A Sub-Millimeter Precision Distance and Orientation Sensor for Close-Proximity in Air and Water

by

Lawrence "Zack" Bright

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Signature redacted

Author .............................................................

Department of Mechanical Engineering

May 22, 2015

Signature redacted

Certified by ......

H. Harry Asada
Ford Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Accepted by ......

Anette Hosoi
Associate Professor of Mechanical Engineering
Undergraduate Officer
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Abstract
High precision sensing is a widely applicable technology that ranges in use case from manufacturing, mobile devices, and robotics among more. Specifically inspired by the need for a high precision orientation sensing for an underwater inspection robot with high maneuverability, we explore the design of an underwater-capable sensor that can provide fast response and easy integration into the overall architecture of the robot.

Ultimately, the sensor design opted for cost-minimization (<$50) in tandem with the high precision capabilities to create a design that would be further accessible. The sensor array consists of three Time-of-Flight sensors, each having ±1 mm precision and accuracy. The sensors sit in a triangular formation to allow for 3-point range finding and thereby constrain the sensing input to locate the robot in 3D space. In addition, custom fabrication of Printed Circuit Boards and implementation of an Extended Kalman Filter allow for integration into nearly any robot, while this was specifically designed for EVIE (Ellipsoidal Vehicle for Inspection and Exploration), a current project within d'Arbelloff Lab. For the sake of yielding useful data for position and orientation, the sensor array outputs a vector of Distance perpendicular to the surface, Yaw difference, and Pitch Difference. This is then fed back into the trajectory planning algorithms onboard EVIE.

With full EKF implementation, and tuned noise parameters, the system exhibited precision and response beyond the typical sensor range. Typical accuracy of the Perpendicular Distance measure output was found to be ±.52 mm while the Pitch and Yaw respectively held accuracy of ±2° and ±5°.

Thesis Supervisor: H. Harry Asada
Title: Ford Professor of Mechanical Engineering
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Chapter 1

Introduction

1.1 Motivations in Underwater Robotics

Concurrent with the development of this sensor array and in part its motivation is the work on EVIE (Ellipsoidal Vehicle for Inspection and Exploration). This small autonomous robot is designed for inspection of underwater structures, boat hulls, port security systems, and other submerged structures including nuclear reactor tanks. However, discussing the motivation for this project is beyond the scope of this thesis.

It is proposed by the developers of EVIE that she would be doing inspection using ultrasonic phased arrays or high resolution camera systems to achieve good inspection. For it to be possible for EVIE to accomplish this task, the robot must be able to precisely control its position and orientation with reference to the surface it inspects. Current phased array technology ranges from .5-4MHz and therefore, with needed distancing from the surface of shown in-vivo to be viable at ranging 3-4 cm, but needed precise offset from the surface.[11] Therefore high precision is demanded of the sensor array. As well, the sensor must give orientation data to the robot to allow posturing with respect to the surface with high accuracy and allow for fully autonomous capability in localization and path planning.

We define then the criterion for fully autonomous capability as being capable of a feedback controlled system with surface tracking and approach path planning. This criterion is selected because in an underwater environment, turbulence, undersea
currents, and debris supply a high level of noise to the robot. Hence, in most existing underwater ROVs rely on sensor feedback to control their location, however typical sensors are not as reliable underwater as they are on land.

1.2 Detailed Functional Requirements of the Sensor

Heretofore, we base our functional requirements off of the assumption that the robot will be operating in a port security environment and utilizing an ultrasonic phased array located on-board to complete inspection. This means that operation will be at shallow depths, open to varying light levels, and inspecting objects of varying shapes, roughness, and reflectance. Given these assumptions and those outlined above there are several requirements on the sensor.

1.2.1 3D Space Localization

As already noted, the position and orientation sensor must fully locate EVIE with respect to the inspection surface. This localization would be in distance to the surface and planar angular orientation. It is noted that EVIE in its current iteration has only control of its Yaw and Pitch directly due to its design of jet propulsion and jet layout [2]. Therefore, we take the 3D rotation angles as a formulation of these two principle directions, with our Yaw in with respect to the surface not being interpretable by our distance measurement, we are then limited to planar orientation. In this sense our sensor measures the distance to the surface and the angle between normal vectors of EVIE and the surface in the direction of Pitch and Yaw. This Pitch and Yaw orientation out is to later be formulated into the closed loop motion control of EVIE.

1.2.2 Precise Positioning

Precision of the measurement is critical to the use case described. In order to accurately complete phased array ultrasonic measurement of the surface without excessive computational costs, we must keep the sensor array near the surface with a stable
hold on this distance. In order to establish stable control on the order of XXX% of the wavelength of the ultrasonic frequency, we have established a benchmark precision of $<\pm 1\text{mm}$, with angular precision of $<\pm 2^\circ$. In conjunction with this requirement, this precision and an accurate measurement must be capable on the range of 1-200mm as we intend to make an initial approach by some other long range distance sensor yet under investigation by our group developing EVIE.

1.2.3 Tolerance Against Ambient Light Variation

In a variety of environments, especially in port security situations, light levels and opacity of the water vary over the course of a few hours. Our sensor array must give accurate data with these factors accounted for. The sensor should be functional in high and low ambient light situations, and be tolerant to rapid changes in ambient light levels.

1.2.4 Tolerance Against Surface Texture and Features

In our proposed use case, a variety of surface textures are to be encountered. The surface may be featureless and smooth such as a well maintained boat hull, or it could be plastered with barnacles and other debris; EVIE may be inspecting objects of any color, from white to black to silvered metal, all having varying degrees of reflectance and absorption of various elements of the light spectrum. Angle of incidence is also very important. The sensor should reduce complication of the overall complexity if it is tolerant to different angles of incidence. The angle of incidence can also be an issue when working with highly refractive or even simply rough surfaces that may be encountered in inspection tasks. In addition, it ought to be considered that while not necessarily relevant to port security for obvious reasons, the sensors would also benefit from tolerance against clear or translucent surfaces, as these are common on commercial and recreational watercraft and other objects found at sea.
1.2.5 Stable Integration with Position Control

In order to be a viable sensor for position control, the response rate and sampling frequency should be sufficiently high as to allow for the data received to still be relevant to the control system. A benchmark velocity for EVIE based off of current prototypes is .15m/s [2] and therefore, with an angle of deviation of only 30°, EVIE can be .08m from the surface in one second, and if we are to maintain control, we need accurate feedback at at least this rate equivalent to our precision. This amounts to 80mm/s and with 1mm precision we need 80Hz to accurately position ourselves with respect to the surface at least; this estimate could be extended to Nyquist Frequency of this or 160Hz. This is a reasonably high rate of sampling with a period of 6.25ms.

In addition to a high sampling rate, the sensor needs to feed accurate data to the controls system, and in theory could be well served if it were integration-ready with the position data given by the on-board IMU (Inertial Measurement Unit) and Gyroscopes. It is posited that an Extended Kalman Filter would succeed in this approach and qualifies as part of the functional requirement for the final sensor array.

1.2.6 Small Profile and Mechanical Integration

The physical dimensions of EVIE are slight. At only roughly 20x30x15cm in its current iteration, EVIE is very small, and very light as well with low volume of water displaced. Therefore, the sensor array must be small in terms of size as that it doesn’t affect the overall design of EVIE, and it should be lightweight so as it doesn’t sink the robot by pushing her beyond neutral buoyancy. In addition, as outlined in previous work [2], EVIE is inherently unstable in design due to Munk Moment, and her controls are specifically designed to interact with these instabilities. As is the case, the sensor array should be designed such that it does not affect the hydrodynamic profile of the underwater ROV.
1.2.7 Reliability at Close Proximity

For typical proximity sensors, there is a non-linearity for close range. This is not permissible in the sensor array to be used unless compensated for in the controls (i.e. linearizing data) or physical design (that is to say, offset the sensor inside the robot). The final output should be an accurate measure all the way up to 1mm from the underside of EVIE. This is likely one of the more challenging of the functional requirements for a non-contact sensor.

1.3 Overview of Work enclosed

This thesis then will consist of the design, development, characterization, and testing of such a sensor array. Subsequent chapters of this thesis divide the work into the following categories:

- Base Sensor Selection and Characterization - This is the general assessment of the available technologies that may be utilized for this sensor array.

- Physical Design and Testing of Prototype - The design of the sensor array is fully explored and initial prototyping is explained.

- PCB Design and Fabrication - The ultimate iteration of the sensor array prototype is designed and completed.

- Extended Kalman Filter Implementation - The algorithm and software developed are explained as well as covariance matrices and design choices made in calculating Jacobians.

- Final Results - The resulting data an analysis of the sensor array.

- Conclusion - The final overview and any future work and proposed control theory considerations made are described.

As such, this thesis intends to encompass the complete development of the sensor array and explain its application possibilities as it extends beyond EVIE.
Chapter 2

Sensor Selection and Characterization

In order to develop the sensor, most all avenues within reasonable price range were initially explored and/or evaluated based off of the design constraints presented and enumerated in Chapter 1. All of this work is to be contextualized with relation to the prior work completed by our group in the development of EVIE and earlier iterations of multi-DOF small, submersible ROVs.

2.1 Prior Work and Current System

The current prototype of EVIE is well underway. The Autonomous, untethered and appendage robot can move in 5 DOF using 6 jets and is currently underway in expanding to a higher number of jets and full 6 DOF control. Shown in Figure 1 is the most recently published iteration of EVIE.

As outlined in work previously publish on this robot[3]:

"Throughout this thesis we will be using terminology and nomenclature derived from the field of Ocean Engineering. Specifically we will use kinematics and dynamics based on a body-centered coordinate system shown in [Figure 2-2]. This system was developed by the Society of Naval Architects and Marine Engineers in 1952 and is prevalent in the underwater vehicle literature [12], [13]. As the figure illustrates, u, v, w represent translational velocities about the x, y, and z axes respectively.
These motions are also described as surge, sway, and heave, respectively. Similarly, rotational velocities about the x, y, z axes are referred to as p, q, r respectively. These motions are also known as roll, pitch, and yaw."
2.2 Conventional Sensors

Although these below sensors were not selected in the end, the reasoning behind why is of import to the overall justification on the final design.

2.2.1 IR Sensor Evaluation

IR distance sensors are highly relevant as they are the most common sensors for distance sensing in low cost systems. Their mode of function is typically based in the amount of light received back and the attenuation of light based on what is reflected. This leads to a function of $1/x^2$ as the fit for voltage vs. distance.

However, we found that in testing these sensors that they showed serious hysteresis in that they never showed irregular drift and once submerged in water, were highly unpredictable, as shown in Figure 2-3 below. These unpredictable non-linearities prevent us from using such a sensor. As well, no IR sensors could give us accurate enough readings to reach a precision of 1mm.

![Figure 2-3: Voltage Output of IR sensor when tested underwater in sealed container](image-url)
2.2.2 Sonar Sensor Evaluation

Sonar sensing was immediately discounted, as there were no available systems that gave us ranging near anything better than 1cm precision off the shelf or at reasonable costs.

2.2.3 Machine Vision Evaluation

We discussed the possibility and are still open to the promise of later integrating a machine vision system into the robot, however, it was thought to be beyond the scope of this work, and we were interested in finding optical sensing solutions as much promise in this field has been addressed in earlier work. [3]

2.3 Time of Flight Sensor

Here we outline the use and evaluation of the sensor ultimately chosen for use in our sensor array. This sensor is a novel and newly developed Time-of-Flight distance sensing chip, developed by ST Microelectronics.

2.3.1 Time of Flight Sensor Evaluation

The VL6180x, as it is called, has ± 1mm ranging precision with a typical noise of ± 2mm standard deviation on 100 measurements. The sensor seems ideal to our purpose as it functions on the principle of time-of-flight. This means that the principle of measurement is based on the time it takes for a light pulse, sent from the chip at a specific timing/clock cycle, to be reflected back to the chip. A high frequency clock counts the time taken between the pulse send and receive, does this a few times, and then outputs the distance in millimeters. The clock timing on board is on the order of ps, which gives the system its high precision.

The way in which this functions also integrates an on-board ambient light sensor to make it intolerant to changes in light by compensating the internal signal-to-noise
threshold; however, in principle, we believe that since this is based off of timing, and not intensity, ambient light should only matter for high intensity light situations.

As well, the output is to be very linear and does not matter on the amount of light received, making it ideal for the other listed function requirements of angle of incidence, the reflectance of the object, and the features or roughness of the material.

In order to evaluate the sensor we test it under various conditions.

### 2.3.2 Time of Flight Sensor Characterization

Shown in Figure 2-4 is the results of multiple measurements taken with the VL6180, varying distance. We see very accurate and precise measurements with some variation due to sensor noise. The major impact is in comparing this to the other plots shown. In taking these measurements, the procedure was to set up a vertical wall or plate and incrementally increase distance from the object and collect the output from the sensor.

![Figure 2-4: Measured Distance versus Real Distance in standard operation in open air](image)

Figure 2-4 shows that changing surface reflectance does not affect output, as we maintain linearity and accuracy and precision. It should be noted that these objects were also of varying roughness as well and thereby validate the assumption that this is not a factor as well.
This same tolerance is shown to ambient light in Figure 2-6. The output is unaffected by changing environment.

Ultimately, the only factor that changes output is submersion in water. Since light moves at .77 times as fast in water, we have to correct the timing difference created by the discrepancy. In Figure 2-7, we show that a linear fit shows 1.30 times the real output, or $\frac{1}{.77}$. This can be corrected for by multiplying the output by .77 which yields a new precision of the system of $\pm .77$mm which is a great improvement to the system.

Overall, we show then that the new VL6180 is a good sensor that exhibits all requisite properties of our sensor.
Figure 2-7: Measured Distance versus Real Distance comparing air and water, with a single fitted and compensated dataset with linearity corrective factor
Chapter 3

Physical design and testing of prototype

In order to get the correct 3D positioning intended by our functional requirements, we elected to make a sensor array of 3 VL6180 chips in a triangular formation, which then allows us to derive planar distance and orientation with simple geometry.

3.1 Sensor Array Design

3.1.1 Sensor Arrangement and Measurement Principle

Figure 3-1 shows the early prototype of the sensor array, demonstrating the triangular configuration of the system. Each of the three distance sensors has a know x and y position with respect to the center of the sensor array, a z dimension is established by the distance measurement made. Thus, we have 3 points in 3D space to reference and establish our pose. In this triangular configuration we can define a surface plane, and its distance and orientation with respect to EVIE. With \( (r - p_1) \cdot n = 0 \) defining our plane, we can solve for our normal vector by taking the cross product of two two-point vectors on the plane i.e.

\[
\begin{align*}
  p_{12} &= p_1 - p_2; \\
  p_{13} &= p_1 - p_3;
\end{align*}
\]
Where \( p_1, p_2, p_3 \) are the x,y,z coordinates of the points in space.

\[ n = p_{12} \times p_{13}; \]

From this we may calculate the distance perpendicular to the surface to EVIE.

\[ D_\perp = \frac{|p_1 \cdot n|}{||n||} \]

Figure 3-1: Early Prototype of Sensor Array using VL6180 Breakout Boards

In addition, we may calculate the angles of the Yaw, \( \theta \), and Pitch \( \phi \) as such:

\[
(z \times n) = 0 \Rightarrow \theta = tan^{-1}\left(\frac{n_x}{n_y}\right)
\]

\[
\phi = cos^{-1}(n_z - \pi)
\]

Later these are to be formulated as inverse kinematics for implementation in the Extended Kalman Filter.
Chapter 4

PCB Design and Fabrication

Overall, the circuit is not designed for optimization, as this is for an initial prototyping phase, however, it was decided to test the mechanical mating design and space constraints as well as full integration within EVIE. Therefore, upon iteration, a full PCB was designed and fabricated with the intent that it still connect peripherally to the MCU being used as a central control system within EVIE.

4.1 The VL6180x Device

The VL6160x chip has a pinout clearly defined in the datasheet[4] provided by the manufacturer. As well, Sparkfun has distributed the footprint of the device as open source on their website. This makes integration and design of the overall circuit much simpler.

4.1.1 Mechanical Mounting

The VL6180 chips must be flush against a acrylic window of EVIE to function properly, and be repeatably placed and held. To accomplish this, a pseudo-kinematic coupling is used to locate the sensor array as shown in Figure 4-1, while a small screw down plate applies pressure to hold the chips flush to the window surface.
4.1.2 Circuit Schematic

Figure 4-2 shows the overall Schematic, and in following the specific components will be discussed.

The Circuit and subsequently the board itself was designed using Eagle.
4.1.3 I2C Communication

The VL6180 device uses the I2C protocol to communicate its data output, so we design a simple joined bus for SDA and SCL that connect to the microcontroller inputs. The microcontroller used has a fully integrated I2C channel on board, but on the VL6180 we need to design pull-up resistors as shown in the schematic.

4.1.4 Voltage Level Constraints and Power Electronics Design

However, the VL6180 has very specific power constraints. All power and I/O is done with 2.8V. This does not match with the 3.3V used in our MCU. Therefore, we design an I2C level shifter with an integrated voltage regulator so that we may take in the 3.3V from the MCU and power a level shifting I2C channel.

This is implemented with 1 voltage regulator and 2 power MOSFETs. The FETs are arranged to bring the power high or low on either side with one channel feeding the 3.3V side and another feeding the 2.8V side.

This circuit is used centrally for all of the VL6180 chips to use as redundancy is not necessary here and only increases cost.

4.2 Full I2C/GPIO Design

Another issue with the VL6180 chips is that they are all asserted to a specific I2C address that is re-asserted every power cycle. To allow communication with three units simultaneously, the GPI/O line is used to bring each unit into reset mode at individually addressed pins by setting GPIO0 to low. Once in reset, the chip cannot listen to the I2C channel, so, we bring one unit out of reset, then proceed to set a new address by writing to its address register. Then, we bring the next unit out of reset and command it to change addresses. Finally the last is brought out of reset and left in factory default address. Now our three units all can be commanded separately.
4.3 PCB Layout and Design

Figure 4-3 shows the final PCB layout of the board. Here, all the major components are visible, three holes are in place for the mechanical mounting outlined above, and we see that the board has a grounding copper dump on the bottom side for giving a clean ground source.

![Figure 4-3: View of Circuit Layout](image)

4.4 Finished Prototype Boards

Figure 4-4 shows the finished prototyped boards. These boards were manufactured by an outside supplier after prototyping in-house led to too high of lead time.

![Figure 4-4: Final Board PCBs](image)
Chapter 5

Extended Kalman Filter
Implementation

5.1 Principles of Extended Kalman Filter

The Extended Kalman filter is a powerful tool designed to allow for non-linear state and measure equations as well as robust sensor fusion. Both of these are very promising to the sensor array we designed here. Using a C++ library that based the design of the library off of the original Kalman paper and algorithms based off of other implementations of the EKF, we are able to implement a filter fully integrated and compatible with the Arduino MCU used to control EVIE currently, and as C++ is versatile and compileable down to many lower-level languages, in theory any other MCU we may use in the future.[5, 6]

5.1.1 Background Mathematics

The Kalman Filter requires a defined state matrix, describing the current state of the system and for us, a corresponding prediction matrix defining the state estimation, our output variables, a defined measure matrix which will be our measured distances, the noise covariance matrices that define the assumed error of the measure and the process noise and prediction equation, and the Jacobian matrices relating each of
these to one another accordingly.

5.2 EKF Implementation

Below we outline the ultimate implementation of the Kalman Filter: with $x_k$ as our state, $z_k$ as our measure, $A_{ij}$ as the prediction-state Jacobian, $W_{ij}$ as the process noise-state Jacobian, $H_{ij}$ as the measure-state Jacobian, and $V_{ij}$ as the measure-measure noise Jacobian,

$$x_k = \begin{bmatrix} \frac{d_\perp}{dt} \\ \frac{d_\perp}{d\theta} \\ \frac{d_\phi}{d\theta} \\ \frac{d_\phi}{dt} \end{bmatrix}$$

$$z_k = \begin{bmatrix} d_L + v_1 \\ d_R + v_2 \\ d_T + v_3 \end{bmatrix}$$

$$A = \frac{df}{dx_j}; \quad H = \frac{dh_i}{dx_j};$$

$$W = \frac{df}{dw_j}; \quad V = \frac{dh_i}{dv_j};$$

Our state estimator is: $x_k = f(x_{k-1}) = x_{k-1} + T \times \frac{d}{dt}x_{k-1}$; for all non derivative terms and simply,

$$x_k = f(x_{k-1}) = x_{k-1};$$

for all derivative terms of the state.

Our measure estimator

$$z_k = f(x_{k-1}) = \begin{bmatrix} \frac{(\tan(\theta)x_L + y_L)}{\cos(\phi+\pi)} \frac{(1-\cos^2(\phi+\pi))}{1+\tan^2(\theta)} \\ \frac{(\tan(\theta)x_R + y_R)}{\cos(\phi+\pi)} \frac{(1-\cos^2(\phi+\pi))}{1+\tan^2(\theta)} \\ \frac{(\tan(\theta)x_T + y_T)}{\cos(\phi+\pi)} \frac{(1-\cos^2(\phi+\pi))}{1+\tan^2(\theta)} \\ \frac{\tan(\theta)x_{k-1} + y_{k-1}}{\cos(\phi+\pi)} \end{bmatrix}$$

Our Process Noise Covariance, $Q = \begin{bmatrix} 1.1^2 & 0.0 & 0.0 \\ 0.0 & 1.0^2 & 0.0 \\ 0.0 & 0.0 & 1.0^2 \end{bmatrix}$

Our Measure Noise Covariance, $R = \begin{bmatrix} 0.98^2 \\ 0.98^2 \\ 0.98^2 \end{bmatrix}$

32
Our Predictor Error Covariance, \( P = \begin{bmatrix}
1.0^2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 25.0^2 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & .50^2 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 10.0^2 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & .50^2 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 10.0^2 
\end{bmatrix}; \\

All the above covariances were either procedurally tuned to yield ideal output, or were based off of actual noise covariance of the sensor.

### 5.3 EKF Validation

Figure 5-1 shows the precise following of the Kalman Filter when compared with the instantaneously calculated values for the Distance, and Pose Angles. We see that the filter follows very tightly to these curves, but eliminates the noise inherent to the system. The overall computational costs were low in that the timing of the measurements for 20 separate trials of 1 minute of measurements shows and average measurement time of 5.12ms. This is reasonably close to the established 6.25ms set in the functional requirements, but, in theory there should be optimization yet to be completed on the EKF.
(a) Distance Measured vs Instantaneous Calculated Data

(b) Pitch Measured vs Instantaneous Calculated Data

(c) Yaw Measured vs Instantaneous Calculated Data

Figure 5-1: Final EKF Output Data compared with the instantaneously calculated version based off of the input distances $d_L$, $d_R$, $d_T$
Chapter 6

Conclusion

6.1 Overview

In conclusion, we have outlined herein a novel sensor array for fine positioning and control in small underwater robotics. The array has high precision, ± 1mm and accuracy at .52mm with Pitch and Yaw respectively holding accuracy of ± 2° and ± 5°. The sensor should be noted to ultimately have low cost, as the VL6180x sensors cost $5 each, and other components summed to approximately $15 per board. This figure does not include PCB Fabrication costs. That figure is dependent on scale and may be the driving factor due to its large area.

The array is tolerant against various environmental stresses and changes in lighting and surface texture, making it ideal for such a chaotic environment as underwater robotics.

6.2 Discussion

It is worth noting that high precision tooling was unavailable to test the accuracy of the sensor finely, and accuracy measurements of the angle outputs are solely based off of zeroing and well measured angles such as 30°. This may therefore overestimate the accuracy of our sensor array in these domain. As well, it is worth noting that not all experiments to external stimuli were completed underwater as well due to time
constraints, which may not allow for full understanding of the effective tolerance of the sensor against these stimuli. It is fair to assume due to the fact that the final sensor was validated underwater and in the air against the stimuli and showed no measurable deviation that the assumption should be valid.

6.3 Future Work

6.3.1 Control Algorithms

Full development of position control algorithms using this system are possible avenues for future work. The full integration of this into EVIE including sensor fusion has yet to be accomplished and seems requisite for full autonomy. Closed loop control of EVIE’s movement is well into development within the group and therefore this work should smoothly transition into aiding this effort.

6.3.2 Mass Production Evaluation

This sensor also has much promise as a commercial product in that it may be very easily scaled to mass production such that it may be used in other applications on a wider scale. For that to be accomplished further work needs to be completed in evaluating the design for manufacturing involved and whether costs will scale as posited earlier.

6.3.3 Other Applications

The sensor array is low-cost and high precision and tolerant to many external stimuli. This suggests that robotics in many applications should find the array of use. In aeronautics, land ROVs, autonomous multi-rotors and with low-cost accessible instrumentation systems, this array ought to see much possible room to expand.
Bibliography


