AC 2011-1856: JUNIOR DESIGN OF AUTONOMOUS SURFACE UTILITY VEHICLE (ASUV): A PROJECT BASED APPROACH FOR KNOWLEDGE INTEGRATION

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I am a Junior level, undergraduate student at Florida Atlantic University, majoring in Ocean Engineering with a geology minor in Marine Geosciences. I was born and raised in Orlando, Florida by the parents of Mario and Susan Miranda. I have previously worked for Harbor Branch Oceanographic Institute as a project intern for the design of the Red Lobster sponsored lobster collection vessel that is undergo in the Turks and Cacaos. I currently hold the Propulsion chair for the Human Powered Submarine team at FAU, making my duties responsible for the design of the power-train and propeller characteristics and autonomously controllable pitch system. I am also developing an acoustic modem for subsurface telemetry under the guidance of Dr. Ravi Shankar and Dr. Pierre-Philippe Beaujean, FAU. I have taken it upon my self to expand my knowledge as a highly motivated undergraduate student and my goal is to share the experience that I have been given the opportunity for in hope, to inspire other system engineering students alike. As a team, the effort of this project has been in part by the help of the Department of Ocean and System Engineering staff including Ed Henderson, Tom Pantelakis, Robert Coulson and Frederick Knapp. Most importantly, this project and the many doors of opportunity it has brought me would have never have happened if it weren't for the Project Mentor, Dr. Edgar An, Director of Advanced Marine Systems at Florida Atlantic University.

Junior Design of an Autonomous Surface Utility Vehicle: A Project Based Approach for Knowledge Integration

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Abstract

The effectiveness of an engineering curriculum is measured by how well students can apply and integrate their technical knowledge to solve real life problems. The current engineering curriculum has been designed to only to provide the theory, however, it doesn't provide the integration of how this knowledge can be applied. The courses that are taken as preparation for system engineering students include standard mechanical studies such as statics, dynamics, and structural analysis, but also, computer software and hardware courses that study C programming, circuit analysis and electronics. These types of collegiate engineering classes that are taken on a general level in all system engineering disciplines, are supposed to provide the theory that is needed to build a system; however, they do not teach the tools that are needed to know how to integrate these concepts together during the system development process. The downfall reflects in the student when they cannot develop a successful senior design project.

As a solution, a state-of-the-art education is being presented as a project-based learning experience. This type of educational method has been designed to push motivated students into a fast pace, learn as you "build" environment in which students need to integrate educational theory with applications. While not being a requirement by the university, a directed independent study was performed by a junior level student in the summer of 2010. The objective of the study was to apply compartmentalized knowledge obtained from previous technical courses, such as circuits, logic design, and engineering mathematics, to design and build an autonomous surface vehicle (ASV), given a set of requirements. At the end of this project, the student was evaluated in terms of his technical and educational accomplishments: the ASV was successfully built that met the given requirements, and the student has demonstrated a deeper understanding of how to apply and integrate educational knowledge to solve a real-life problem.

The outcome of this project is a needed experience for any engineering scholar. It provides a stepping stone from the collegiate environment to professional development, while linking the integration of educational knowledge with practical design tactics. We envision that this type of project can be implemented effectively as a regular course so students can learn hands-on experience in system engineering design that cannot be found in a text book.

I. Introduction

Embedded system design is the lifeblood of cutting edge technology. It is now becoming ever increasingly popular with the availability of low-cost microprocessor modules and advanced modular C programming based development platforms. With the newest designs of embedded systems taking over the cellular and PDA industry, embedded system developers are also making a big move into the energy, military and research support industries for both mobile and static (in-situ) intelligent devices.

Department of Defense and Homeland Security facilities such as the Space and Naval Warfare System Center Pacific, located in San Diego, California, are currently calling for the use of robust embedded systems to carry their payload of sensors. Navigation, obstacle avoidance and the path planning are integrated using a sensor suite consisting of monocular vision, binocular vision, radar and LIDAR systems capable of detecting a kayak as far as 50 meters away [1]. The SPAWAR System Center Pacific is also supporting the Program Management Office for Explosive Ordnance Disposal (EOD), PMS-408, in developing an entire fleet of autonomous marine vehicles [1], in which, are planned to carry a payload of video cameras, sonar systems, current/temperature/density (CTD) sensors and Acoustic Doppler Current Profilers (ADCPs) [1].

Professionals from other countries are now becoming involved in underwater embedded system research, such as Portugal, as they have already constructed control algorithms and tested them using the Hydroid REMUS and Naval Postgraduate School's ARIES vehicles in heterogeneous collaborative missions [6].

As an attempt to bring this knowledge to education, research is being provided by grants from the Office of Naval Research (ONR), and alike sponsors, to participating schools such as the University of Michigan for autonomous marine systems. Other schools such as the University of Pennsylvania, University of Tennessee, Princeton University and Virginia Tech are also conducting research in autonomous marine coordination [2]-[5]. However, these research opportunities are only performed by graduate students and very few senior level students.

The complexity of building a system limits this type of work mostly to graduate students and the professionals of which whom are the pioneers of the field. The problem that our nation faces is that it does not produce enough undergraduate engineers that have sufficient effective experience to compete against the never ending demand of highly sophisticated students that are being offered elsewhere in the world. This forces the nation's free market economy demands to seek those other countries that do provide better qualified engineering graduates. This movement lifts the burden off of our nation's education system; but, it also deprives the country's production of quality home-bread engineers that are needed to hold positions in our country's confidential sectors. This lack of effective knowledge is even more hindering to a student whom decides to join the free market workforce upon graduation, where anyone in the world that is more qualified can compete for the same job.

There is a solution to this problem that has been developed by using project-based learning methods. This directly independent embedded system design research project provides a learning curve in which has been used to accelerate opportunities into such studies for rapid professional future development.

The project goal is to prepare the student for successful capstone senior design in research, testing and management port ions of both the project and professional development process. Nonetheless, the essence of this paper is to communicate the intricate progression that has resulted from the intended educational involvement.

Our objective was to design a fully autonomous surface utility vehicle (ASUV) that runs on a time based mission using dead reckoning navigation via an electronic compass. The requirements of the design procurement was to ensure that it is cost effective, simple to deploy, lightweight, robust and easy to operate, and should have adequate payload capacity to carry a variety of sensory devices. The navigational, propulsion, data logging and communication systems are fully controlled by a Rabbit Core microcontroller that runs on a C programming based platform. The application of this vehicle has been designed to serve the military and scientific research industries. The naval background of this utility vehicle can be used to carry an onboard sensor suite for surface to subsurface telemetry, port and hostile water surveillance with acoustic imaging systems, or it can even be interfaced in a swarm of other ASUVs to work as a fleet carrying multi-bean sonar systems and useful sensors that perform bathymetric and environmental surveys.

II. System Development Process

There are endless amounts of purposes for embedded systems, and thus it was the student's job to create a system from a "ground-up" platform using available tools, that can be useful to an Ocean related application. The design and topic relevance for the project was the choice of an Autonomous Surface Utility Vehicle that can be used to carry a payload of sensors for the use of education, research, resource management, commercial and military defense support. This new platform can be used as a stand-alone vehicle that can be programmed for maneuverability and transport in time-based missions using dead reckoning navigation techniques. The vehicle can be used to investigate,

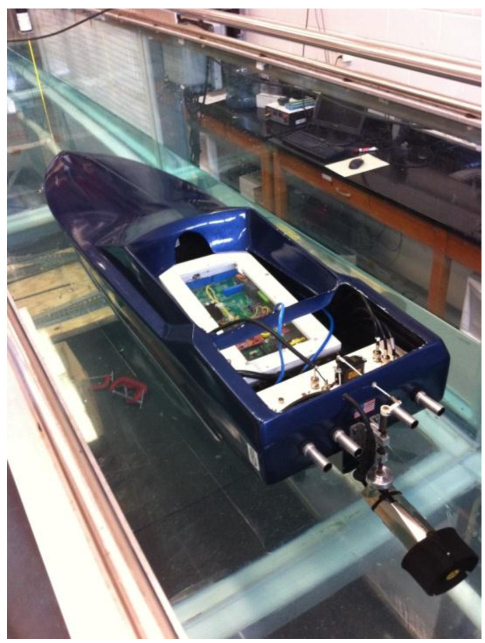

Figure 1: Vessel in water flume of hydrodynamics lab.

detect, data log and transmit real-time data to a local desktop or can even be used in further research as a platform to host a swarm of vehicles in collaborated missions and high order control system development. The following are the basic needs that the vehicle was designed to be capable of accomplishing:

- The vehicle should be able to autonomously move from one waypoint to another waypoint
- The vehicle should be capable of maneuvering forward, left, right, reverse, brake and coast
- The vehicle will need a means of propulsion, steering, navigation and data logging system

It was essential that each component was developed and evaluated as a separate entity before they were integrated together. Layering the development and decoupling each component in such a way made debugging the system exponentially easier at the end when it became time for the

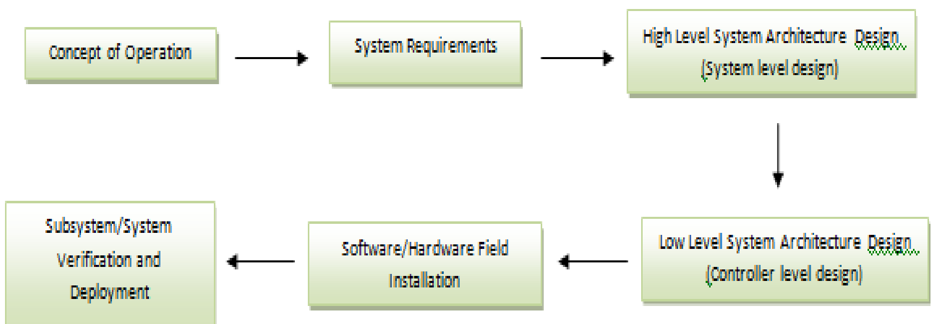

Figure 2: Shows the basic development process.

vehicle to be characterized. This framework architecture also allows for modular interchangeability within the system if needed.

System engineering overlaps the technical and human-centered methods on the management and coordination of how complex systems should be designed. Before the design could be started it was first necessary to obtain a full understanding of the system engineering process to ensure a standard procedure had been developed with a plan of action on how the design process would be carried out. The engineering process requires critical stages that must be met before a new phase of the process can be started. The order in which things are logistically carried out is essential to the project because it determines the projects life cycle and efficiency quality of the product's development.

III. Hull Design and Fabrication

The hull was originally used for NAVY Sealed Recovery Vehicle testing and is a scaled model that was used in test tow tanks and therefore has already been designed and characterized.

The plug used however, required for a mold to be first made and to allow a new plug to be popped out of that mold.

The overall length of the hull is 60 inches (1.52 meters) long and weighs 31 pounds (14.06 kg). The small size proves to have a large payload capacity to be able to hold a large variety of sensor devices simultaneously and still be able to operate in very shallow waters to perform adaptive missions and advanced maneuvering techniques.

In fabricating the hull, many aspects had to be taken into consideration including the material used, its weight, rigidity, surface smoothness and cost. The choice of material used for this project is a fiberglass-foam composite core. The outside of the hull has a Harbor Blue polyester gel coat and is then immediately layered with 1½ oz. fiberglass mat. The resin chosen is an Isophthalic resin, which is more conducive to the saltwater and high heat environment than typical polyester resin. This type of resin also uses a special MEK-P hardener.

Figure 3: Hull fabrication after gel coat has been applied.

Some areas of the vessel, such as the top-cap, are line with Score Core foam inserts that are fiber-glassed in and the keel of the vessel was also lined with lead inserts to provide a very low center of gravity. The low center of gravity caused by the lead weights and the high center of buoyancy provides stability in the case of small C_B/C_G separation.. This mechanical advantage of the vessel also dramatically reduces the probability of roll-over when maneuvering at high speeds or in high sea states. The outer skin layer and back bone that makes the inside of the vehicle is a double bias Fiberex cloth. This composite construction provides the minimal amount of robust construction needed for this application. Modified fabrication can also be done by using a new basaltic glass and Kevlar composite technology, which costs more, however, provides superior results.

IV. Propulsion and Steering System

The ASUV system is equipped with a Sea Botix BTD 150 AUV thruster and an Airtronics 94737Z RC servo. The thruster and servo both operate using pulse width modulation signals that are proportional to the thruster propeller speed and also to the servo arm position. The direction of thrust of the propulsor (thruster) will then determine the direction in which the vehicle will move (no rudder is used in this system).

The thruster mount design was inspired by researching RC boat drive mounts. The basic support

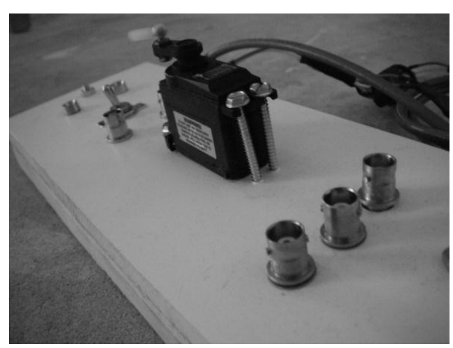

Figure 4: Photo of servo control box.

structure is drilled to the transom of the vessel and is connected via dowel pin that is screwed into the top of the thruster. The servo mount is simple because the servo contains mounting flanges that are used to drill into a support structure. The servo needed to be raised to fit the connecting rod elevation and was done so with a block of foam and PVC material that the screws can drill into. The support structure was attached to the vessel by using a strong material called Dual-Lock, which is a very strong form of Velcro. This allows the servo box to be easily removed from the vessel with no damage to the surface of the material of the hull.

V. Sensor and Control System Suite

The raw platform of the standard system is accommodated with an efficient and low-cost sensory suite that was integrated using simple ingenuity. The organized modulated framework architecture allows for one that is unfamiliar with the system to quickly become easily acclimatized and up-to-date allowing for system overhaul just by small modifications. The system is standard with a magnetic sensor for Mission start capabilities. The prototype vehicle is also stock equipped with a PNI TCM2 digital compass (with 3-axis magnetometer for pitch and roll capabilities), Vinculum VDrive 2 USB flash data logger, Airtronics 94737Z high torque servo, Seabotix BTD 150 AUV/ROV thruster, and a Critical Velocity HB-310 H-Bridge amplifier. The vehicle's processing computer is a low-cost Rabbit Core 2000 8-bit microcontroller module.

Device	Voltage	Current	Power
SeaBotix BTD 150	12V	4.25 A (nominal)	51.0 W
PNI TCM2	5V (regulated)	20mA	0.10 W
Airtronics 94737Z	5V (regulated)	320mA	1.60 W
VDrive 2	5V (regulated)	20mA	0.10 W
SRF05	5V (regulated)	30mA	0.15 W
HB-310	5V (regulated)	20mA	0.10 W
RCM 2020	6V	98mA	0.588 W
Total	18V	2.98 A	53.638 W

Table 1: ASUV's system power budget.

A dutycycle conversion algorithm was formulated by constructing a linear equation that can model its input/output values. The linear equation was chosen because the calibration of the heading to dutycycle needs to be a proportional value (proportional controller). When approached from this manner, it was necessary to develop the boundary conditions of this application that were set by the physical range of motion of the servo while operating. These boundaries are only for the input of the equation, which is the heading. The boundaries developed for the output of the equation was based on the systems 40% to 90% dutycycle operating range. The goal in this procedure was to map out each angle between -45˚ and +45˚ with a corresponding dutycycle between 40% DC and 90% DC, respectively. The software program that has been used to implement its application has been created as a stand-alone controller that is equipped in the microcontroller module's system library. The beauty of this code is that it can easily be modified or rebuilt to fit the application needs. It also utilizes both C and assembly language, making the source file more efficient when being carried out. The code also has been set up to contain two match registers so that it can control two separate pins at the same time, allowing control of both the servo and thruster from the same routine. Once the codes operational function was confirmed, it was very important to analyze the systems clock to ensure adequate resolution capabilities in order to allow for smooth operation.

VI. Onboard Computer

The electronic system is the most important feature of this design because it allows for the autonomous control of the propulsion, navigation and data logging of the system at the fraction of the cost of most systems. The design version of the vehicle at this phase of the system's development was to employ the basic backbone that can perform the discussed requirements. The onboard computer's breakout board contains four available ports, an analog-to-digital converter, a digital-to-analog converter, temperature sensor, pressure sensor, two stepper motor controllers, test LEDs, various amplifiers, and LCD screen technology. The low-power consumption requires about 5.00 V ± 0.25 VDC and 98 mA, with capabilities of operating up to 29.4912 MHz. The breakout prototype module provides a 5volt regulated source to all I/O and test pins and is powered by a 12 VDC, 7 amp-hr lead-acid battery. The system's endurance has been design to have a mobile lifetime 1.56 hours of mobile movement before the power in the thruster runs out. The rest of the electronic system has been design for an endurance of up to 63 hours.

Pressure ratings, material permeability, saltwater intrusion, reverse polarity, over amperage, heat dissipation, signal disturbances, and even shock absorbance factors were all considered in the electrical system design by the use of properly vented and sealed areas, electronic diode protection and a fuse box that regulates the systems power from over amperage.

VII. Navigation and Guidance

The navigation software is a stand-alone path planner that can be implemented on any type of vehicle that uses a C programming based platform to incorporate a dead-reckoning navigation system. The architecture behind the program is based off of the Cartesian coordinate system. A proportional controller is used to have a set point value called "mission heading". This mission heading is determined by the control statements found in the main function. The control statements themselves are synchronized by the real-time clock (RTC). This software is the digital implementation of the sensor feedback comparator that will determine the system error. This error is called the "target heading" because this value is the output (in dutycycle) that the vehicle's response is intended to settle to.

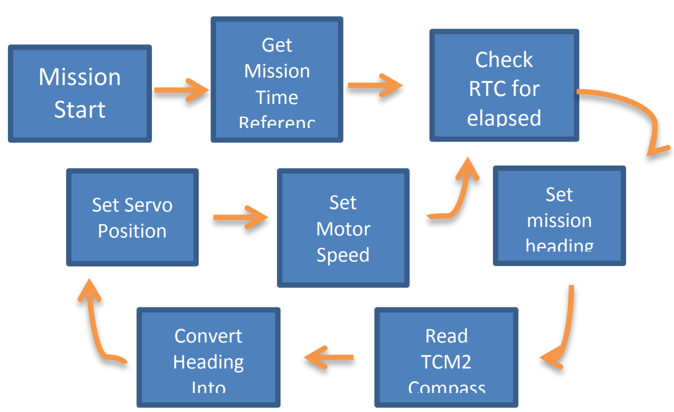

Figure 5: Software block diagram flow chart.

VIII. Cables and Connectors

The thruster uses a Belden 8428 two-wire cable. This particular cable is a high-end cable because of its low impedance characteristics. The Hall Effect sensor uses a CAT5 cable and the servo is connected to an RG-58 coaxial cable, which are both often used for low power signal applications. The batteries use a Belden 9463 two-wire cable. This particular cable is an industrial controls 20.0 AWG cable with a voltage rating of up to 300V. It contains a PVC jacket, polyethylene insulating material with a tinned copper core. It is very important that wires and cables were kept as short as possible to reduce the amount of signal absorption that robs the systems power, due to its own natural resistance.

To reduce cost, the servo and thruster motor use BNC connectors that were provided in donation by the University staff. Inside the electronics enclosure, there are two DC plugs that are utilized. One DC plug, labeled with the black heat shrink wrap, is connected to the fused battery pack. This plug also is connected to a flip switch that is located on the front control panel. The flip switch can then be used to turn the batteries off without having to open up the electronics enclosure or having to disconnect any waterproof connectors. The other DC plug, with the red heat shrink wrap, is desired for when a wall unit power outlet is being used, such as in testing or updating the system. The user can simply insert the wall unit plug into the DC jack located on the front panel mount. When the board is properly plugged in and powered on, a red power LED located on the front

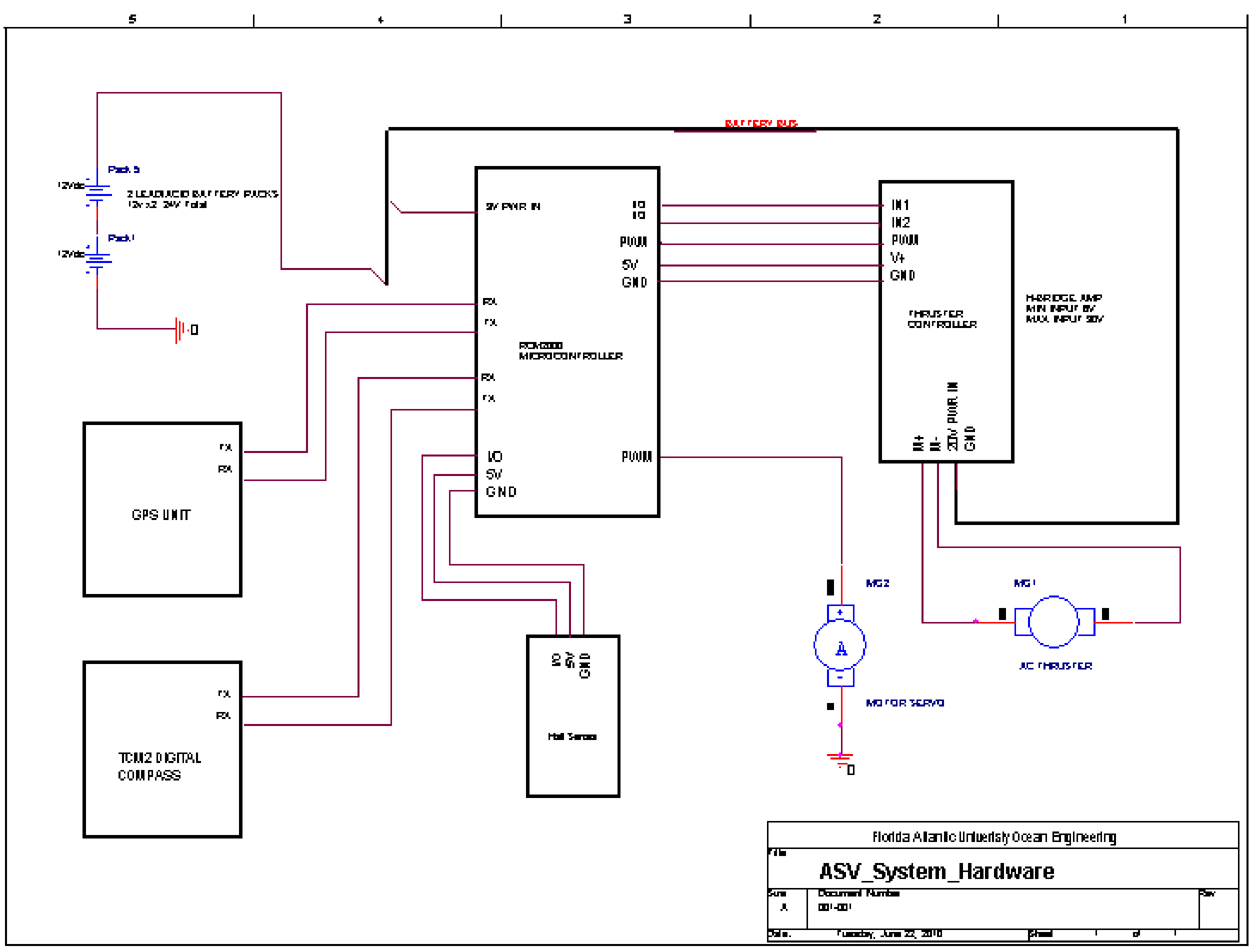

Figure 6: High level functional diagram.

IX. System Testing and Validation

The system has been tested in a swimming pool under strict constraints that govern the vehicles operating space. Tests were conducted to assess the vehicles response and sensitivity levels using hardware controller tests with open-source HyperTerminal programs and simple oscilloscope analysis techniques. The software controller tests were analyzed using MATLab to create input/output calibration curves. Custom software control codes were also created to test the servo and dutycycle ranges and resolution practicability. One software test for the navigation controller inputs 30 randomly generated input values and plots them against the proportional calibration curve that was theoretically calculated. The results show a successful test because of the plots lie on the linear proportional line, as seen in Figure 9.The robustness of the vehicle proved to exemplify predictable and reputable results. The vehicle was programmed to assume a heading along the edge of the pool's wall, then follow along the pool's perimeter and return back to its original home position. A video of the test run has been attached to this summary in the design package. Test plans and reports can be found in the Appendix section of this report.

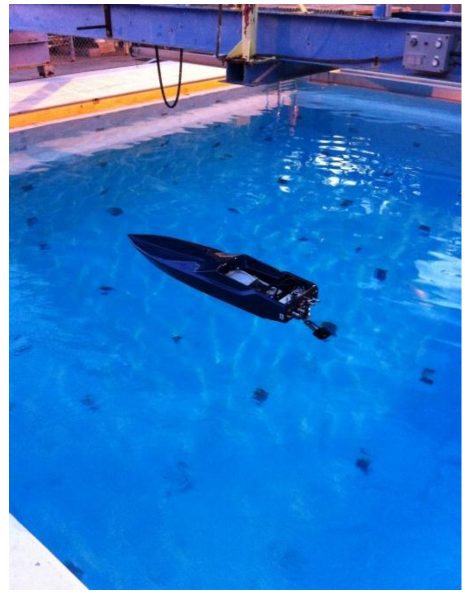

Figure 7: Testing at OE Hydrodynamics Laboratory.

In order to program the vessel to perform the desired maneuver, a rigorous path plan had to first be design by hand. The process consisted of

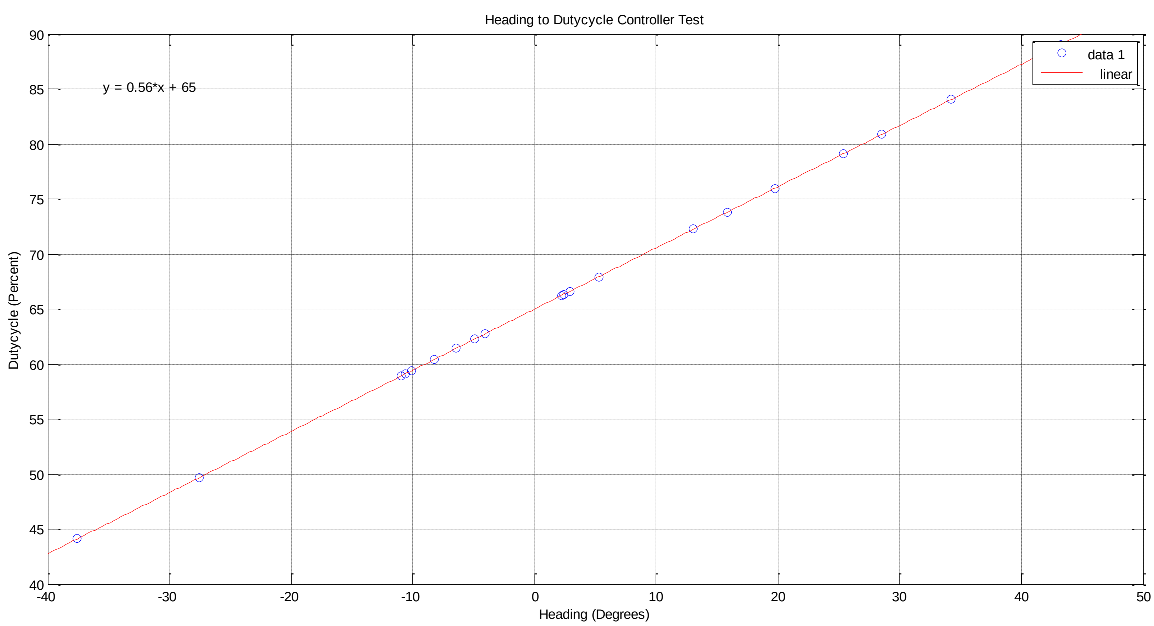

Figure 8: MATLab calibration curve that was performed during testing and interfacing.

System Data Characteristics:

Max Speed	About 5 knots
Minimum Turning Radius	About 7 feet
Approximate Weight	31 lbs
Hull Length	60”
Hull Draft	4-5”
Hull Material	Isophthalic Fiberglass Composite
Nominal Voltage	24 volt System
Nominal Power	53.638 watts
Endurance (thruster)	1.56 hours
Endurance (computer)	63 hours
Propulsion	Direct drive DC brushless motor
Thruster Type	Shrouded 3-Bladed Prop
Control Effort	Servo Motor and Software Controller
ON/OFF	Magnetic Switch
Navigation	Time based, dead-reckoning algorithms
Standard Electronics	Digital Compass, H-Bridge Amplifier, Servo Motor, Thruster
Software	C-based modular framework platform
Data Export	Flash drive

Table 2: The table above shows the system characteristics.

gathering the necessary heading data using an analog compass. This data was then used in trigonometric functions and a simple rate equation to determine the necessary timing effects

based on the vehicle’s projected velocity and position. The data was then programmed into the appropriate control statements and downloaded to the board. Before each subsystem was tested, a subsystem verification plan and system validation plan was created as to have written guidelines that confirm the integrity of the design.

X. Future Development

The limitation of this project is based on funding and most importantly the amount of time consumption that is needed and the fact that there is minimal amount of time to research and to implement a design in a summer terms time frame. There are many overhaul implementations and system updates that have been realized that can be done, however, the time constraint restricts many opportunities. Some of the system update advice is either underway or presented for future research.

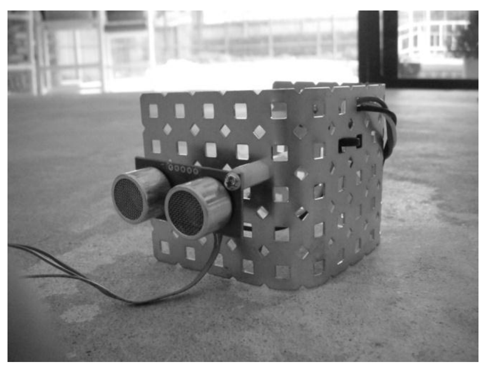

Figure 9: SRF05 Ultrasonic Ranger

An obstacle avoidance system is currently being developed using an Devantech SRF05 ultrasonic ranger. The ranging device is a proximity sensor that is analyzed using PWM signal processing. The signal detection will then correspond to an avoidance routine that can be implemented as a control effort. With several ultrasonic sensors onboard, the vehicle can then use simple sonar capabilities to maneuver through unpredictable fields. The navigation methods are currently in the research and development process inspired by obstacle avoidance reports for the REMUS 100 written by distinguished professor, Anthony J. Healey, which constitutes a method of using a Gaussian probability curve based on range and bearing of the object to create weighted task functions.

Other improvements can be done by unpacking some of the sensor payload on the breakout prototype board, such as removing unnecessary diodes and electrical semi-conductors that rob the system of power. Also, the TCM2 is currently powered by a 9 VDC battery and can then be powered by the 5 VDC regulated source. This will remove the need of a 9 VDC battery and provide sufficient power to maintain the reliability of the device. The battery system should also be upgraded to using nickel cadmium (NiCad), nickel metal hydride (NiMH), or lithium-ion (Li-ion) batteries. All of which are used in high power electronic systems that demand fast response. The system should then also contain a power monitoring system to ensure the integrity of its functional ability.

The implementation of a hydrophone is also currently in progress to control the vehicle by transmitting an underwater signal using simple acoustic mechanics for sub-surface telemetry. Another research project is to interface a radio frequency or Ethernet modem that can be used to transmit real-time data to and from a local host for interrupted control of the autonomy of the vehicle in remotely operated conditions. This allows the user to take over complicated and critical tasks or even receive real-time system feedback.

XI. Conclusion

The purpose of the design of this vessel, as stated in the introduction, was to serve the marine industry for low-cost, rapidly developed autonomous surface utility vehicles that can carry a wide range of high performance technology and also can be used to serve for as a perfect research and development prototype platform.

The design methods that have been learned in this project are the basic fundamentals that are needed to be taught to any Embedded Control System Engineering student who plans to design autonomous systems. The project topics covered microprocessor basics such as I/O and serial device programming, timers, interrupt controllers, high and low level system architecture, system analysis and debugging, electromechanical integration and fabrication techniques. However, the discussion theories are general methods that should not be limited to only autonomous vehicle designs.

The direct independent study also required learning non-technical project management responsibilities such as time management, resource management, communication skills, organizational studies, and professional development skills. A well groomed engineer that has proficient understanding in the computer science, computer engineering, electrical engineering, mechanical engineering and the control system theory that has been discussed in this report, has endless opportunities and should thus then give the inspiration and know-how to continue their personal research and set the bar for the future modern marvels.

It is also essential to understand that successful development requires a thoroughly considered and organized approach which includes an efficient, disciplined direction from extensive planning, analysis and documentation. Developing innovative technology will quickly introduce risks; therefore it was of the upmost importance to consider the most promising technological approach that included the associated risks and thus eliminated those that outweighed the rewards. Once these fundamental guidelines were developed, the primary focus was to ensure successful completion of the systems objectives with successful operation in the field. The skill sets learned provided the specialized characteristics that are needed for project management and lead design positions. It is essential to understand that this project gives the basic foundation that is needed to now carry on further development of design methods at a highly competitive level when entered into the work force. The experience that is acquired from this report is nearly impossible to find and is rarely so eloquently put and proves to be a possibility for any highly motivated student.

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