. See (18) for the circuit schematic.
### 5.5 Construction Notes

This section details methods that can be used during construction to aid in the process of fabrication and assembling of the final vehicle. A parts list is included here in addition to the part drawings in the appendix (D).

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Name</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVK-0001</td>
<td>Main Body</td>
<td>Sch. 40 PVC</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0002</td>
<td>Viewport</td>
<td>Acrylic</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0003</td>
<td>End Cap</td>
<td>PVC or Acrylic</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0004</td>
<td>Side Motor Bracket</td>
<td>Fiberglass / Epoxy</td>
<td>2</td>
</tr>
<tr>
<td>SVK-0005</td>
<td>Rear Motor Bracket</td>
<td>Fiberglass / Epoxy</td>
<td>2</td>
</tr>
<tr>
<td>SVK-0006</td>
<td>Shell Bracket</td>
<td>Fiberglass / Epoxy</td>
<td>4</td>
</tr>
<tr>
<td>SVK-0007</td>
<td>Shell</td>
<td>Fiberglass / Epoxy</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0008</td>
<td>Sled</td>
<td>Acrylic</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0009</td>
<td>Sled Wheels</td>
<td>Nylon</td>
<td>8</td>
</tr>
<tr>
<td>SVK-0009.01</td>
<td>Wheel Retaining Clip</td>
<td>Steel</td>
<td>16</td>
</tr>
<tr>
<td>SVK-0010</td>
<td>Sled Support Rail</td>
<td>PVC or Acrylic</td>
<td>4</td>
</tr>
<tr>
<td>SVK-0011</td>
<td>Camera Tilt Mount</td>
<td>PVC, Acrylic, or Al</td>
<td>1</td>
</tr>
<tr>
<td>SVK-0012</td>
<td>End Cap Mounting Flange</td>
<td>PVC or Acrylic</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 5.5.1 SVK-0001-Main Body

This is an ordered part. Ends should be checked and milled true, if not flat, to end cap tolerances. O-ring grooves may be machined into either end for inclusion of extra protective rings. Clarity of material is critical since the side-looking video camera must film through this pressure vessel.

#### 5.5.2 SVK-0002-Viewport

This is an ordered part. Attachment to the main body (SVK-0001) can be achieved through the use of IPS Weld-On #40 to bond the acrylic viewport to the PVC. An
O-ring groove can also be machined into the flange of the viewport to ensure a seal between the viewport and main body.

5.5.3  SVK-0003-End Cap

The replaceable end cap is held in position through eight bolts, which clamp the end cap to the end cap mounting flange (SVK-0012). It is recommended to machine an O-ring groove in the end cap mounting flange and use a Viton® O-ring to ensure a watertight seal between the end cap and the end cap mounting flange.

5.5.4  SVK-0004-Side Motor Bracket

The side motor brackets fabricated from West Systems Epoxy 105/205 and are attached to the main body using either IPS Weld-On #40 adhesive or the 105/205 system from West Systems.

5.5.5  SVK-0005-Rear Motor Bracket, and SVK-0006-Shell Bracket

See section for part SVK-0004. This part will depend on the dimensions of the thruster nozzles.

5.5.6  SVK-0007-Shell

The shell is fabricated using a BGF Industries E-Glass fiberglass (17,18) cloth of 170g (6oz.) weight with a 76.2cm (30in) width and 10.06m (11 yd) length. To obtain the
22.86cm (9in) inner diameter and 24.13cm (9.5in) outer diameter, a mold may be constructed using chicken wire and thick cardboard paper. After a rough 9in outer diameter has been fashioned out of the chicken wire, the wire should be covered with cardboard paper to ensure a smooth interior of the shell. A release agent should be sprayed over the entire mold, and then Fiberglass should be applied to the wire-reinforced cardboard tube. Perhaps it would be best to install the mold horizontally on a rotating shaft, such that the mold can be rotated during layout. Once the fiberglass has been built up to the 9.5in outer diameter and cooled, the chicken wire and cardboard should be removed to release the fiberglass material. Machining the part to final specifications is easily accomplished using a bandsaw.

The shell should also serve as a mounting surface for removable deployment/retrieval loops or hooks. These should be attached to the top of the shell to provide the most direct access to the lines which will be used to insert or extract the vehicle from the water.

### 5.5.7 SVK-0008-Sled

The sled can be constructed using channel or square/rectangular tubing cut to dimension or from three pieces cemented together. Channel will be the cheapest method in terms of material costs if correct dimensions can be located. This is not a strength member as long as the battery weight is not prohibitive.

### 5.5.8 SVK-0009-Sled Wheels

This is an ordered part. The shaft should be removed from one half of the assembly and two grooves machined on the remaining half for E style retaining clips (E-ring).
These rings will hold the wheel shaft to the electronics sled. The exact dimensions of the grooves will depend on the size of E-clip. Alternatives to this are shaft collars, spring clips, external rings, and other shaft retaining rings/clips (19).

5.5.9 SVK-0010-Sled Wheel Support Rail

The support rails can be machined from 1in by 0.75in bar stock. The total length of the finished rails is 9.25ft, made up of four 2-foot sections and four 4-inch sections. These are attached to the inside of the main body tube using an adhesive such as Weld-On #40 or the 105/205 system. Positioning the rails is critical and should be done using a wooden guide. A wooden guide of 4in height and 4.5in width with two 1in by 1in protrusions on each side (simulating wheel position) and all of length 36in. should be positioned inside the main body before an attempt is made to glue the rails into position. This maintains relative alignment along with providing a jig for the rails during adhesive curing.

5.5.10 SVK-0011-Camera Tilt Mount

The camera-tilt mount can be fabricated from either plastic or aluminum. A two-part weldment (if using aluminum), or a two-part adhesion (if using plastic), is the preferred method of fabrication. The part drawing 11 does not include mounting holes. The mounting holes should be positioned once final attachment methods have been decided upon for the sled.
5.5.11 SVK-0012-End Cap Mounting Flange

The end cap mounting flange is fabricated from a .5in sheet of plastic (acrylic or PVC) with width and height of 8.5in. A rotary table is recommended for use in first drilling the mounting holes, then in positioning and drilling the center hole.

<table>
<thead>
<tr>
<th>Part #</th>
<th>Supplier</th>
<th>Supplier #</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVK-0001-Main Body</td>
<td>ALSOC</td>
<td>1395-061</td>
<td>$365.68</td>
</tr>
<tr>
<td>SVK-0002-Viewport</td>
<td>Calif. Qual. Plastics</td>
<td>Custom</td>
<td>$100</td>
</tr>
<tr>
<td>SVK-0003-End Cap</td>
<td>McMaster</td>
<td>8560K265</td>
<td>$19.63</td>
</tr>
<tr>
<td>SVK-0004</td>
<td>West Marine</td>
<td>($65)</td>
<td></td>
</tr>
<tr>
<td>SVK-0005</td>
<td>West Marine</td>
<td>(above)</td>
<td></td>
</tr>
<tr>
<td>SVK-0006</td>
<td>West Marine</td>
<td>(above)</td>
<td></td>
</tr>
<tr>
<td>SVK-0007-Shell</td>
<td>Fiberglass Florida Inc.</td>
<td>See Notes</td>
<td>$40-fiberglass $60 Epoxy</td>
</tr>
<tr>
<td>SVK-0008-Sled</td>
<td>McMaster</td>
<td>8560K356</td>
<td>$32.88</td>
</tr>
<tr>
<td>SVK-0009-Wheels</td>
<td>AllElectronics.com</td>
<td>WH-14</td>
<td>$2.50</td>
</tr>
<tr>
<td>SVK-0010-Sled Rails</td>
<td>McMaster</td>
<td>8557K812</td>
<td>5x$31.93</td>
</tr>
<tr>
<td>SVK-0011-Camera Tilt Mount</td>
<td>8548K25</td>
<td></td>
<td>$61.25</td>
</tr>
<tr>
<td>SVK-0012-End Cap Flange</td>
<td>8560K265</td>
<td></td>
<td>$19.63</td>
</tr>
</tbody>
</table>
5.6 Chapter References


5. http://www.cruiseships.fsnet.co.uk/carnival%20valor.htm


   Disney_Cruise_Line_Ship_Magic_Wonder.shtml


17. http://sweetcomposites.com/Fiberglass.html


Chapter 6

Conclusions

6.1 Laser Apparatus

The laser apparatus designed to test the concept of visual distance and orientation information gathering performed well and proved very reliable and accurate (less than 0.4in of error) for the cost (less than $80). The addition of the 80-20 Inc. T-Slotted tubing aids tremendously in calibration. By situating the apparatus on a linear bearing inserted into the slotting of the frame, the apparatus can be positioned with ease and precision. In testing, an average of one hour was spent during calibration using the apparatus mounted on a standard photography tripod. The T-Slotted frame system allowed the same number of calibration images to be acquired in approximately 20 minutes. As was mentioned in section 2.5.7, the optimal environment for use of this system is clean (low turbidity) ocean water with a minimum of environmental influences such as fish, seaweed, or other occluding features.
Table 6.1: Laser RangeFinder Comparison

<table>
<thead>
<tr>
<th>Cost</th>
<th>Min Range ft</th>
<th>Max Range ft</th>
<th>Accuracy ± in</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Apparatus</td>
<td>$60.00</td>
<td>&lt;1</td>
<td>&gt;50 ft</td>
</tr>
<tr>
<td>See 3. ATN Ranger Eyes 800</td>
<td>$199.00</td>
<td>45.00</td>
<td>2400</td>
</tr>
<tr>
<td>See 4. Nikon Laser 400</td>
<td>$329.00</td>
<td>5.00</td>
<td>1311</td>
</tr>
<tr>
<td>See 5. Sears Craftsman</td>
<td>$34.99</td>
<td>2.00</td>
<td>50</td>
</tr>
<tr>
<td>See 6. Acuity AR-4000 LIR</td>
<td>$3,495.00</td>
<td>0.00</td>
<td>40</td>
</tr>
<tr>
<td>See 7. Impulse 200</td>
<td>$2,495.00</td>
<td>5.00</td>
<td>1886.4</td>
</tr>
<tr>
<td>See 8. CST LT1 Disto</td>
<td>$720.00</td>
<td>1.00</td>
<td>300</td>
</tr>
<tr>
<td>See 9. Pacific Laser Systems PLS1</td>
<td>$328.00</td>
<td>0.50</td>
<td>300</td>
</tr>
<tr>
<td>See 10. Stabila LE-100</td>
<td>$430.00</td>
<td>1.00</td>
<td>600</td>
</tr>
<tr>
<td>See 11. Leica Disto A6</td>
<td>$649.00</td>
<td>0.16</td>
<td>328</td>
</tr>
<tr>
<td>See 12. Hilti PD-28</td>
<td>$485.10</td>
<td>0.33</td>
<td>328</td>
</tr>
<tr>
<td>See 13. Trimble HD 150</td>
<td>$380.00</td>
<td>1.00</td>
<td>500</td>
</tr>
<tr>
<td>See 14. High Precision LR</td>
<td>$42,000.00</td>
<td>9.00</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

The accuracy and range for the new apparatus are dependent on the calibration.
6.2 Image Processing

The Hough method is currently the optimal candidate for a real-time system due to its high reliability rate and speed (2fps). Through the careful choice of Hough parameters based on the mission environment, the laser-location scheme works very well. These parameters are dependant on the calibration environment and can be maximized through experimentation. As mentioned in section 2.5.2, if the vehicle is traveling at a rate of 6 knots and the data acquisition frequency is 3 Hz, the image processing software will acquire one distance/orientation measurement every meter (three feet). The work described here shows that the three-laser system in conjunction with a low-cost and low-quality video camera can produce accurate results through the use of elegant software schemes.

6.3 Vehicle and Tether

The SVK-1 is a uniquely suited vehicle for ship hull analysis that when used in conjunction with the supplied software and laser orientation apparatus forms a powerful, yet incomplete, system for both hull scanning and other scientific and commercial missions. While there exist several hull-scanning systems available on the market (1, 2), none incorporate side-looking cameras with forward-looking cameras and the necessary sensors for visual ship-hull analysis. The combination of work done at the Florida Institute of Technology by the CCBC, Dr. Ribeiro’s image processing, and the SVK-1 form an ideal system for cruise lines and navies of the world to assess the condition of the hulls of their fleets.
6.4 Software

The software package created for this thesis is a powerful, yet modular, system that presents a foundation for future advancement. The Scout topside control software is written in the very easy-to-read VB language and allows end users to modify many parameters without the need to recompile the source code. Onboard software is arranged to take advantage of the PicMicrocontroller architecture, and the simple fiber-optic communication scheme allows fast communications from the surface to the vehicle.

The laser apparatus software demonstrates the potential to use vision as a means of distance- and orientation-sensing within real-time systems. With residuals less than 1.0cm (0.36in) (achieved in the ten-image calibration set, simple linear regression) for a range through 7 ft from the target surface, the laser apparatus is an excellent alternative to far more expensive devices.


http://www.videoray.com/Products/ShipHull_Intro_Tutorial.pdf


Chapter 7

Future Work

7.1 Laser Apparatus

For inclusion on a vehicle, the lasers could be mounted tightly together in a pod with a small diverging angle of radiation instead of the current converging setup. The camera would then be fixed directly to the outside of the pod. This placement ensures that the camera moves along with the lasers and would greatly reduce the total space required for the system. Transistor switches might be utilized to alternate between lights for the camera and lasers for range and orientation information, or future experimentation might show that both lights and lasers can be used simultaneously.

In addition to the relocation of lasers to fit the compact space, upgrades in laser quality would greatly enhance the system. Due to the absorption qualities of seawater, red lasers are the least efficient in range. A green laser would penetrate farther into the distance, although tests would be necessary to determine proper functionality in this system. Green laser pointers (532nm) at less than 5mw output power cost around $60 and up, while 15mw output power lasers may range into the hundreds of dollars.
Although the low-quality, low-cost CCD camera provided sufficient results, a higher quality camera would greatly increase the resolution of the system. If possible, an off-the-shelf digital camera of three or more megapixels could potentially be used to stream images directly through a USB cable to an onboard PC. This method eliminates the need for a TV tuner card.

### 7.2 Image Processing

The laser-location code does not benefit from full optimization of code and can be accelerated with some attention. The intensity-only scheme is fast, but still misses the laser occasionally. With optimization, the image processing could reach speeds as fast as 4-6 Hz. This would acquire, at a vehicle speed of six knots, distance/orientation measurements every 0.77m to 0.51m (2.53ft/s to 1.69ft/s). At the slower speed of three knots, measurements would be taken every 0.39m to 0.26m (1.27ft to 0.84ft). At speeds of less than four knots, and sample rates of 4-6 Hz, the UUV would acquire measurements faster than one per 0.46m (1.5ft). This is sufficient for pilots and software to maintain vehicle position relative to the ship hull.

### 7.3 Vehicle and Tether

The design presented in this paper for construction a ship-hull inspection vehicle will provide the basic platform upon which upgrades are critical. The vehicle is dependant on still-in-design motor control circuit boards from the Florida Institute of Technology, and a PC-104 computer stack would allow the automation of many tasks. In future deployment versions of the tether, utilizing multiplexers and purchased equipment, it should be possible to reduce the number of transmission lines between the
topside controls and the vehicle. This would serve to reduce the outer diameter of the tether and to minimize drag on the vehicle.

7.4 Simulation

In the future, an ROV simulator could be integrated into the control package to give pilots the opportunity to practice their skills with a virtual vehicle instead of the actual device. This would easily be accomplished through the use of the multiple document interface (MDI) scheme that was used to code the project. Future pilots could hone their operational dexterity by testing missions with various scenarios using computer-generated terrain.

7.5 Control

The body was designed with the PC104 standard in mind. In the future, substituting a pc104 control system in place of the microcontroller system would be beneficial for data storage and enhanced onboard processing and decision-making. Missions could be programmed for full autonomy and to sever the ties that bind the vehicle to the surface. Much work is needed in the motor control area of the vehicle, although current progress at the Florida Institute of Technology is approaching a working solution.
Bibliography


Appendices
A ROV User Notes

A.1 Setup

The Scout system includes a topside software package, universal control system interface box, communications tether, battery charger, and the Scout vehicle. The ROV control software should be installed on a PC with an available serial port and USB port for interface with the UCS interface box. The USB cable from the UCS interface box should be connected to an available port in the computer; similarly, the serial connector on the UCS box should be attached to an available serial port on the computer. The tether should then be connected to the two fiber-optic inputs in the UCS box, and the video input of the UCS box.

A.2 Testing

Once this initial setup is complete, it should be possible to begin testing the various functions of the vehicle. After the topside control software is used to enable all systems, the sensors should begin passing data to the control software. The video cameras should be operational, and the pilot should have full control over all features, such as motor control, video tilt control, etc. Before the vehicle is deployed, it is critical to test each function to ensure operability.

The Scout has an operational depth limit of 30.48msw (100fsw) and the communication tether is 29.56m (97ft) in length. This operational depth should never be exceeded during normal usage in either ROV or AUV modes.

Once operation of all functions has been confirmed on deck, the vehicle is ready for deployment. Lowering should occur through the appropriate lift lugs included on the
vehicle shell, and functions should be tested again in-water and at the surface. When the vehicle passes this final operability inspection, the mission can proceed as planned.

A.3 Maintenance

The Scout has been designed to minimize the maintenance involved in the upkeep and daily usage of the vehicle. Critical components such as O-rings should be inspected after each use and replaced when permanent distortion occurs. It is considered a good practice to lubricate the O-ring before installation into the body with a silicon-based lubricant. If non-sealed batteries are utilized, the packs should be thoroughly inspected before and after each deployment to ensure proper functionality. In the case of the camera lenses accumulating dust or other contaminants, it is safe to use a lens-cleaning solution to moisten a cloth or lens-cleaning paper to gently wipe away dust or debris. Many online and hard copy photography magazine articles outline cleaning methods for camera lenses.

B Definitions and Explanations

B.1 RS-232 Communication

RS-232 communication occurs by means of a three-line interface in which outgoing and incoming signals are sent through dedicated lines, in addition to the common ground line. PC serial transmissions generally occur through the serial port (COM ports) and a standard DB9 connector. RS-232 communications are accomplished by driving a line high with +12v to signify a TRUE state, while -12v signifies a FALSE state. The region between +3v and -3v exists to absorb line noise. The standard DB9 connector uses pin 2 to receive data, pin 3 to transmit data, and pin 5 as a ground.
For asynchronous communication without handshaking, these are the only necessary connections. Typically, a MAX232 IC is used to interface the ±12v to the ±5v Pic 1.

### B.2 Fiber-Optic Communication

The fiber-optic communication scheme implemented in this work involved a simple two cable connection and two pairs of fiber-optic transmitters and receivers. The transmitter used was the IF-E96 from Industrial Fiber Optics, Inc. This device is a 660nm LED encased in a connector housing ready for 1000µm core jacketed plastic (PMMA) fiber cable. The receiver chosen was the IF-D92, which is a phototransistor situated in a housing similar to that of the IF-E96.

Both the receiver and transmitter are powered with a microcontroller friendly +5v and are integrated easily with the MAX232 IC for RS-232 communications over long distances. The cabling used to connect the IF-E96 and IF-D92 is Agilent Technologies’ HFBR-RUS100. This cable is made up of a single step-index fiber sheathed in a black polyethylene jacket. More details of the cable can be found in the product datasheet (2).

### C Code

#### C.1 Simple Linear Least-Squares Regression

```c
0001 %--------------------------------------------------------------------------
0002 % Title:  AllEst3
0003 % Author: Hunter Brown
```
calSet = [1 2 3 4 7 10]; % The indices of the calibration images

myCnt = 2; % Index of the test image

degree = 4; % Degree+1 for least-squares estimation

% Calibration Images

% Order: L1x L1y L2x L2y L3x L3y
all = [176 216 340 214 349 377; % updated 1
       187 220 335 223 345 367; % updated 2
       193 222 331 228 340 359; % updated 3
       199 225 328 231 337 353; % updated 4
       205 226 326 235 335 347; % updated 5
       209 227 325 238 333 343; % updated 6
       212 228 322 240 332 340; % updated 7
       214 231 320 241 330 337; % updated 8
       218 231 320 243 330 334; % updated 9
       219 231 318 244 329 332; % updated 10
       ];

allDist = [36;
           42;
           48;
           54;
           60;
           66;
           72;
           78;]
calib = cat(1,all(calSet,:)); %select used images
distances = cat(1,allDist(calSet)); %only distances of used images
test = all(myCnt,:);

%Form x and y matrices
number_of_calibration_images = size(calib,1);
n=number_of_calibration_images;
X = ones(n,degree);
Y = distances;
b =zeros(degree,size(calib,2));

for j = 1:size(calib,2) %For each column of calib
    for k = 2:degree
        X(:,k) = calib(:,j).^(k-1);
    end
    bSol = inv(X'*X)*(X'*Y);
    b(:,j) = bSol;
end

%Compute Least-Squares estimates for Laser Lines
L1_x = ones(n,degree);
L1_x(:,2:3) = [calib(:,1),calib(:,1).^2];
L1_y = calib(:,2);
L1_b = inv(L1_x'*L1_x)*(L1_x'*L1_y);
L2_x = ones(n,degree);
L2_x(:,2:3) = [calib(:,3),calib(:,3).^2];
L2_y = calib(:,4);
L2_b = inv(L2_x'*L2_x)*(L2_x'*L2_y);

L3_x = ones(n,degree);
L3_x(:,2:3) = [calib(:,5),calib(:,5).^2];
L3_y = calib(:,6);
L3_b = inv(L3_x'*L3_x)*(L3_x'*L3_y);

%------------------------------------------------
%Least-squares estimates for each of the X,Y values for each laser
%------------------------------------------------
Test Image

distEst=0;
for i = 1:degree
distEst=distEst+b(i,:).*test.^(i-1);
end
%This is the distance estimate based on each singular coordinate
distEst=distEst';

% Take average of distances estimations for each coordinate
%(3 pairs of 2 coordinates = 6 distance estimates)
avgDistEst = sum(distEst)/size(distEst,1)
realDist = allDist(myCnt)
L2_Dist = (distEst(1)+distEst(2))/2;
L1_Dist = (distEst(3)+distEst(4))/2;
L3_Dist = (distEst(1)+distEst(2))/2;

C.2 Multiple Linear Least-Squares Regression

%------------------------------------------------
calSet = [1 2 3 4 7 10];
myCnt = 2;
degree = 4; %Degree+1 for least-squares estimation

% Calibration Images
% Order: L1x L1y L2x L2y L3x L3y
all = [176 216 340 214 349 377; %updated 1
       187 220 335 223 345 367; %updated 2
       193 222 331 228 340 359; %updated 3
       199 225 328 231 337 353; %updated 4
       205 226 326 235 335 347; %updated 5
       209 227 325 238 333 343; %updated 6
       212 228 322 240 332 340; %updated 7
       214 231 320 241 330 337; %updated 8
       218 231 320 243 330 334; %updated 9
       219 231 318 244 329 332; %updated 10
       ];

allDist = [36;
          42;
          48;
          54;
          60;
          66;
          72;
          78;]
calib = cat(1,all(calSet,:));  % choose only used images
distances = cat(1,allDist(calSet));  %only distances of used images
test = all(myCnt,:);  

%Form x and y matrices
laserColumnNum=5;  %1, 3, or 5
number_of_calibration_images = size(calib,1);
n=number_of_calibration_images;
X = ones(n,3);
Y = distances;
b = zeros(degree,size(calib,2));
X = cat(2,ones(size(calSet,2),1),calib(:,laserColumnNum:laserColumnNum+1));
b = inv(X'*X)*X'*Y;
distEst=0;
distEst = b(1)+b(2)*test(laserColumnNum)+b(3)*test(laserColumnNum+1);
estimate(myCnt) = distEst

C.3 Simple Linear Least Squares for Parabola Matching
0006 calSet = [1 2 3 4 7 10]; %indices of calibration images
0007 myCnt = 2; %index of test image
0008 degree = 4; %Degree+1 for least-squares estimation
0009
0010 %Calibration Images
0011 %Order: L1x L1y L2x L2y L3x L3y
0012 all = [176 216 340 214 349 377; %updated 1
0013 187 220 335 223 345 367; %updated 2
0014 193 222 331 228 340 359; %updated 3
0015 199 225 328 231 337 353; %updated 4
0016 205 226 326 235 335 347; %updated 5
0017 209 227 325 238 333 343; %updated 6
0018 212 228 322 240 332 340; %updated 7
0019 214 231 320 241 330 337; %updated 8
0020 218 231 320 243 330 334; %updated 9
0021 219 231 318 244 329 332; %updated 10
0022 ];
0023
0025 allDist = [
0026 36;
0027 42;
0028 48;
0029 54;
0030 60;
0031 66;
0032 72;
0033 78;
0034 84;
0035 90;
0036 ];
0037
0038 calib = cat(1,all(calSet,:)); % choose only used images
distances = cat(1,allDist(calSet)); %only distances of used images
test = all(myCnt,:);

%Form x and y matrices
test = all(myCnt,:);

number of calibration images = size(calib,1);
n=number_of_calibration_images;
X = ones(n,degree);
Y = distances;
b = zeros(degree,size(calib,2));

j = 5; %column 3 [1,3,5]
Y = calib(:,j+1);
for k = 2:degree
X(:,k) = calib(:,j).^(k-1);
end
bSol = inv(X'*X)*(X'*Y);
b(:,j) = bSol;
distEst=0;
for i = 1:degree
distEst=distEst+b(i,:).*test.^(i-1);
end
b(:,j)

D Mechanical Drawings

These drawings were created using AutoDesk Inventor 10. All dimensions are in inches unless otherwise specified. View is third-angle unless otherwise specified.
1. SVK-0001 Main Body (Pressure Housing)
2. SVK-0002 Clear Hemispherical Viewport (Video Housing)
3. SVK-0003 Removable End Cap
4. SVK-0004 Side Motor Attachment Bracket
5. SVK-0005 Rear Motor Attachment Bracket
6. SVK-0006 Shell Attachment Bracket
7. SVK-0007 Protective Shell
8. SVK-0008 Electronics Sled
9. SVK-0009 Sled Wheels
10. SVK-0010 Sled Wheel Support Rail
11. SVK-0011 Side-Looking Camera Mount
12. SVK-0012 Replaceable End-Cap Mounting Flange
13. Internal Sled Assembly
14. SVK-1 Assembly
Figure 1: Main Pressure Housing
Figure 2: Clear Acrylic Hemispherical Viewport
Figure 3: Removable End Cap
1. Material: Fiberglass and Epoxy
2. Dimension are dependent on the thruster nozzle size. Inner radius is fixed (called out)
3. Side motors should be closer to body than rear motors, but do not have to completely clear water path to rear motors.

<table>
<thead>
<tr>
<th>SHEET</th>
<th>DRAWING</th>
<th>TITLE</th>
<th>SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SW-0024</td>
<td>Side Motor Attachment Bracket</td>
<td>1:1</td>
</tr>
</tbody>
</table>
Figure 5: Rear Motor Attachment Bracket

1. Waterjet: Fiberglass and Epoxy
2. Dimensions are dependent on the thruster nozzle size. Inner radius is fixed (called out).
3. Side motors should be closer to body than rear motors, but do not have to completely clear water path to rear motors.

<table>
<thead>
<tr>
<th>DRAWN</th>
<th>DRAWN ON</th>
<th>SIZE</th>
<th>APPROVED</th>
<th>REV.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5/21/2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SW-005</td>
<td></td>
</tr>
<tr>
<td>SHEET</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6: Shell Bracket
Figure 9: Sled Wheel
Figure 10: Sled Rail Support
Figure 11: Side-Looking Camera Mount
Figure 12: End-Cap Mounting Flange
Figure 13: Internal Sled Assembly
Figure 14: SVK-1 Assembly
E  Circuits

15. Universal Control System Interface Circuit Diagram
16. Communications Board Circuit Schematic
17. Sensor Board Circuit Schematic
18. Video Motor Circuit Schematic

Figure 15: Universal Control System Interface Circuit Diagram
Figure 17: Sensor Board Circuit Schematic
Video Motor Driver

Figure 18: Video Motor Board Schematic
F Least-Squares Estimation

Following [14], it is possible to construct multiple linear regression models using linear algebra techniques (Gauss and Yule, [11] [25] [2]). To estimate a curve (or line) to a series of data points (i.e., to estimate the distance to the laser point), all one must do is the following:

Algorithm 1  Given a set, $S \in ( (x_1, y_1), (x_2, y_2), \ldots )$, of 2D Cartesian coordinates . . .

1. Construct $X$ such that

$$
X = \begin{bmatrix}
1 & x_1^1 & x_1^2 & \cdots & x_1^d \\
1 & x_2^1 & x_2^2 & \cdots & x_2^d \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & x_n^1 & x_n^2 & \cdots & x_n^d 
\end{bmatrix}
$$

Where $d$ is the degree of the estimator $(\hat{\mu}_{y|x}) - 1$. ($d=1$ is linear, $d=2$ is quadratic, etc.)

2. Construct $y$ such that

$$
y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}
$$
3. Construct $b$ such that

$$b = \begin{bmatrix}
    b_0 \\
    b_1 \\
    \vdots \\
    b_n
\end{bmatrix}$$

4. Let $b = (X'X)^{-1}X'y$

Therefore, the estimation is

$$\hat{\mu}_{y|x} = b_0 + b_1 x + b_2 x^2 + \cdots + b_n x^n$$

**Note** Code for matrix inverses can be found here [22],

The inverse matrix function used in this project is based on the augmentation method with the identity matrix and then subjecting the result to Gauss-Jordan elimination to find the reduced row-echelon form. The inverse lies in the solution space of the final matrix. For singular matrices (i.e., matrices whose determinant is equal to zero), the inverse does not exist. In such a case, the least-squares estimation cannot be computed; and the continuous mapping will delay computation resumption until a valid data set (laser coordinate set) is produced.

## G Software Tools

1. MathWorks Matlab 5.3.0.10183 R11

2. GhostView and Ghostscript v4.8

3. AutoDesk Inventor 10

4. SolidWorks 2001

5. MiKTeX X 2.4.1543 and L2eXe 2e
6. Latex Helper 1.2.2 by Hunter Crenshaw Brown

7. Adobe Acrobat 4.05c

8. Microsoft Excel 10.6789.6735 SP3

9. Cadsoft Eagle Layout Editor 4.11

10. Microsoft Visual Basic 6.0

H Appendix References


2. Plastic Optical Fiber Cable and Accessories for Versatile Link, Agilent Technologies,

Index

acrylic, 8, 32, 80, 83, 87
Adventure of the Seas, 78
algorithm, 34, 39, 41, 48, 49, 51–54
Amsterdam, 78
angle of view, 34, 35, 35, 41
AUV, 1, 2, 81
backscatter, 37
biofouling, 2
C++, 57
calibration, 5, 6, 10, 11, 13, 22, 28, 31, 32–34, 39, 42, 54, 93
camera, 3, 5, 9, 9, 24, 32–34, 38–40, 52, 55, 62, 79, 81, 82, 92, 95, 96, 102
Carnival Cruise Lines, 78
CCD, 9, 35, 38, 40, 96
Celebration, 78
centroid, 34, 49, 51, 53
chlorinity, 3
Communication Board, 81
Control Systems, 58
Costa Atlantica, 78
CTD, 78
Dazzle D90, 62
DB9, 61, 103
Destiny, 78
Diamond Princess, 78
Disney Magic, 78
diver, 2
E-ring, 85
Elation, 78
Error, 33
error, 12, 17, 22, 25, 33, 34, 37, 55, 90
factor of safety, 79, 80
fiber-optic, 61, 71, 71, 73, 74, 81, 93, 102, 104
fiberglass, 85
field of view, 31, 33, 34, 38, 41
fisheye, 36
FIT, 97
floodfill, 51, 53, 54
Florida Institute of Technology, 2, 3, 92
Galaxy, 78
GUI, 57, 62
HCI, 59
Hough, 10, 25, 92
Hough Transform, 12, 25, 39, 41, 47–49
hull, 1–3, 32, 37, 72, 78, 79, 92, 93
hull inspection, 6, 78
IC, 104
image processing, 51
intensity, 25, 51, 51, 55
joystick, 59–61, 63, 64, 69
laser, 2, 3, 5, 5, 6, 8, 10, 11, 24, 28, 32–35, 37–42, 48, 49, 51, 52, 54, 55, 92, 95, 96
laser apparatus, 37, 90, 92, 93
laser cloud, 34
laser spot, 34
least-squares, 10, 11, 13, 22, 24, 28, 39, 132
LED, 104
Legend, 78
lens, 9, 33, 34, 35, 35, 36, 38–40
level, 32
linear regression, 40
LNG, 78
Long-Baseline, 5
Marco Polo, 78
Matlab, 11, 24, 28
Max232, 104
MDI, 64
mosaic, 2
Motor Control Board, 82
NTSC, 62
O-ring, 84, 103
optimization, 96
PC104, 81, 96, 97
Pic, 93, 104
Plane Estimation, 40
PMMA, 80, 104
PVC, 79
Queen Mary 2, 78
rectilinear, 36
residual, 13, 17, 34
Ribeiro, Eraldo, 2
ROV, 1, 2, 58, 59, 61–63, 102
RS-232, 61, 63, 82, 103, 104
RS-485, 61
segmentation, 51, 52
Sensor Control Board, 82
serial port, 61, 63, 102
Short-Baseline, 5
SVK-1, iv, 2, 37, 62, 76, 79–82, 92, 93, 102, 103
135
temperature, 3
TTL, 61
tuner card, 62
turbidity, 3
tv, 62
tv tuner, 34, 62, 96
UCS, 59, 62, 102
Ultra-Short-Baseline, 5
USB, 62, 102
USN, 2
USS Nimitz, 79
UUV, 5
Valor, 78
Video Control Board, 82
video streaming, 96
viewport, 83
Visual Basic, 12, 24, 36, 57, 62, 93
Viton, 84