ASSESSING THE FEASIBILITY OF INTEGRATING AN INERTIAL NAVIGATION SYSTEM AND DVL INTO AN A-SIZED AUV

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ASSESSING THE FEASIBILITY OF INTEGRATING AN INERTIAL NAVIGATION SYSTEM AND DVL INTO AN A-SIZED AUV

BY

ANTHONY R SCUDERE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

This work accesses the feasibility of integrating an inertial navigation system (INS) and Doppler Velocity Logger (DVL) into an A-size AUV that is 4.875” in diameter. The mechanical integration solution developed during this effort focused on developing a low size, weight, power, and cost (i.e. low SWaP-C) navigation module for the Bluefin SandShark. Unlike other approaches currently pursuing this same navigation problem, including those attempting novel acoustic based tracking or novel hydrodynamic model based navigation, this effort, instead, integrated a novel navigational software system developed by Charles River Analytics, called CAMINO, into the available internal volume of an A-size pressure vessel. CAMINO functionality is enabled by a set a suite of low SWaP-C electronics, and Teledyne Marine’s smallest commercial available DVL, the Pathfinder. These components, once mechanically integrated into a novel navigation module, are capable of providing low SWaP-C navigation capabilities to small AUVs. Furthermore, this work has the potential ability to have a significant impact on the proliferation of these easy-to-use, man portable vehicles that have otherwise been plagued with having a reputation of not being able to execute meaningful missions due to lacking navigation capabilities. Through Finite Element Analysis simulations, the mechanical design was proven to be pressure tolerant to a depth of 200m, with a minimum FOS of 2.16. Experimental testing of the CAMINO software demonstrated that over a 2,015m figure-8 pattern course, the system accrued 42m of positional error in both the X and Y directions, or a total of 2% of the distance traveled.
ACKNOWLEDGMENTS

First, I would like to thank my thesis advisor, Dr. Stephen Licht of the Ocean Engineering department at the University of Rhode Island. When I embarked upon this journey of pursuing a Masters Degree, I had yet to identify the focus of my research. Prof. Licht’s expertise in underwater vehicles afforded URI with an opportunity to work with a Bluefin SandShark autonomous underwater vehicle (AUV). It was the presence and availability of that underwater vehicle that ultimately spawned the idea for this Thesis. I am lucky to have been in the right place, at the right time, and to have been associated with the right people. Prof. Licht was then exceedingly supportive, reassuring, and patient through my five-year tenure as a Graduate student. I am extremely grateful for his time and energy.

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Finally, but the farthest from least, I would like to thank my family. My wife, Sarah, was instrumental in my successful pursuit of this degree (as she is with any success I have), and I cannot overstate the amount of work she put in to enable my dream of earning a Masters degree. With her as my support system, and our children as my inspiration, I had everything I needed for success. I am forever grateful.
DEDICATION

This Thesis is dedicated to my three children: Lyla Grace, Hadley Caroline, and Theo James. You all are the reason I pursued this degree. Your very existence changed my perspective on life and made me want to better myself and, for that, I owe you everything. I love all of you. Thank you
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CHAPTER 1

PROBLEM STATEMENT

Autonomous underwater vehicle (AUV) navigation and localization in underwater environments is particularly challenging due to the rapid attenuation of radio frequency (RF) signals through water. (Paull, 2014) Due to this condition, sources for underwater communications (e.g. acoustics) tend to be low bandwidth and unreliable, and, once the vehicle dives below the surface, it has no access to global positioning system (GPS) signals. Without access to these means of communication and navigation, underwater vehicles have historically been left two opposing options for underwater navigation and localization solutions: those that are expensive and accurate, or those that are inexpensive and inaccurate.

Past approaches to solve the AUV navigation and localization problem have generally fallen into three categories. First, there are inertial navigation systems (INS) – a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. Linear position and angular orientation are supplied to the INS by Inertial Measurement Units (IMUs). (Shkel, 2010) These systems are also the most expensive, with costs that can well exceed $100,000.

Second, there are acoustic positioning systems – systems that are based on measuring the time of flight (TOF) of signals from acoustic beacons or modems to perform navigation. (Paull, 2014). The two most popular forms of this means of
navigation are long baseline (LBL) navigation systems and ultra-short baseline (USBL) navigation systems.

With LBL navigation, localization is achieved by triangulating acoustically determined ranges from widely spaced fixed beacons. In most cases, the beacons are globally referenced before the start of the mission by a surface ship, a helicopter, or even another AUV. In normal operation, an AUV would send out an interrogation signal, and the beacons would reply in a predefined sequence. The two-way travel time (TWTT) of the acoustic signals is used to determine the ranges. (Paull, 2014) LBL navigation is contingent on the manual emplacement and retrieval of anchored beacons in the mission area. This task is expensive, time-consuming, and negatively impacts one’s ability to perform operations covertly. It also puts personnel, such as deck hands, at risk, by typically requiring them to lean outboard of a low-freeboard vessel to set and haul beacons and their anchors. Also, by relying on external navigational references, constrained to a predetermined mission area, mission length and variance is drastically limited compared to navigation with internal sensors. Beacons that are anchored to the ocean floor are also prone to drift with current and wind forces, which similarly compromises navigation accuracy. Finally, beacons are expensive to replace, which is problematic because they can break free from anchors and drift long distances or fail to release when triggered acoustically.

USBL navigation allows an AUV to localize itself relative to a surface ship, but its accuracy is limited to a short-range operations. Relative range and bearing are determined by TOF and phase differencing across an array of transceivers, respectively. A typical setup would be to have a ship supporting an AUV. (Paull,
2014) In both acoustic based navigation scenarios, the ability to navigate accurately is contingent on the deployment of external components, in the water, and the range is limited to the effective range of the acoustic signals.

Finally, there is dead reckoning – a simple system that relies solely on counting the vehicle’s propeller rotations to estimate its distance traveled. This method requires frequent and often resurfacing of the AUV to correct for quickly accruing positional error. Although this means of navigation is known to be highly inaccurate, it is still the standard means of navigation offered for most small AUVs.

Historically, these three available options for AUV navigation have mapped with the corresponding size and budget of the vehicles they support, in descending order, with respect to accuracy and cost.

Large vehicles with large budgets (e.g. Boeing’s $43M Orca XLUUV) (https://news.usni.org/2019/02/13/41119) tend to navigate and localize with expensive INS solutions. They are able to utilize these systems because they can support the large size, weight, power and costs associated with them. While INS navigation is arguably the most accurate means of navigation possible, the accuracy comes at an often-burdensome cost. These systems are expensive because their combination of onboard sensors, including fiber-optic gyroscopes (FOG), are capable of achieving accurate navigation over long distances and can do so without the need of external components. The technology associated with attaining this metric has historically come at great costs.

Mid-sized vehicles with similarly sized budgets (e.g. Kongsberg’s $1M Hydroid REMUS 600)
tend to navigate and localize with the assistance of LBL or USBL systems. While these workhorse AUVs can be purchased with an optional, proprietary navigation system from Kongsberg, the Navigation Processing Suite (NavP), their ability to navigate accurately is best realized by an accompanying LBL or USBL system. These acoustic solutions function by creating a local acoustic range that can accurately determine a vehicle’s position as long as it stays within said range. LBL and USBL systems are less expensive and lower size, weight, power, and cost (SWaP-C) than the aforementioned INS, making them one the most practical solution for mid-sized vehicles; however, if a transponder beacon drifts away from its anchored position, or if a vehicle moves outside of the local acoustic range, the ability to navigate accurately is lost. This means missions that cover far distances are not possible.

Finally, small vehicles with small budgets (e.g. Bluefin’s $65k SandShark) tend to navigate and localize via the simplest of means, dead reckoning. This rudimentary form of navigation has dominated the world of small AUVs, much to their chagrin. The addition of a single inertial measurement unit (IMU) is typically included with these small AUVs, but its purpose is determining gross vehicle attitude, not aiding navigation. While dead reckoning represents the lowest possible SWaP-C
solution, requiring only the proper characterization of an inexpensive propeller, it is highly inaccurate.

This landscape of available solutions has historically rendered small AUVs as unreliable and, therefore, a non-viable option for most mission scenarios, due to their inability to navigate accurately. Even mid-sized AUVs that rely on LBL or USBL technology are limited to executing missions only within the locally established acoustic range. This has meant the only way of achieving accurate navigation for AUV missions not bounded by the confines of a local acoustic range, was the inclusions of an INS. Moreover, for the wide array of AUVs that have been unable to justify the overbearing cost of an INS, or for those that have been unable to accommodate their large size, weight and power demands, accurate navigation has simply not been possible.

Following the trend of the AUV market for the past two decades, there is significant reason to believe that smaller form-factor AUVs will continue to grow in prevalence, including the A-size AUV. The 4.875” outer diameter of the A-size vehicle is significant because it is the same as the widely used A-size sonobuoy, an electronic sensor dropped, by the millions, into the oceans worldwide to provide the data required to detect, localize and destroy submerged submarines. (https://fas.org/man/dod-101/sys/ship/weaps/sonobuoys.htm.) By developing vehicles that conform to the A-size envelope, commercial AUV companies like Bluefin (SandShark), Hydroid (M3V), and Riptide (µUUV) are hoping to take advantage of the fact that military aircraft and ships already have existing infrastructure to launch A-size sonobuoys. They think this strategy of leveraging the existing LARS
infrastructure will help accelerate the proliferation of AUV usage by reducing the burdens generally associated with launch and recovery operations. Even beyond their potential for military applications, A-size AUVs, like the Bluefin SandShark, offer significant advantages over larger AUV platforms for those in academia, and industry a-like, where shallow water operations in the littoral zone are desirable. This is, again, due to the easing of requirements for storage, transport, and launch and recovery (LAR) operations that are usually associated with larger vehicles. By providing the end user with the ability to one-man carry a vehicle over to the water’s edge and lower into the water by hand, unassisted, small AUVs provide a level of practical functionality that larger vehicles simply cannot offer. Unfortunately, the benefits of this practical functionality have yet to be fully realized because of the inability of these vehicles to perform meaningful missions. This regrettable reality has hindered their acceptance and rendered them as unsuitable for most meaningful military and scientific missions.

It was not until recently that the potential for achieving accurate navigation within an A-sized AUVs became a possibility. Advancements in the size reduction of critical enabling components, such as a Doppler Velocity Logger (DVL), along with the development of sophisticated low SWaP-C navigation software, such as Charles River Analytics’ Combining Aiding Sensors with Multiple IMUs for Navigation Optimization (CAMINO), have made the possibility of integrating a low SWaP-C navigation system into an A-size AUV a potentially feasible achievement.

Knowing that the long-awaited technological advancements required for achieving low SWaP-C navigation on small AUVs may very well currently exist, and
recognizing that the proper assembly of those components could have a major impact on the advancement and proliferation of small AUVs, the genesis for this Thesis was born. It is, therefore, the purpose of this Thesis to assess the feasibility of integrating a complete INS system, including a DVL, into an A-size AUV. At its core, this effort is predominantly a mechanical integration task that solves the non-trivial problem of physically integrating a complete INS solution and DVL into the form factor of smallest commercial AUVs currently available.
The idea of a Small AUV Navigation System (SANS) is not necessarily new, though the definition of small has changed over the course of time. A study performed by the Naval Postgraduate School (NPS) in the late 1990’s entitled “Testing and Evaluation of an Integrated GPS/INS System for Small AUV Navigation” shows that this topic has been considered for some time now. (Yun, 1999) However, this study was focused on integrating these capabilities onto the Naval Postgraduate School (NPS) Phoenix AUV, which was 235 centimeters long, 41 centimeters wide, 25 centimeters tall and displaced 198 kilograms. (Davis, 1996). At the time the study was performed, the AUV landscape was dominated by larger form factor AUVs that were primarily focused on oceanographic research (Gafurov, 2015) and so, in comparison, the Phoenix AUV was considered small. Electronic components size reduction, among other technological and software advances, has given scientists the opportunity to develop compact AUVs. (Gafurov, 2015) In the past 20 years of development, the definition of “small” in the AUV world has gone from a 235cm long, 41cm wide, and 25cm high vehicle that displaces 198kg to a 12.4cm diameter by ~80cm long (depending on configuration) SandShark that displaces ~15kg. Although the definition of small has changed over time, the desire to provide accurate navigation to these platforms has remained the same. This means that there are multiple competing efforts looking to provide accurate, low SWaP-C navigation to today’s small AUVs.
One example of a competing effort looking to solve the navigation and localization problem for small, A-size AUVs, does so by relying on one-way travel-time inverted USBL technology. The proposed system uses a single acoustic transmitter placed at a reference point and is acoustically passive on the AUV, reducing cost and power use, and enabling AUV localization. The AUV has an ultrashort baseline (USBL) receiver array that uses one-way travel-time (OWTT) and phased-array beamforming to calculate range, azimuth, and inclination to the transmitter, providing an instantaneous estimate of the vehicle location. This estimate is fed to a particle filter and graph-based smoothing algorithm to generate a consistent AUV trajectory, without the use of conventional sensors such as a DVL or high-grade INS. (Rypkema, 2017) The system has two defining characteristics: the use of a single periodically broadcasting beacon, which improves usability and lowers cost; and a vehicle-mounted passive USBL array for beacon signal detection and processing, which enables scalability. Acoustic processing calculates both range and angle between the AUV and the beacon, and closed-loop navigation on a low-cost embedded computer is achieved by closely coupling beamforming and particle filtering, allowing the vehicle to fuse acoustic measurements and odometry in a computationally efficient manner. Results from closed-loop navigation experiments have demonstrated the effectiveness of the system at performing absolute navigation, with verification provided by an independent LBL system. In addition, initial results of relative navigation against a moving beacon have demonstrated the feasibility of this operating paradigm, opening a path toward multi-AUV operations over large spatial length scales. (Rypkema, 2018) Although this system provides low SWaP-C navigation, it is
still contingent on externally deployed acoustic sensors in the water, either via the fixed beacon or ship mounted beacon. In either scenario, the ability for the AUV to accurately navigate is lost if the accompanying acoustic signal is lost.

Another approach to solving this problem involves the implementation of a hydrodynamic model-based navigation. This hydrodynamic model-based localization and navigation system was designed to support small (AUVs) that are limited to a micro-electro mechanical system (MEMS) inertial measurement unit (IMU) without the aid of a DVL. The hydrodynamic model was uniquely developed to directly determine the linear velocities of the vehicle using the measured vehicle angular rates and propeller speed as inputs. The project worked to generalize and automate the process of hydrodynamic modeling, model parameter estimation and data fusion (i.e., fusing the localization solution with those from other available aiding sensors and feeding to the navigation loop) so that a model-based localization system can be implemented in any AUV that has backseat computing capability. A major limitation of this work is the inability to estimate the velocity of the water column without more cost intensive additional hardware such as a tactical/navigational grade INS, an acoustic positioning system or an acoustic Doppler current profiler (ADCP). (Randeni, 2018)

Another method sought to demonstrate multi-robot operations for low-cost AUVs via a novel and user-friendly operating paradigm that allows intuitive command and control of an AUV group. With this system, each vehicle is equipped with a low-power and inexpensive acoustic system for navigation and receipt of operator commands. Consisting of a passive array of hydrophones and a timed acquisition and
data processing stack, the system allows each AUV to self-localize relative to a time-synchronized acoustic beacon. Switching between different operational “modes” on the beacon causes it to broadcast different acoustic signals which, when received by the AUVs, result in the vehicles switching between different autonomous behaviors. These behaviors are defined in a beacon-centric coordinate system using pre-defined parameters unique to each vehicle; as a result, the movement of the beacon itself allows the operator to control the group-wide movement of all vehicles concurrently. Field experiments with three SandShark AUVs demonstrated operational mode and beacon movement, both of which were controlled by an operator. However, by installing the beacon on an autonomous vehicle, this paradigm would provide a method for remote command and control of an arbitrarily large number of miniature, low-cost AUVs, without the need for sophisticated navigational sensors or acoustic modems. (Fischell, 2019)

A review of literature shows that, not only is providing accurate navigation capabilities to small AUVs a popular problem, with multiple competing efforts attempting to find a solution across a wide range of varying approaches, but that the implementation of an accurate low SWaP-C navigation system is highly non-trivial. It also shows that most other solutions actively being sought still rely on some form of acoustics to provide localization and navigation capabilities. This is done, primarily, to the lower costs associated with these systems but, unfortunately, this also means that these systems will still be plagued with the same shortcomings of their predecessors. The hydrodynamic model approach does not rely on acoustics, however it admittedly states that it requires a better velocity estimate to be accurate. Once an accurate
velocity sensor is introduced to the system, such as a DVL, there is good reason to argue that the velocity input could be better used in a more sophisticated INS to produce better navigation results rather than the hydro model can produce. For these reasons, a novel solution that utilizes a suite of low SWaP-C components and can achieve INS level accuracy may very well present the best chance to attaining low SWaP-C navigation that is not bound by the limitations of acoustic signals.
Unlike the approaches detailed above, where the primary means of achieving accurate, low SWaP-C navigation for A-size AUVs relied on acoustics, this Thesis seeks to solve the problem by integrating a low SWaP-C INS, and DVL, into an A-size AUV. If successful, this could mark the first time that such a system has been produced. To accomplish this, three criteria must be met.

First, the proper identification and selection of novel, sophisticated navigation software is required. This is true because the high SWaP-C characteristics of existing navigation systems cannot be scaled down to accommodate small AUV. By not having enough internal payload space to accommodate a traditional INS, including their accurate but large, bulky, ring laser gyroscopes or fiber-optic gyroscopes, the low SWaP-C INS selected for this integration must rely on smaller, cheaper sensors.

Advancements in fuzzy logic and Kalman filtering have resulted in software programs capable of increasing the accuracy and reliability of these inexpensive sensors by comparing the output of one sensor to another. This approach of using multiple, low cost sensors is supported by the Central Limit Theorem, which states that multiple noisy, independent measurements of the same system will converge on the true system state. (Dudley, 1999) Considering small, inexpensive sensors are required for achieving the proposed low SWaP-C navigation solution, it is critical that a
a sophisticated software package, capable of making these inexpensive and noisy sensors viable, is properly identified and selected.

Second, the proper identification and selection of the required electronics and enabling sensors is required. This means every component required for full INS functionality, including a DVL, must first be able to meet the minimum requirements for system functionality, and then selected on their ability to minimizing the overall SWaP-C characterization of the system. All of the components and sensors selected must fit within the 4.875” outer diameter envelope of a Bluefin SandShark, but the optimization of SWaP-C must also be considered. In practice, this means that if two competing sensors can both satisfy the minimum requirements set forth for functionality, the one with the lower SWaP-C characteristic should be selected.

Finally, the selected hardware and software must be physically integrated into a payload module that is no greater than 4.875” in diameter, ensuring it can be attached to a Bluefin SandShark AUV. The payload module must be pressure tolerant to a depth of 200m, the maximum operating depth of the SandShark, neutral or positively buoyant, and it must also be designed such that fabrication and manufacturing costs are not prohibitively expensive. Finally, the payload module must address the challenges associated with the wiring, assembling, and installing small electronics components into a small enclosure.
CHAPTER 4

SOFTWARE SELECTION

Charles River Analytics’ Combining Aiding Sensors with Multiple IMUs for Navigation Optimization (CAMINO) was selected as the navigation software for this Thesis. CAMINO uses an Extended Kalman Filter (EKF) to combine noisy measurements from multiple IMUs, and direct observations of vehicle state from aiding sensors (e.g., depth sensors), to produce an accurate estimate of AUV geolocation and orientation. (Eaton, 2011) CAMINO is built using the robot_localization package available on the open-source Robot Operating System (ROS) platform (Moore & Stouch, 2016). ROS robot_localization is the standard navigation package onboard Clearpath Robotics’ Husky unmanned ground vehicles. The CAMINO EKF combines data from multiple, noisy sensors to produce highly accurate position estimates. This fused data produces estimates of acceleration, velocity, and pose, which are combined with the previous location estimate to provide an updated location estimate in place of a GPS position. The CAMINO system architecture is shown in Figure 1.
Six degrees of freedom (6DOF) are needed to fully describe a UUV’s location and orientation: latitude (x), longitude (y), depth (z), roll (θ), pitch (φ), and yaw (ψ). Low-SWAP-C sensors can directly measure four of these DOF: depth sensors measure the z dimension, magnetic compasses measure ψ orientation, and inclinometers measure θ and φ angles.

DVLs have reasonable SWAP-C requirements and can measure x and y velocity (x \dot{} and y \dot{}) as long as bottom lock can be maintained, which is generally possible in littoral environments. Low cost IMUs are also available to measure acceleration along all 6DOF (x \ddot{}, y \ddot{}, z \ddot{}, \theta \ddot{}, \phi \ddot{}, \psi \ddot{}), and GPS is a viable option for measuring x, y, and z location when an AUV is surfaced. Table 1 summarizes how currently available low-SWAP-C sensors map to these DOF. In combination, these sensors should be able to provide adequate navigation accuracy, but the challenge is fusing information from these various sensors to overcome the lack of a direct measurement for x and y.
CAMINO combines measurements from several low-SWaP-C, limited-accuracy sensors via a novel hierarchical particle filter to yield a high-accuracy navigation solution that meets the SWAP-C requirements of small AUVs. Specifically, CAMINO uses several small, low-cost, low-power IMUs to independently measure the linear and rotational accelerations of the platform. These measurements are combined in a novel hierarchical particle filter algorithm to produce multiple estimates of the platform’s 6DOF state. The hierarchical particle filter also takes input from a variety of other low-SWaP-C sensors (called aiding sensors), and uses these measurements to determine the best estimate of the platform’s location and orientation. By combining several low-SWaP-C sensors and taking advantage of each sensor’s strengths, CAMINO produces a high accuracy estimate of the AUV’s 6DOF state, enabling high-fidelity navigation. (Eaton, 2011)

The first critical component of the CAMINO system is multiple IMUs. The acceleration measurements from each IMU are double-integrated to produce location and orientation estimates. Each IMU, in isolation, accumulates error, or drift, over time, eventually making accurate localization and pose determination impossible. However, the drift along each dimension is independent of the other dimensions, and the drift from each IMU is independent. Therefore, using multiple IMUs provides

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DOF Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth Sensor</td>
<td>z</td>
</tr>
<tr>
<td>Compass</td>
<td></td>
</tr>
<tr>
<td>Inclinometers</td>
<td>θ, φ</td>
</tr>
<tr>
<td>Doppler Velocity Log (DVL)</td>
<td>x, y</td>
</tr>
<tr>
<td>Inertial Measurement Unit (IMU)</td>
<td>x, y, z</td>
</tr>
<tr>
<td>Global Positioning System (GPS)</td>
<td>x, y, z (when surfaced)</td>
</tr>
</tbody>
</table>
CAMINO with an oversampled state-space, and while there may be no single correct measurement, the state estimate obtained by combining these erroneous measurements is more accurate than any of the individual measurements (Bancroft, 2009; Guerrier, 2009).

CAMINO further improves navigation accuracy by incorporating observations from several aiding sensors, which do not suffer from accumulated drift (Hegrenaes et al., 2009). As noted in Table 1, these aiding sensors allow direct observation of 4 DOF \((z, \theta, \phi, \psi)\). Two other dimensions \((x, y)\) are indirectly measured by integrating the velocity measurements from a DVL. GPS is used to directly measure \(x, y, \) and \(z\) location when the UUV is surfaced. (Eaton, 2011)

CAMINO combines these aiding sensor measurements with the estimates from multiple IMUs using a multi-stage, hierarchical particle filter. As in a classic particle filter (Carpenter et al., 1999), each particle represents a slightly different estimate of the 6DOF platform state, and particles are updated in three stages: prediction (based on measured platform motion), proposal (based on expected measurement error), and correction (based on direct observation of platform state). However, because the classic particle filter does not have a mechanism for modeling the different error rates of different IMUs, CAMINO couples each IMU to its own initial particle filter that performs prediction and proposal based on the individual IMU’s error rate. The proposed particles from all the initial particle filters are then accumulated in a second-stage aggregate particle filter. This aggregate particle filter performs correction, but because CAMINO’s aiding sensors can only directly observe four of the six state components \((z, \theta, \phi, \psi)\), the correction step cannot proceed as in the classic particle
filter. Instead, the aggregate particle filter reweights particles based on both direct observation and particle density to reduce drift that would otherwise occur in the x-y plane. Particles that are inconsistent with the observed platform state or that differ from the majority of particles in the x-y plane are given a lower weight and eventually eliminated and replaced by copies of higher weighted particles during weighted resampling. Weighted resampling in the hierarchical particle filter differs from the classic particle filter because each initial particle filter receives a unique set of particles sampled from the entire particle population. This has the added benefit that if one initial particle filter generates no quality state estimates (perhaps due to a bad IMU reading), the aggregate particle filter can still provide that initial particle filter with some quality state estimates sampled from the populations of other initial particle filters. The hierarchical nature of the filter provides a convenient framework for combining relative motion estimates of differing reliabilities with both constant and intermittent direct state observations, as well as particle-density information, to maintain a reliable 6DOF platform state estimate and model the complex error distribution of the platform state accumulated over time. (Eaton, 2011)

CAMINO has been successfully demonstrated on AUVs. On an AUV traveling a 3.1-km straight-line path, the system accumulated only 13.76 meters of error, or 0.44% of the distance traveled. While this metric is not as accurate as some of the industry leading INS, such as the iXblue PHINS, which has a stated accuracy of 0.1% of the distance traveled when aided by a DVL, this system is an order of magnitude less expensive, making its integration onto an A-size a feasible option. (http://www.ixblue.com/sites/default/files/datasheet_file/ixblue-phins-03_2017.pdf_)
CHAPTER 5

ELECTRONIC COMPONENTS SELECTION

To enable CAMINO functionality, a suite of electronics and a DVL are required. Considering Charles River Analytics originally developed CAMINO as a low SWaP-C navigation system, the electronics associated with CAMINO were already optimized for low SWaP-C. These electronics include IMUs, computer, Ethernet switch, data storage/memory, and a power converter. In addition to mechanically integrating these core CAMINO electronics into the payload module, the DVL and its own set of electronics are also required. A list of the selected components with low SWaP-C characteristics is provided in Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>P/N</th>
<th>QTY</th>
<th>Extended Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU</td>
<td>Lord Microstrain</td>
<td>6253-4220</td>
<td>4</td>
<td>$6,410</td>
</tr>
<tr>
<td>Computer</td>
<td>ADL Embedded Solutions</td>
<td>ADLE3800PC-E3827</td>
<td>1</td>
<td>$1,419</td>
</tr>
<tr>
<td>Ethernet</td>
<td>RTD Embedded Solutions</td>
<td>LAN10257HR</td>
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<td>$445</td>
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<tr>
<td>Memory</td>
<td>Samsung</td>
<td>MZ-M5E250BW</td>
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<td>$108</td>
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<tr>
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<td>CUI Inc.</td>
<td>102-3188-ND</td>
<td>1</td>
<td>$40</td>
</tr>
<tr>
<td>DVL</td>
<td>Teledyne Marine</td>
<td>PATH-OEM-OPT001-012</td>
<td>1</td>
<td>$15,000</td>
</tr>
</tbody>
</table>

| Total Electronics Cost | $23,422 |
The selection of electronics described in Table 2 represents the complete set components that must be mechanically integrated into the proposed navigation payload module for the Bluefin SandShark. The low SWaP-C characteristics of most of the electronics listed have been available for a number of years now, however, a low SWaP-C DVL was not available until recently.

The CAMINO software was originally developed using Teledyne Marine’s Workhorse Navigator DVL as its velocity input. This particular model of DVL has been widely used in military and commercial vehicles for many years and is considered to be the industry standard, however it is large, heavy, and expensive. At the start of this Thesis, five years ago, Teledyne was offering a smaller version of this same technology called the Explorer. The Explorer DVL provided nearly the identical performance specs as the larger Navigator DVL, except for depth rating, but it did so in a considerably smaller form factor. Considering it was, at the time, the smallest DVL offered by Teledyne, the Explorer DVL was actually selected as the candidate DVL for this Thesis and considerable design efforts were put forth to find a way to mechanically integrate it into a 4.875” outer diameter pressure vessel. However, because of the on-going and continued reduction in the size of electronic components, Teledyne was able to release an even smaller form factor DVL in 2017 called the Pathfinder. A comparison of performance and size specifications for these three DVLs is presented in Figure 2.
Although the product selection guide shown in Figure 2 indicates that both the Explorer and Pathfinder can be applied to small diameter AUVs (4” min, ID), the length of engagement required for sealing the DVL inside a pressure vessel housing is different for each system and greatly impacts the feasibility of integration. For it to be feasible for either of these DVLS to be integrated into a small AUV, they must be procured in an original equipment manufacturer (OEM) configuration. The OEM version of these products includes the DVL transducer head, and its associated electronics, as standalone entities that are not housed in an enclosure. This means that the system cannot function without first being designed and integrated into a custom designed enclosure that is depth rated to accommodate the operational depths of the DVL, or target integration vehicle, in the event the vehicle depth rating is less than the
DVLs. A side-by-side comparison of the OEM versions of the Explorer and Pathfinder is presented in Figure 3.

![Figure 3: Side-by-side comparison of the OEM versions of the Explorer DVL (top) and Pathfinder DVL (bottom).](image)

(Image provided by Teledyne Marine)

As seen in Figure 3, the size reduction that achieved between the Explorer and the Pathfinder is significant. Not only is the DVL transducer head smaller, but the accompanying DVL electronics are significantly smaller, as well, including their associated cabling. It is also important to note the way these two DVLs seal, as previously mentioned.

The Explorer DVL achieves its seal by being the male glad of an o-ring sealing regime and by carrying the require o-ring for sealing. These male and female sealing geometries are well defined in the Parker O-ring Handbook and are extremely successful at generating a depth rated seal as long as they are designed, machined, and implemented correctly. With the DVL functioning as the male gland, and with it
carrying the o-ring, the housing of the DVL must be larger than what is minimally required for functionality. This is due to the fact that the o-ring groove has an associated depth that must be present for proper compression and sealing to occur. This required increase in the diameter of the male gland makes the overall size of the DVL larger than it needs to be. Also, to affix the DVL to the pressure vessel housing a large flange with bolt holes is present. This feature necessitates that the pressure vessel housing have a large, flat, corresponding flange cut out with matching bolt holes for proper affixing and sealing. The design of the Explorer DVL ultimately did not achieve the level of size reduction optimization required for feasible and realistic integration into an A-size AUV. Conversely, the Pathfinder DVL sought to solve these problems, and did so in a package that was truly meant for small AUVs.

The design of the Pathfinder improved upon the shortcomings of the Explorer by moving the o-ring groove to the female gland. Although less intuitive and less used than its opposing option, the decision to locate the o-ring groove in the female gland allowed Teledyne to remove extraneous material and reduce the size of the transducer head down to its optimal minimum. The Pathfinder design also eliminated the large flange and bolt holes that were used by the Explorer for affixing, rather it seals to a pressure vessel housing with four screws that interface with blind tapped holes on the inward facing surface of the DVL (the side opposite of the transducer face). While this elimination further reduced the size of the Pathfinder and further increased its feasibility for integration onto small AUVs, the act of removing the mounting flange greatly increased the complexity involved with affixing the Pathfinder to a custom designed housing. This is simply true because a set of bolt holes that are accessed
externally to the vehicle are easier to engage and use than a set of blind tapped holes that must be accessed internally. In fact, accounting for this particular mounting feature proved to be one of the more challenging mechanical design considerations associated with the development of the custom pressure vessel housing.

After thoughtful consideration of the two available options, the Pathfinder DVL was selected as the best DVL for this effort. As mentioned above, if two systems have the same performance specs, but one offers lower SWaP-C characteristics, the lower SWaP-C component should be chosen. Therefore, despite the challenges associated with mechanically integrating the Pathfinder into a pressure vessel housing, given the location of its mounting features, it was still the best option.

With a suite of low SWaP-C electronics and a low SWaP-C DVL selected, the next step was to access the feasibility of mechanically integrating said components into a pressure vessel housing that is only 4.875” in diameter.
CHAPTER 6

MECHANICAL DESIGN

The mechanical design of the pressure vessel housing was extremely non-trivial. To ensure the design was well suited for its intended task, it needed to account for five critical consideration. First, the design needed to accommodate a suite of electronics, including a DVL with a known mechanical mounting challenge, inside of a small diametrical footprint. This is consideration represents the primary goal of this integration problem. Second, the design needed to ensure that manufacturing and fabrication costs were not prohibitively expensive. This is important because the final system needs to have low SWaP-C characteristics for it to be considered as a feasible navigation option for small, low-cost AUVs. The price of the electronics and DVL are fixed, but the cost to manufacture can be positively or negatively affected, depending on the choices made during the design process. Third, the design needed to be executed in a way that accounted for how wiring and assembly activities would be completed. This is critical when considering the fact that the electronics are housed in a very small volume, making ease of accessibility a potential challenge. Fourth, the design needed to be pressure tolerant to a depth of 200m, the maximum operating depth of the Bluefin SandShark. Although the Pathfinder DVL is depth rated to 300m, the SandShark cannot meet that metric and, therefore, there was no reason to design the navigation module to meet depth ratings lower than 200m. Finally, the design
needed to ensure that the end system produced would be, at a minimum, neutrally buoyant, with slightly positive buoyancy being the desired goal.

The number of iterations attempted before finding the optimal arrangement of components was substantial, and an attempt to explain every design decision changed along the way would be prohibitively long to describe. Therefore, this section will focus on describing only the final configuration selected for manufacturing and fabrication, and it will not necessarily detail all of the iterative steps and intermediate designs attempted along the way.

Because of its strength to weight ratio, and its ability to be easily machined, 6061-T6 aluminum was chosen as the material for the pressure vessels and end caps in this design. This particular aluminum alloy is the industry standard and preferred metal used in nearly all pressure vessel housings designs. All components were also anodized with Type III hard coat anodizing to protect them from the corrosive salt water environment they would be routinely subjected to.

With a material and corrosion protection method chosen, the first mechanical integration hurdle was determining how to fit all of the electronics into a small, cylindrical housing. A review of each electronics’ specification confirmed that they were each individually small enough to fit inside the housing, though it was clear early on that the final aggregate of all the sensors would consume nearly all of the available internal space. For this reason, the proper orientation would be critical. As mentioned before, the DVL also presented its own unique set of integration challenges. Because of the difficulties associated with mounting and sealing the DVL, it became the component that the rest of the mechanical design revolved around. The final DVL
pressure vessel design chosen for manufacturing and fabrication is shown in Figure 4, as a solid, and then again in Figure 5, as transparent, so that the details of the internal cavity can be seen.

![Figure 4: DVL pressure vessel.](image1)

![Figure 5: Transparent view of DVL pressure vessel](image2)
The diametrical body of the DVL transducer, itself, represents the sealing surface of male o-ring gland. This means that the outer diameter of the transducer casing was purposefully selected by Teledyne to match the diameter of a male gland for a 2-152 size o-ring. Teledyne also provided the corresponding design specification for the female gland, which, in this application, is also where the o-ring groove is located. The mechanical drawing provided by Teledyne has been included in Appendix 1. To create the female gland, a socket needed to be milled into the cylindrical body of the pressure vessel housing. This requirement meant that the pressure vessel housing would need to be machined for a billet, or single, solid piece of metal. Another feature that necessitated fabrication from a billet was the 45° conical beam of the DVL signal, which requires unobstructed propagation. Because the transducer head could not stick proud of the 4.875” diameter, it needed to be recessed inside the pressure vessel to a depth that corresponded with the diameter of the DVL being tangent with the outer diameter of the pressure vessel. This is geometry seen in Figure 6, where, on the left hand side of the image, the outward facing face of the DVL is touching the outer diameter of the pressure vessel housing.

Figure 6: Required DVL depth engagement.
Due to the requirement that the 45° conical beam signal have unobstructed propagation, a swath of the pressure vessel housing need to be removed. This unwanted material is seen in the right hand view of Figure 6. By executing a 45° swept cut under the DVL transducer’s outward facing face, the material was successfully removed, allowing for unobstructed signal propagation. This step is shown in Figure 7.

![Figure 7: Material removal enabling unobstructed signal propagation.](image)

With the DVL properly positioned inside the pressure vessel, the next step was to include all of the o-ring sealing features required for depth-rated water tightness. This particular facet of the design represented an opportunity to lower the overall cost associated with fabrication. By choosing to integrate as much complexity as possible into the DVL pressure vessel design, considering it was already being machined from a billet, the opportunity to reduce the complexity of the other components became possible. This meant that the terminating ends of DVL pressure vessel would be male glands that carried the redundant, double o-ring grooves required for sealing the DVL.
pressure vessel to the other pressure housings. It would also include the geometry required for attaching one pressure vessel section to another, known as an Ortman Key. The Ortman Key is a means of attaching one pressure vessel section to another by feeding a Teflon filament into corresponding, opposing grooves on male and female mating glands. The Teflon filament fills the space created by the two grooves and overlaps each one by half, respectively. This configuration means that one component cannot decouple from the other without shearing the entire Teflon cord. The sealing surfaces, and Ortman Key groove, are shown in Figure 8.

![Figure 8: O-ring and Ortman Key grooves.](image)

The next features integrated into the design were the mounting holes required for affixing the DVL to the pressure vessel. The DVL affixes itself to the pressure vessel via blind tapped holes that are located on its inward facing face (the side opposite of the transducer face). By intentionally keeping the distance from the openings of the pressure vessel to the centerline of the DVL as short as possible, the ability to access
the blind tapped holes by hand and engage them with a screw was realized. In addition to the four blind tapped holes, the DVL also has a dowel pin that ensures proper alignment of the sensor within the pressure vessel housing. This step in the design also included the removal of all other remaining internal material, thus creating the internal cavity and allowing pass through from one opening to the other. This step required calculating the wall thickness required to achieve a 200m depth rating.

To calculate the required wall thickness, a spreadsheet generated by Roger Cortesi of MIT in 2002 entitled “Failure Modes of Simple Pressure Vessels” was used. This spreadsheet allows pressure vessel designers the ability to quickly determine the required wall thickness for pressure vessel tubes and end cap bulkheads by simply inputting the material properties of the proposed components (Young’s modulus, yield strength, and Poisson’s ratio). The spreadsheet uses the material properties entered to generate thickness to outer diameter ratios (T/OD) for a given depth. Per the spreadsheet, a 6061-T6 aluminum pressure vessel rated to 200m needs to have a T/OD ratio of 0.023 to resist cylindrical buckling and a T/OD ratio of 0.048 to resists end cap yielding. For a pressure vessel with an outer diameter of 4.875”, these two ratios equate to wall thickness of 0.112” for the pressure vessel and 0.234” for the end cap bulkhead. The spreadsheet showing the calculated ratios can be seen in Appendix 2. The minimum pressure vessel and end cap wall thicknesses chosen for this design were 0.125” and 0.25”, respectively. The minimum pressure vessel wall thickness occurs in two locations. The first occurs between the inner diameter of the pressure vessel and the Ortman Key grooves of the male gland. The second occurs between the o-ring grooves for the female gland of the DVL and the wall that is formed when
material is removed moving inward from the opening up to an offset distance of 0.125” from the female o-ring grooves. The internal cavity created by removing all internal material up to the minimum wall thickness and the clearance holes for the DVL mounting screws and dowel pin are shown in Figure 9.

Figure 9: Internal Cavity with DVL mounting holes.

Recognizing that the large, internal boss created around the DVL was solid metal, two options for what to do with the feature were considered. First, the material could be removed. This would reduce the overall weight of the system and help achieve low SWaP-C and positive buoyancy, both critical goals to achieve. Although both of these outcomes were enticing, they were, unfortunately, unable to be realized because today’s fabrication methods cannot execute material removal operations in spaces that small and that deep, at least not at a price that is competitive with the option of just leaving the material in-place. Unable to remove the material, the second option of
using the material as a location for affixing the internal electronics became the obvious solution for how to leverage the feature and make the most out of it.

Because the weight of the CAMINO and DVL electronics are so small, the ability to mount them onto a cantilevered support structure is possible. To enable this functionality, drilled and tapped holes were introduced to the “dead space” of the large boss around the DVL, as shown in Figure 10. This approach not only made use of material that would have otherwise been unused, it also helped to solve the problem of how to ease the burdens associated with the wiring and assembly of electronic components in such as small volume. Because the distance between the large flat face of the internal boss and the openings of the pressure vessel were kept as short as possible, mounting the electronics to cantilevered mounts results in the electronics being mostly exposed and easily accessible for wiring and assembly.

![Figure 10: Mounting holes for CAMINO and DVL electronics.](image-url)
To finish the design of the DVL pressure vessel, two more features were included. First, dowel pin holes were introduced to resist rotational movement of one pressure vessels to another, once they are mated. Second, removal features were included that allow a small removal jacking tool to be used for the purpose of easily separating one pressure vessel section from the others. These features are seen in Figure 11.

![Figure 11: Dowel pin holes and removal features.](image)

With the DVL pressure vessel design complete, the next step was to design the electronics mounts for both the CAMINO and DVL electronics. The DVL electronics’ enclosure provided four blind tapped holes along it’s long sides for mounting, but their location along the these sides of the enclosure, rather than the end that would have naturally interfaced with the mounting holes in the large internal boss, posed a design challenge that required a clever solution. Fortunately, there was enough space between
the enclosure and the ID of the pressure vessel that a cantilevered mount comprised of two extending arms that reach out and engage with the mounting holes on the DVL enclosure was designed. This mount is shown in Figure 12.

![DVL electronics mount](image)

**Figure 12: DVL electronics mount.**

For the CAMINO electronics, a much simpler cantilevered mount was designed. This mount simply extended a flat mounting surface out and away from the large flat face of the internal boss. By providing a flat mounting surface that was nearly on the vertical centerline, components could be mounted on the top and bottom side to make the best usage of the available volume. To help reduce weight and provide locations for wire pass throughs, lightening holes were cut into the large, flat cantilevered plate that is shown in Figure 13.
To ensure that all of the electronic components actually fit within the available envelope, as anticipated, models were generated for each electronics component and then integrated onto their respective chassis. This is shown in Figure 14.

The configuration shown in Figure 14 represents a nearly complete CAMINO system, however it is still missing the four IMUs that are so critical for proper functionality. These components posed their own mounting challenge because they have associated cabling and connectors that are nearly the same size as the...
components themselves. To account for this, a custom mount was designed that nested the IMUs in both horizontal and vertical directions. The mount was designed to interface with the bottom side of the DVL electronics enclosure and made good use of that available but otherwise unused volume. This mount, populated with the four IMUs is shown in Figure 15.

![Populated IMU mount.](image)

Figure 15: Populated IMU mount.

It is important to note that all of the electronics mounts were 3D printed with PLA filament. This was done to lower the SWaP-C characterization of the finalized system by choosing a material that was light weight and a manufacturing process that was inexpensive.

With the completion of the IMU mount, all of the electronics required for full CAMINO functionality were housed inside the internal volume of an A-size AUV, however the design was not complete. To bring the design to fruition, pressure vessel tubes had to be designed to slide over the electronics components and interface with the male o-ring glands on the ends of the DVL pressure vessel. Because the decision
was made, early on, to include as much complexity as possible in the DVL pressure vessel design – resulting in the inclusion of the male o-ring gland - the design of the corresponding tubes for mating could be made extremely simple. These tubes represented the female o-ring gland – which is effectively nothing more than an appropriately sized bore hole– and the only complexity involved in their design was the inclusion of the Ortman Key groove. By taking this approach, stock aluminum tubing could be used to produce these vessels with a minimal amount of lathing. Also, by taking this approach, the opportunity to produce tubes of different lengths is possible. An image showing both pressure vessel tubes, one solid and one transparent, attached to the DVL pressure vessel is shown in Figure 16.

![Figure 16: Simple pressure vessel tubes.](image)

With the design of the tubes complete, the final step remaining was completing the design the end cap bulkheads. Because each SandShark section has one male gland and one female gland on opposing sides that serve to daisy chain all of the sections together, it was important to create two different end cap bulkheads, one that
terminated in a male gland and one that terminated in a female gland. Also, because of
the decision to make the design of the pressure vessel tubes extremely simple, the
complexity associated with the male gland and o-ring grooves fell upon the end cap
bulkheads. This meant that each end cap bulkhead would need to have at least one
male gland, but then one would have a second male gland while the other would have
a female gland to allow for the daisy chain connectivity. These end cap bulkheads also
needed to house bulkhead fittings for underwater cabling and a pressure port for
vacuuming and backfilling. To accommodate these needs, each bulkhead was
designed with two #4 SAE port fittings, or what are commonly known as o-ring boss
(ORB) fittings. This design for these SAE ports provides the geometry required for
making an o-ring seal underneath a pressure fitting. Conveniently, the same thread
size is used by both the bulkhead connectors and the pressure fittings, meaning a
single hole callout on the mechanical drawing can be used. Per the wall thickness
calculation described earlier, the end cap bulkhead walls were designed to be 0.25”
厚. The male-male end cap bulkhead designed for this effort is shown in Figure 17
while the male-female end cap bulkhead is shown in Figure 18.
Figure 17: Male-male end cap bulkhead

Figure 18: Male-female end cap bulkhead.
It is important to note that the design of the female gland of the bulkhead was done in such a way that it is able to be interfaced and seal with the male gland of another bulkhead, or the male gland of the DVL pressure vessel. This was not a requirement, rather the result of recognizing the benefit of modularity when designing these kinds of designs. The depth of the female gland only needed to be deep enough to accommodate the terminating male gland on the Bluefin SandShark, which only has an Ortman Key groove, and no o-ring grooves. While an end cap made to the depth of just an Ortman Key groove would have successfully satisfied the requirements, it would have served but only one purpose. Rather, by designing the female gland to be deep enough to accept the male glands designed into the other components, interfacing with the SandShark is still possible – it simply does not use the full length of engagement available – but the number of possible other configurations achievable is dramatically increased.

Upon the completion of modeling, a mechanical drawing for each component was generated. These drawings server as the means of communication between the design engineer and the machinist fabricating the parts. These drawings were drawn to meet Basic Geometric Dimensioning and Tolerancing standards and are included in Appendices 3 through 6.
CHAPTER 7

MECHANICAL DESIGN VALIDATION

To validate the mechanical design, Finite Element Analysis (FEA) simulations were performed on each component of the pressure vessel housing. These simulations were performed to ensure the designs sufficiently met the 200m depth requirement, with a particular emphasis on the DVL pressure vessel. Because the spreadsheet used to calculate the pressure vessel and end cap wall thicknesses used simple hoop strength calculations, the introduction of the large internal metal boss for mounting and sealing the DVL transducer posed a potential concern. The concern was that the introduction of the internal metal boss, and the associated DVL cavity, resulted in the elimination of a continuous hoop, and therefore may have potentially eliminated the simple hoop strength assumptions. This area is shown in Figure 19.

Figure 19: Cross section of DVL pressure vessel with hoop discontinuity
As Figure 19 shows, at this particular cross section, which is directly at the centerline of the DVL pressure vessel - the location of the large internal boss and DVL cavity - is not a continuous hoop. This particular hoop discontinuity was the driving force behind confirming explicit validation through FEA simulations and, to be thorough, FEA simulation were performed on all of the other components, as well.

The FEA simulations were performed using the Static FEA capabilities of Solidworks, a computer aided design (CAD) program. The results of the FEA simulations are presented in Figure 20 through Figure 23.

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<th>Type</th>
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<td>von Mises Stress</td>
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</table>

**Figure 20:** Von Mises stress results from DVL pressure vessel FEA simulation (deformation scale of 298:1)
Figure 21: Von Mises stress results from Simple pressure vessel FEA simulation (deformation scale 420:1)

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</tr>
</thead>
<tbody>
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Figure 22: Von Mises stress results from male-male end cap FEA simulation (deformation scale 64:1)

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The results presented in Figure 20 through Figure 23 are shown at varying deformation scales to exaggerate the visualization of the results. Each individual component of the pressure vessel housing successfully passed its respective FEA simulation, including the DVL pressure vessel. The criterion used for design validation was Von Mises stress. Von Mises stress is always positive in sign and depends on the whole stress field, making it a widely used parameter in mechanical design, especially for the assessment of yield criteria. (Pegoretti, 2002) In this application, Von Mises stress it as an indicator of the average stress level in the material of the component, where the higher its value, the higher the possibility of damage occurrence. The Von Mises yield strength of 6061-T6 aluminum is $2.750 \times 10^8$
Pascal (N/m²). This value was used to determine the safety factor of each component by dividing the maximum Von Mises stress determined via the simulation by it. The maximum Von Mises stress and associated factor of safety for each component is presented in Table 3.

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<tr>
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<th>Simple PV</th>
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<th>Male-Female EC</th>
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<td>Maximum Von Mises</td>
<td>1.119e⁸ Pascal</td>
<td>1.042e⁸ Pascal</td>
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<td>Factor of Safety</td>
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<td>2.63</td>
<td>2.97</td>
<td>2.16</td>
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Although each component successfully passed the FEA simulations, the male-female end cap had a maximum Von Mises stress of 2.114e⁸ Pascal, which resulted in an initial FOS of only 1.30; a value considerably lower than the average 2.68 factor of safety for the other three components. The peak Von Mises stress that drove this lower FOS only occurred in one location on the model, which was in the filleted corners of the Ortman Key opening, as shown in Figure 24.
Because the hot spot anomaly only occurs in the male-female end cap model, despite the same feature occurring in the simple pressure vessel model without the same results, it is most likely an erroneous result. To confirm this, the FEA results were filtered, via a feature called iso-clipping, to show only the areas in the model experiencing Von Mises stresses that result in a factor of safety of less than 2.00, or only those areas experience stresses in excess of $1.375 \times 10^8$ Pascal. The iso-clipped results are shown in Figure 25, where they are highlighted by red circles. These areas, like the hot spot, only occur in the filleted corners of the Ortman Key groove openings, which is a non-critical feature that occurs in a free-flood location. For this reason, their occurrence is not of concern for this application. To determine the actual FOS for this component, the iso-clipping feature was used to determine when stresses started to build in an area that was critical to the design. These results are shown in Figure 37, where the first instance of stresses occurring in a critical location are experienced. The Von Mises stress associated with this location is $1.269 \times 10^8$ Pascal, or a FOS of 2.16. This FOS better represents the true FOS of this part and was, therefore, included in Table 3 above.
Figure 25: Iso-clipped FEA results showing areas that experience a FOS < 2.000

Figure 26: Iso-clipped FEA results showing where the 2.16 FOS occurs for the male-female end cap.
CHAPTER 8

TESTING AND EVALUATION

To confirm that the CAMINO Navigation Module developed for this effort functioned properly, experimental testing with the University of Rhode Island’s Bluefin SandShark was planned. However, due to firmware issues that required the vehicle be sent back to Bluefin for upgrades, the vehicle was not available for planned testing activities. As a result, alternative testing arrangements were made to test the CAMINO Navigation Module as a standalone navigation module by towing it behind a boat. This methodology, while not 100% analogous to testing on an actual vehicle (e.g. there was no GPS input to CAMINO), was able to prove functionality of the system by confirming it tracked the positional changes experienced while under tow.

To accommodate this unanticipated testing arrangement, additional mechanical parts were required, and so, a nose and tail cone were specifically designed to support towed testing. The nose cone was designed with a female gland to interface with the male gland of the forward facing end cap. It also was designed with a hole at the leading edge to allow the required underwater cable to pass from the forward bulkhead, through the opening and up to the topside power supply. The tail cone was designed with a male gland to interface with the female gland of the aft facing end cap. It was also designed with stabilizing fins that are the NACA0014 foil profile. The nose and tail cone designs are shown in Figure 27 and Figure 28. The parts were 3D printed out of PLA and attached to the CAMINO module, as shown in Figure 29.
Figure 27: Nose cone for towed testing

Figure 28: Tail cone for towed testing
A test plan was developed to demonstrate how CAMINO tracks its path by measuring positional changes over time. Testing activities were planned for the Point Judith Harbor of Refuge, and multiple waypoints were established to define predetermined routes, such as a large rectangle and a set of figure-8s. The latitude and longitude of each waypoint is provided in Table 4 and a map of the waypoints location in the Harbor of Refuge is provided in Figure 30.

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Figure 30: Map showing tow test waypoints in the Point Judith Harbor of Refuge
Using the waypoints shown in Figure 30, two patterns were established to demonstrate how CAMINO tacks a path by measuring its positional changes over time. The waypoints used to define the paths of these two patterns are detailed in Table 5. The patterns chosen were a large rectangle and a set of figure-8s.

Table 5: Tow test patterns to demonstrate CAMINO

<table>
<thead>
<tr>
<th>Test</th>
<th>Waypoint Tracks</th>
<th>Distance</th>
<th>Estimated duration @ 3 knots</th>
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<tr>
<td>Rectangle</td>
<td>1 → 2 → 7 → 8 → 1</td>
<td>2 km</td>
<td>22 minutes</td>
</tr>
<tr>
<td>Figure-8</td>
<td>7 → 11 → 5 → 10 → 3 → 9 → 4 → 10 → 6 → 11 → 8 → 7</td>
<td>2.015 km</td>
<td>22 minutes</td>
</tr>
</tbody>
</table>

The patterns detailed in Table 5 were followed during an experimental tow test that was performed on 4/18/19. The CAMINO Navigation module was successfully towed behind a United States Marine, Inc. (USMI) ridged hull inflatable boat (RHIB) at a speed of approximately 3 knots.

To ensure the positively buoyant pressure housing maintained a depth of ~1m below the surface while under tow, two 1.5 pound clumps of lead weight were added to the underside of the CAMINO module. The first clump was positioned just aft of the junction between the nose cone and the rest of the CAMINO module while the second was positioned just forward of the junction between the tail cone and the rest of the CAMINO module. By positioning the weight on the underside of the module, the Center of Gravity (CG) was lowered and the separation distance between the vehicle’s CG and Center of Buoyancy (CB) was increased, resulting in increased vehicle stability with respect to roll.
A Dyneema rope was used as a towline for this test. It was wrapped around the CAMINO module both forward and aft of the DVL transducer cut out and then ran forward to the nose. It continued up and alongside an underwater cable that ran from the module to the RHIB. Considering this CAMINO module was designed specifically for integration with the Bluefin SandShark AUV, it did not have proper mounting features for affixing a towline. As a result, Gorilla Tape was used to ensure a positive and secure connection between the towline and the CAMINO module. The ‘rigged for towing’ CAMINO module is shown in Figure 31 with the USMI RHIB in the background.

Figure 31: CAMINO module rigged for tow testing
During the tests, the RHIB’s GPS location was recorded as it transited along the predefined routes detailed in Table 5. These recoded tracks, along with the waypoints used to define the routes for the rectangle and figure-8 patterns, are shown in Figure 32 and Figure 33, respectively.

Figure 32: Plot of the RHIB’s GPS location during the rectangular pattern tow test
Figure 33: Plot of the RHIB’s GPS location during the figure-8 pattern tow test

As the RHIB maneuvered its way along the two paths, the CAMINO module was towed behind and recorded its accelerations via the on-board IMUS and its velocity with the DVL. These values were supplied as inputs to the CAMINO software and were used to make continuous updates of the module’s position as it was towed. After the tests were complete, X and Y positional data was post processed to generate the plots shown in Figure 34 and Figure 35.
Figure 34: Plot of CAMINO’s X-Y positions during the rectangular pattern tow test
Figure 35: Plot of CAMINO’s X-Y positions during the figure-8 pattern tow test

Upon inspection of the CAMINO X-Y position plots in Figure 34 and Figure 35, it becomes immediately clear that they correlate well with the RHIB’s GPS location plots in Figure 32 and Figure 33, respectively. Because the tow test was performed with CAMINO functioning as a standalone entity, there was no way to input GPS into the system in the same way the Bluefin SandShark was going to. This meant that the ability to map CAMINO’s positions directly to the RHIB’s GPS locations and calculate the percent error between the measured and the actual positions was not
possible. However, to demonstrate that the system was measuring distances with a fair degree of accuracy, start and end positions can be compared to one another to determine how well the CAMINO system tracked its position over time.

Unfortunately, in reviewing the data associated with the rectangle pattern, it was discovered that the CAMINO system data collection was triggered a few seconds after the first leg of the rectangle (waypoint 1 → 2) had already begun. This seen in the plot in Figure 34, where the length of the first leg is cut short at the beginning of the run, causing a break in the rectangle. Unfortunately, the occurrence of this error meant the ability to correlate the start and end positions to one another was not possible for the rectangle pattern. Fortunately, the execution of the data collection for the figure-8 pattern was better and the data collected during that run was able to be used for determining the accuracy of CAMINO. This was done in MATLAB by flagging the data points associated with the start and end positions of the data collection, as shown in Figure 36. Using the X and Y data associated with these start and end positions, the delta between the points is found to be 42 m in both the X and Y directions. Knowing that the figure-8 pattern performed was a total of 2,015 m long, the CAMINO system accrued positional error equivalent to 2% of the total distance traveled. This error is notably larger than the 0.44% of the distance traveled during the initial CAMINO testing performed by Charles River Analytics. The most likely reason for this discrepancy is the fact that the data collected for this effort was done so on a towed body that was coupled to a boat with a tether. This arrangement, unlike an AUV swimming under its own power, induced large, transient spikes in the acceleration measurements of the IMUs each time the tether between CAMINO module and the
RHIB was pulled tight. These transient spikes worked to accelerate the accrual of error faster than a vehicle that is moving through the water on its own, untethered.

Figure 36: X and Y positions for the start and end location during the figure-8 pattern tow test
CHAPTER 9

FINDINGS

The efforts put forth in this Thesis to access the feasibility of integrating an inertial navigation system and DVL into an A-size AUV have found that this is, indeed, a feasible objective. This is true because a low cost INS with DVL was successfully integrated into a payload module that fits onto the Bluefin SandShark, an A-size AUV that is only 4.875” in diameter. The mechanical design was proven to be pressure tolerant to a depth of 200m, through Finite Element Analysis simulations, with minimum FOS of 2.16. Experimental testing of the CAMINO software demonstrated that over a 2,015m figure-8 pattern course, the system accrued 42m of positional error, or 2% of the total distance traveled.

The complete and assembled CAMINO is shown in Figure 37 and Figure 38.

Figure 37: CAMINO navigation module internal electronics.
Figure 37 shows the CAMINO navigation module without its pressure vessel tubes and end cap bulkheads, such that the internal electronics are showcased. As anticipated, the aggregate of electronic components nearly completely fills all of the available internal void space, an indication of the time and care taken during both the design and assembly to minimize the size of the system and make the most of the available internal volume. Figure 38 shows the CAMINO navigation module, fully assembled with all of the pressure vessels and end caps.

The final system specification of the CAMINO navigation module are shown in Table 6.

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<tr>
<th>Diameter</th>
<th>Length</th>
<th>Dry Weight</th>
<th>Displacement</th>
<th>Wet Weight</th>
<th>Mean Power Draw</th>
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<tr>
<td>4.875&quot;</td>
<td>20.25&quot;</td>
<td>11lb 12oz</td>
<td>12lb 13oz (364 in³)</td>
<td>+ 1lb 1oz</td>
<td>16W</td>
<td>98%</td>
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CHAPTER 10

CONCLUSION

This Thesis was able to demonstrate that the integration of a low SWaP-C navigation system into an A-size AUV is now possible because all of the components required for such a system now exist. The selected components successfully fit inside the small diametrical footprint of a Bluefin SandShark. This was possible because advancements in software have enabled the intelligent fusion of noisy data from multiple, low cost inertial sensors, to produce accurate navigation and localization capabilities to small AUVs at significantly lower SWaP-C than legacy inertial systems. Specifically, software such as Charles River Analytics’ CAMINO has demonstrated that the integration of an accurate INS into small vehicles is not only possible, but could stand to make a marked difference in the acceptance and use of small AUVs that were previously hindered by poor navigation. Recent reductions in the SWaP-C associated with Doppler Velocity Loggers has yielded products such as Teledyne Marine’s Pathfinder DVL, which was instrumental in making this system possible. By producing a DVL that has the exact same performance specs as the industry’s leading model, at a fraction of the size and cost, truly changes the landscape for attaining highly accurate velocity estimates on small AUVs. This was simply not possible even as little as two years ago, because the sensor was simply not available for purchase, commercially. Finally, with the right mix of ingenuity and creativity, the
ability to conceive a mechanical design that successfully integrates all of the
aforementioned components into a cohesively, final product is what pulled everything
together to make this a reality. As discussed in the Review of Literature, there are
multiple competing efforts currently trying to solve the problem of providing accurate
low SWaP-C navigation and localization capabilities to small AUVs, though none of
those efforts sought to solve the mechanical integration problem of integrating a DVL
and novel software solution into a cohesive system. This Thesis showed that such an
integration is possible, proving the possibility of low SWaP-C navigation not bound
by the limitations of acoustic signals or beholden to dead reckoning, is now a reality.
FUTURE CONSIDERATIONS

Although the efforts of this Thesis successfully demonstrated that the components required for low SWaP-C navigation exist and can be packaged into a payload module that fits an A-size AUV, there is still room for improvement.

As demonstrated by the release of a smaller DVL during the course of pursuing this Thesis, the continued miniaturization of electronics continues to yield smaller and smaller versions of existing systems. Not only do these systems get smaller, they often also realize an improvement in performance. This means that a system seeking to optimize low SWaP-C must continuous seek opportunities to reduce its existing SWaP-C characteristics.

For CAMINO, these efforts should focus on reducing the SWaP-C of its electronics, hence further reducing the overall SWaP-C of the CAMINO system. One way to achieve further SWaP-C reduction would be creating a custom printed circuit board that integrates all of the individual electronic components into a single entity. If the computer, Ethernet switch, and IMUs were integrated onto a single, proprietary carrier board, it could be possible represent enough size reduction to enable the elimination of an entire pressure vessel section. Similar efforts could be taken regarding the Teledyne Marine Pathfinder DVL electronics. By engaging Teledyne and impressing upon them the continued need to further the reduction of size and weight, there is good chance that meaningful reduction can be achieved.
## Failure Modes of Simple Pressure Vessels

Roger Cortesi (SM Mechanical Engineering MIT)  
21-Jun-02

### References:
- Woods Hole Oceanographic Institute Technical Memorandum 3-81  
  Failure Curves of Cylindrical/Spherical Pressure Vessels and Flat End Caps.  
  By Arnold G. Sharp, August 1981.
- Roark’s Formulas for Stress and Strain, 6th Edition  
  By Warren C. Young 1989 McGraw-Hill

### Material Properties Used in Calculations

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BIBLIOGRAPHY


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