Unmanned Surface Vehicles for Undergraduate Engineering Education

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Abstract- **For the past two years undergraduate engineering students from Olin College of Engineering have worked to develop unmanned surface vehicles as low cost educational platforms for scientific research. As an undergraduate project, the work on the USV involved the student team in a hands-on experience that included in-house design, fabrication, and field operations. Working dominantly out of the Olin Field Robotics Laboratory the first fully operational vehicle completed an unmanned field test in the spring of 2008. Previously in 2007, two students from this project team presented the academic benefits of this self-directed work for engineering and science education at the MTS/IEEE Ocean's Conference in Vancouver. Here we present the data collected from the first autonomous trials carried out by the vehicle as well as the continued work since the Oceans 2007 publication. This work includes the completion of the mechanical design, creation and verification of a mathematical model of the vehicle, and implementation of autonomous control. Lastly, this paper continues to testify to the core benefits of an unmanned vehicle as an undergraduate engineering project, leading not only a to viable vehicle platform but also an extremely valuable learning experience for the team involved.**

I. Introduction

The field of robotics continues to gain momentum both in and out of academia as one of the next major engineering growth areas. Outside of scholastic endeavors, commercial and military robots are carrying out field operations previously deemed too physically demanding or dangerous for human completion. Within the realm of the scientific community robotics vehicle platforms are being outfitted with sensing equipment to allow scientists more extensive field work. As academic works robotic projects are becoming increasing useful tools for engineering education.

The Franklin W. Olin College of Engineering's Field Robotics Laboratory began two years ago out of a student led class project to build a small unmanned robotic marine vehicle to carry out water sample collection. Since then, with the aid of Professor Brian Bingham, the laboratory has continued the college's tradition of student led and initiated undergraduate research and has now built two robotic surface vehicles. Through the narrative examples in this paper we convey the continued work at the Olin Field Robotics Laboratory on the *USV Virgil* as well as continue to illustrate the benefits of unmanned marine robotic platforms for undergraduate engineering.

II. Background and Closely Related Work

In a paper published in the proceedings of Ocean's 2007 in Vancouver, the project team laid out the following primary benefits of the student led unmanned vehicle project to undergraduate engineering education:

Accessibility: This refers to the project's capability to be both low in cost and require little to no previous experience in the field of engineering.

Scalability: The scalability of the project is evident in how students with little to no experience are able to tackle a real life engineering project and gradually handle the more complex parts of the problem at their own pace.

Interdisciplinary Education: The design, construction and subsequent testing of the USV forces the project team beyond their specific discipline. This type of multifaceted project is indicative of the Olin educational model and of an authentic engineering project.

The vehicle in development at that time, the *USV Circe*, illustrated these points. Since then the Field Robotics Laboratory completed a second vehicle, the *USV Virgil*. *Virgil* is a continuation of many aspects of the *Circe* most notably in the areas of mechanical design, simulation and mathematical modeling and continued field testing. *Virgil* has also continued the initiative to keep the unmanned vehicles program a student centric and directed project.

The USV Circe

In order to better understand the project growth since the last publication it is relevant to briefly recap the previous work on the *USV Circe*. The vehicle, christened *Circe* (figure 1) was completely designed and fabricated by Olin undergraduates in-house. The vehicle is a two pontoon catamaran with two commercial outboard electric trolling motors, one at the stern of each pontoon. The electrical system consisted of two marine rated AGM batteries with a

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120Ah capacity each. The fully loaded vehicle weights ~200kg with an additional carrying capacity of 150kg.

Figure 1: The *USV Circe* during field operations in the Fall of 2007

For several reasons the full fielding capacity of Circe was never realized, as Circe was retired from active service before it was ever field tested in a unmanned fashion. Instead, *Circe* carried out three manned teleoperated missions in which vehicle dynamics and basic fielding procedures were established. Circe, while a good first pass at a stable unmanned platform was difficult to field due to its weight and size as well poor overall layout. In the end of the fall of 2007 a new mechanical design for the next vehicle, the USV Virgil, were drawn up. The intent of the new design was to be easier to field, and thus to encourage faster development of the unfinished autonomous control elements.

III. Mechanical Design and Fabrication of the *USV Virgil*

The USV Virgil

The *Virgil* (figure 2) shares some of the basic design decision as *Circe*. Both vehicles are two pontoon catamarans, a hull design chosen for its stability. The power and propulsion systems are also identical between vehicles. The major changes in mechanical design focus on the propulsion system location mounting, and the form factor of the hulls.

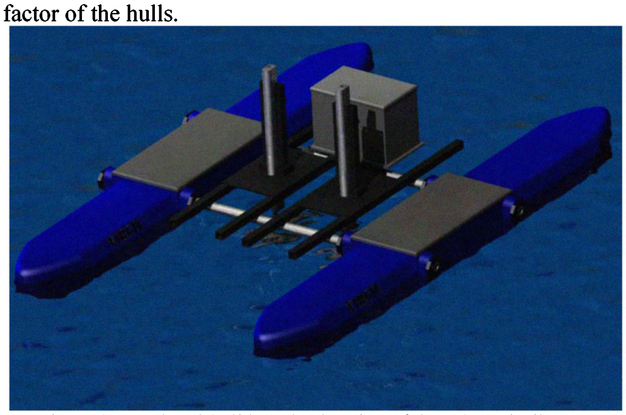

Figure 2: Rendered SolidWorks drawing of the USV Virgil

A. Propulsion System Mounting and Layout

One critical flaw with the *Circe* revolved around the motor mountings to the vehicle hull. On *Circe*, the motors were held on using the commercial attachments which came with the motors. The mounts, designed for the transom of a small pleasure craft, employed a single friction hold applied via a set screw to hold the motors vertical and rotational orientation. The vibrations induced by motor operation, however, were enough over time to turn the motors from their parallel forward orientation, thus requiring repeated readjustment during field testing. To combat this problem a rigid motor attachment and adjustment method was designed and implemented.

The new mount depicted in a figure 3 mounts to the existing motor shaft without need to permanently modify the motors, i.e. drilling mounting holes or any other puncturing of the existing components.

Figure 3: Rendered SolidWorks drawing of the machined aluminum motor mount with the motor and attached U-Channel in place

To accomplish this, a piece of U-channel 5051 aluminum was fiber glassed to the motor shaft and then mounting holes were drilled though it. The square sides of the U-channel also provide a means of securing the motor against rotation. The aluminum plate through which the motor shaft passes is machined so that the motor shaft and U-channel attachment are keyed to fit in only one orientation. This allows a single bolt put through any of the vertical mounting holes to fully constrain the motor, while removing the bolt allows for the repositioning of the motor in its vertical orientation. This one degree of freedom is all that is required since the vehicle steers via differential drive, as will be discussed further later.

In addition to the mounting of the motors, their position on the boat is unique. Most vehicles have the propulsion devices at the stern and commonly furthest from the centerline so as to generate the most turning thrust. In this design, special care was taken to ensure that the CG of the vehicle would correspond with the geometric center of the vehicle. This is accomplished by the adjustable positioning of the batteries, one located within each pontoon.

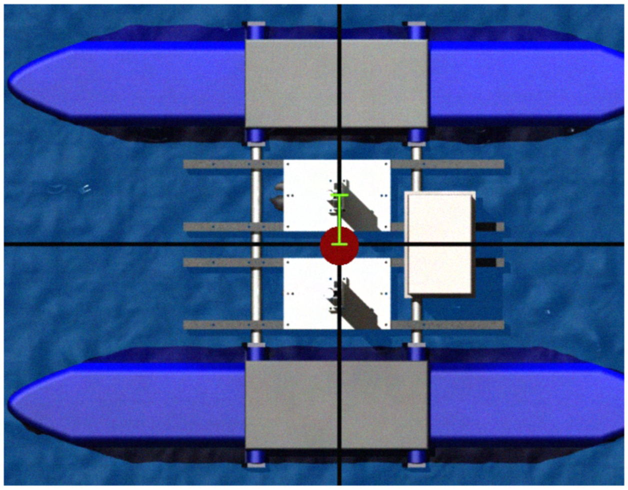

Figure 4: Rendered top view of Virgil. The black lines designate the centerline and midship lines of the vehicle. The red circle designates both the vehicle CG and geometric center. The green line designates the moment arm to the starboard motor.

Figure 4 shows a rendered top view of the vehicle which better illustrates this configuration. This design decision was made in line with the initiative to make the vehicle more easily field-able. The adjustability of the motors allowed them to be raised above the lowest point on the pontoons. This combined with the fact that the motor assembly was confined to the dimensions of the vehicle, made it possible to transport the entire vehicle in the bed of a pickup truck or trailer without any disassembly, and without threat of a peripheral component being damaged in transit. In addition, this configuration affords the vehicle interesting maneuvering dynamics. Since the forces generated by the vehicle's motors are always perpendicular to their moment arm with respect to the vehicle CG, Virgil can turn in place with ease. This has been proven in multiple field tests.

B. Hull Form Factor

The second major design change between *Circe* and *Virgil* is the form factor of the pontoons. With *Circe,* the project team opted to build and design pontoons in-house. While this was an excellent mechanical design experience for the undergraduate students, the final products were large and cumbersome to move into the field. *Virgil* uses COTS pontoons. Commercial documentation as well as field testing observation put the pontoon's total safe load capacity at approximately 125kg. Fully loaded with all the necessary electrical and mechanical components *Virgil* has the capacity for carrying an additional 20 to 30kg of mission specific payload. While this is a loss in total payload carrying capacity, the newfound easy of transportation made this a worthwhile trade off.

C. Relevance to Undergraduate Education

Continuing to echo the claims made in the previous publication from the FRL, the design and fabrication of *Virgil* supports the idea that unmanned vehicles are scalable undergraduate problems. *Circe*'s mechanical design was limited to a much smaller set of design specification and was a much less elegant design. *Virgil* improves upon the design of *Circe* and incorporates more complex specifications such as taking vehicle dynamics into account with propulsion placement. Furthermore, the decision to use COTS components for the pontoons shows the effects of growth and experience in engineering design practices though continued work on this project.

IV. Electrical and Computer Systems

The electrical system, defined as the sensors and power requirements, of *Virgil* have changed little from *Circe*. Both vehicles incorporate the same power supply and both run dominantly on 12VDC electrical systems with a 5VDC bus for some sensors. The basic sensor configuration for *Virgil* is identical to *Circe* with a waterproof GPS[1] and Electric Compass[2] for navigation purposes. Interface between the software control of the vehicles and the propulsion systems is also identical, both using a COTS 75amp continuous draw two channel servo motor amplifier. The major difference between the *Virgil* and *Circe*'s electrical and computer systems revolve around the onboard computer and control software. With the aid of students in the Spring Robotics class at Olin, *Virgil*'s computer system and software was completely replaced and rewritten. *Circe* used two onboard GumStik Microprocessors which ran software written in C. *Virgil* uses a commercial laptop and runs software written in National Instruments LabView.

A. N.I. LabView and Virgil's Software

LabView is a graphical programming language in which the code is not written it is drawn. Block diagram system level drawing can be ported directly into "code" by

[1] Garmin 18-5Hz marine global positioning system unit (an upgrade from *Circe*'s Garmin 16-LVS)

[2] Devantech CMPSO3 magnetic compass

drawing out the diagram and connecting inputs and outputs onscreen via “wires”. This can more clearly be seen below in figure 5.

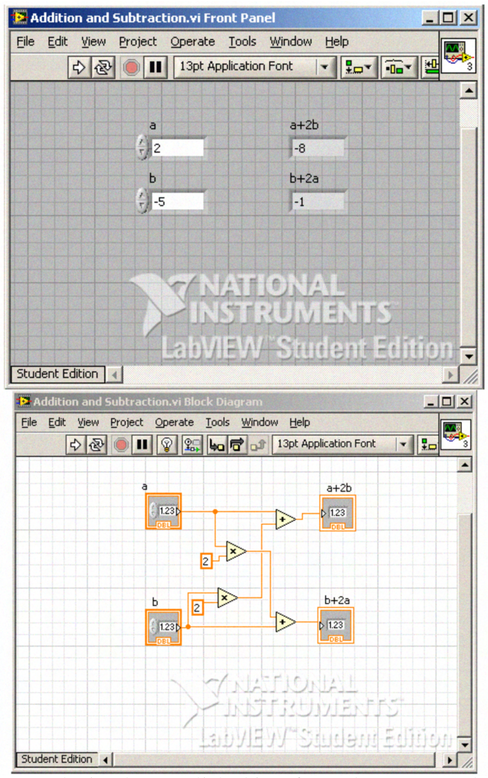

Figure 5: LabView has two linked interfaces, the Front Panel (top) in which the inputs and the outputs of the code are visualized and the Block Diagram (bottom). Each piece of code is a "Virtual Instrument" which can act as a standalone piece of code or can be a sub-Virtual Instrument which is part of a larger piece of code. This allows for easily modular code to be written since changing the code is as simple as dragging and dropping new blocks around the Block Diagram. The code shown above is based off of an example in the LabView 8.5 “Getting Started” manual.

While at first a potentially difficult transition for those familiar and comfortable with text based programming the decision to switch to LabView was pivotal in the development of *Virgil* since the project team historically has been and continues to be made of Mechanical Engineers with limited software experience and formal training due to limited room in the degree requirements to take elective computer science classes.

An additional feature of LabView in many included built in tools for configuring and interfacing with hardware. All of the serial communication protocols existed within LabView as prewritten components which could be modified and controlled as needed for the specific application on the vehicle. Members of the team with little to no software experience were able to write programs in LabView to configure and communicate with serial peripheral devices like the GPS and compass in less than a day using many of the built in LabView tools.

The current code operating on *Virgil* executes in three sequential steps. Within the first step the vehicle initializes and makes sure all sensors are functioning properly. It prompts the user for the input of an origin in order to generate a local XY (in meters) map from the GPS inputs. It also prompts the user for the disk location of the Route Definition File which is a standard text file of sequential waypoints for the vehicle to move though. Lastly, the vehicle allows the user to configure any mission specific parameters before executing the operation.

In the second phase of operation, *Virgil* carries out a waypoint following behavior in which it plots a course between its current location and the next waypoint in the RDF, updating this course at 5Hz— the refresh rate of the faster sensor currently on board. The code is written such that if additional sensors are added to the vehicle, a localization loop is already in place to take any number of state and certainty vectors and compute a common vehicle state and certainty vector. The state vector consists of the three position coordinates X,Y,Z relative the initialized origin as well as the three angular coordinates Yaw, Pitch and Roll. The certainty vector accompanies each sensor’s state vector into the localization loop and gives an indication from 0-100 on the certainty of that sensor’s data. In the case of the GPS, these values can be generated from information about the number of satellites in view at the time of the reading. For other sensors, such as an IMU based dead reckoning, the values can be algorithmically generated based on level of complexity of the vehicle plant model as well as information about the previous certainty of the vehicle on which the new dead reckoning is basing it estimate.

The second operational process of the code also is responsible for actuating the vehicle via its propulsion system. Since with all unmanned vehicles there is a limit to the perception of the vehicle and its ability to handle unexpected events in its environment, a wireless link with a shore based laptop is also established during operation as a safety measure. Through this wireless link a shore based operator can monitor the behavior of *Virgil* and if necessary enact a manual override of the unmanned behavior. Furthermore, if this link is ever unexpectedly broken, the vehicle powers down and awaits recovery.

The third and final operational process triggers after the vehicle has completed the uploaded RDF. At this time the vehicle sits dormant and awaits user input in order to save an operational data log. During the entire field operation the software continually builds an array of the inputs and outputs of all critical processes by appending their states to the data log at the end of each loop iteration (*Virgil*'s processing loop operates currently at 5Hz). After the data log has successfully been saved the program finishes execution and the vehicle can be safely shut down.

B. Relevance to Undergraduate Education

As more developmental tools are being released for use with robotic systems the accessibility of unmanned vehicles becomes even more apparent. The developmental team for *Virgil* consisted almost exclusively out of mechanical engineers with little to no software experience let alone software/hardware interface experience and yet they were successfully able to build a fully functional unmanned vehicle.

V. Field Work and System Verification

While the design of an unmanned vehicle is an educational experience in itself, without proper field testing of that design and mathematical modeling and analysis of the engineering data gathered, it is a limited experience. The Field Robotics Laboratory has fielded *Virgil* twice since the vehicle achieved its most basic level of operational status in the spring of 2007. With each of these tests the vehicle's performance was measured, observations about the system's behavior were made, and improvements were implemented based on those changes. In addition to the field trials, the physical dynamics of the vehicle were modeled extensively and effort has been put forth to design a proper control system.

A. Field Testing

The first field test of *Virgil* was a basic teleoperated mission in order to test all basic system functionality. In addition, the first field operation brought back useful data related to vehicle performance. From the GPS data taken the top speed for the vehicle was measured to be ~3-3.5knots. Other information regarding the different turning radius given different combinations of thrust output from the two motors also helped to build an array of physical constants related to drag coefficients which would be used in a vehicle simulation of *Virgil* as well as in the position estimation code running on *Virgil* currently.

The second field operation was a landmark for the Field Robotics Laboratory in which *Virgil* preformed the first completely unmanned mission made by any vehicle built by the team. The RDF was a simple 5 waypoint mission which served as a proof of concept that the vehicle was capable of autonomous navigation and path planning.

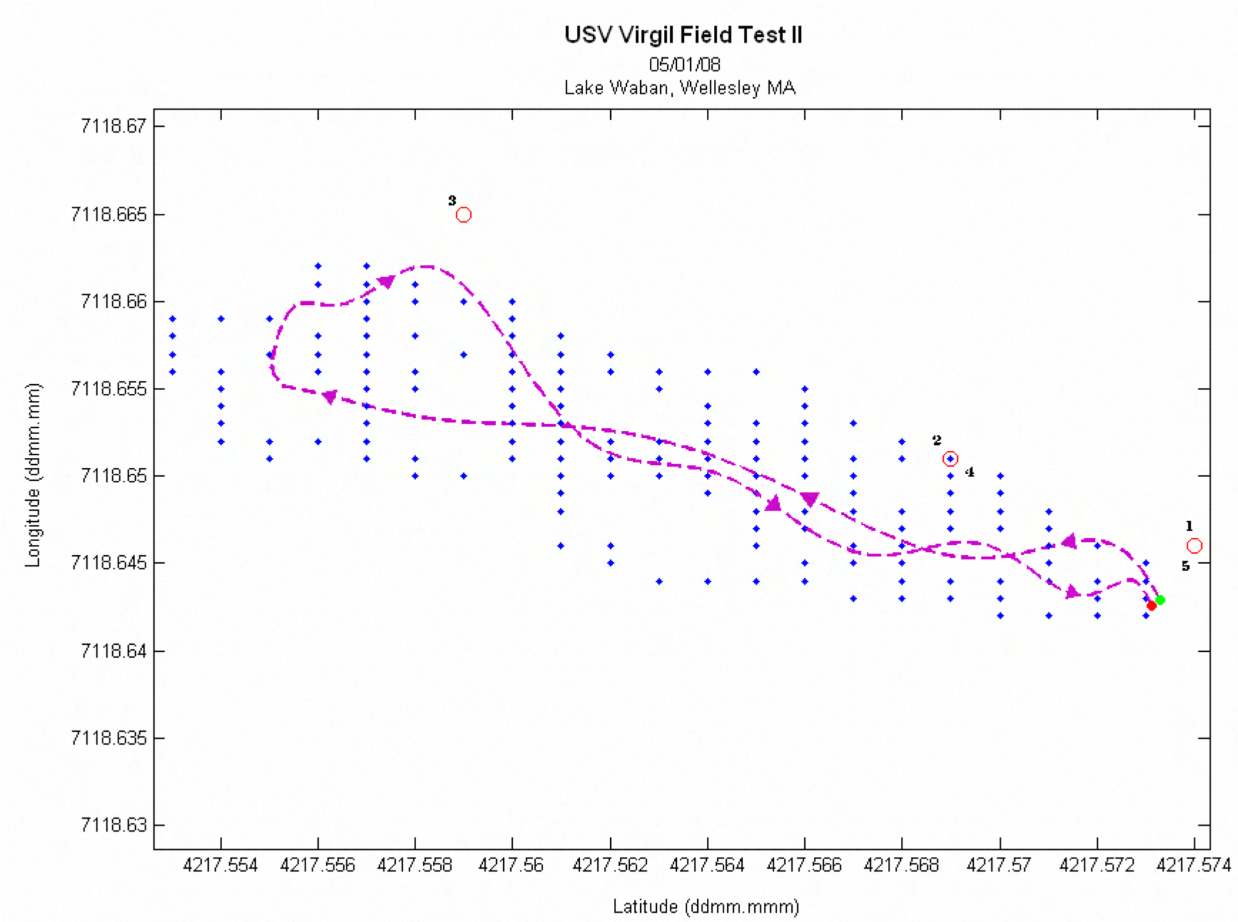

Figure 6: Position relevant data taken from the May 1st field test of Virgil. The red numbered points make up the RDF which the vehicle carried out. The blue points are the raw GPS readings. The purple dotted line is a best fit data interpretation of the GPS point with respect to time. Due to the slow data acquisition of the vehicle at this time and limited resolution of the sensors a best fit line make visualization of the attempted vehicle path easier.

The position relevant components of the data log can be seen above in figure 6. During this operation, the dead reckoning process had yet to be fully implemented and so the vehicle was forced to navigate by GPS and compass alone. In addition, this earlier version of the code only operated at 1Hz which made it difficult to carry out complicated path planning and following behaviors. This is the reason behind the simple "out-and-back" RDF and the need for data fitting to the raw GPS data for visualization purposes. Despite the simplicity of the mission, this test conclusively proved that *Virgil* was a fully unmanned vehicle.

B. Mathematical Modeling and Simulation

In parallel with the field testing, in lab mathematical simulations of the vehicles dynamics were created. Beginning with the canonical 6 degrees of freedom surface craft model, the simulation was simplified to a 3 degrees of freedom model incorporating surge sway and yaw.

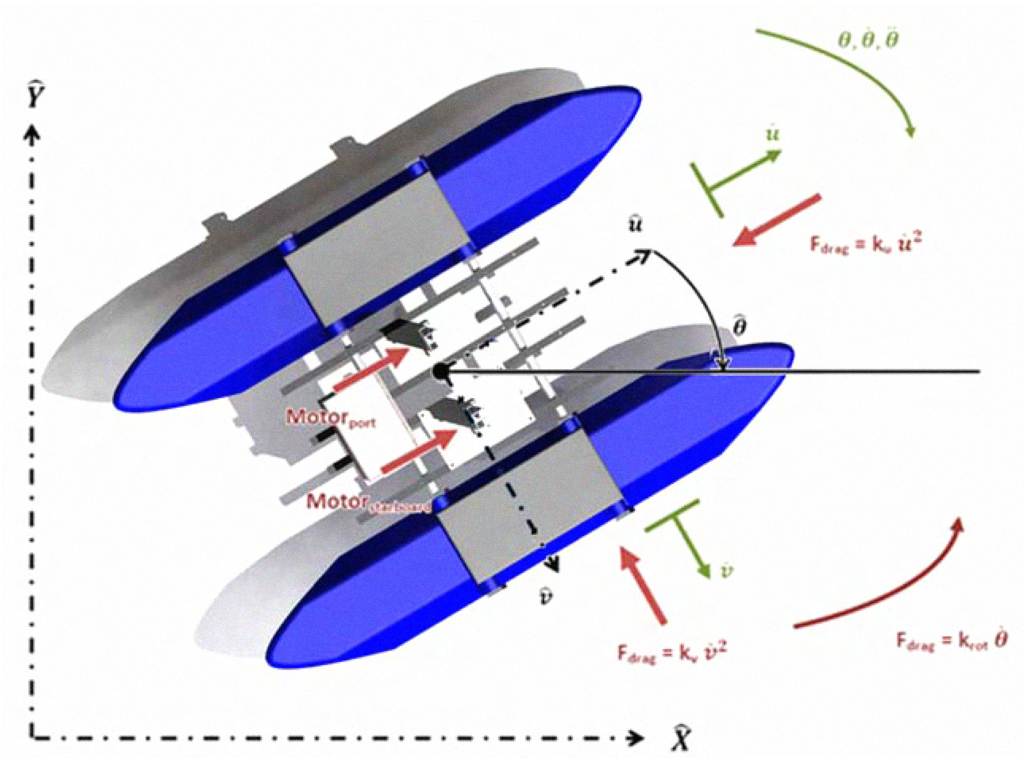

Figure 7: Free Body Diagram of Virgil defining the variables used in the vehicle dynamics simulation

The free body diagram in figure 7 shows two coordinate frames, the main frame (X, Y) in which all final results will be reported and an intermediate frame (u, v) which is a body centric coordinate frame. This FBD was used to derive the basic equations of motion listed below:

$$\vec{\ddot{u}} = \frac{(\mathrm{Motor}_{port}+\mathrm{Motor}_{starbord})}{mass} - \frac{k_u}{mass}\vec{\dot{u}}^2\ \hat{u}\ [1]$$

$$\vec{\ddot{v}} = -\frac{k_v}{mass}\vec{\dot{v}}^2\ \hat{v}\ [2]$$

$$\vec{\ddot{\theta}} = \frac{(\mathrm{Motor}_{port}-\mathrm{Motor}_{starbord})\ r_{motor}}{I_{vehicle}} - k_{rot}\vec{\dot{\theta}}\ \hat{\theta}\ [3]$$

$$\vec{\dot{u}} = \dot{x}\cos\theta + \dot{y}\sin\theta\ \hat{u}\ [4]$$

$$\vec{\dot{v}} = \dot{x}\sin\theta - \dot{y}\cos\theta\ \hat{v}\ [5]$$

$$\vec{\ddot{x}} = \ddot{u}\cos\theta - \ddot{v}\sin\theta\ \hat{x}\ [6]$$

$$\vec{\ddot{y}} = \ddot{u}\sin\theta + \ddot{v}\cos\theta\ \hat{y}\ [7]$$

In deriving the equations of motion, the forces in the û and v̂ were summed and well as the torques in the $\hat{\theta}$ seen in equations 1 through 3. These force equations were then translated into the (X, Y) frame by use of a rotational matrix. Information from the (X, Y) frame is feed back into the (u, v) frame via the expressions for velocity in the û and v̂.

With the physical constants of the vehicle and the equations of motion defined it then became possible to model and determine appropriate control laws for the vehicle. In order to simulate the vehicle, the equations of motion were condensed into three equations for $\ddot{x}$, $\ddot{y}$ and $\ddot{\theta}$ as seen here in equations 11, 12 and 13.

$$\ddot{x} = \left(\frac{motor\_thrust}{mass} - \frac{k_u}{mass}(\dot{x}\sin\theta + \dot{y}\cos\theta)^2\right)\cos\theta - \left(\frac{k_u}{mass}(\dot{x}\sin\theta + \dot{y}\cos\theta)^2\right)\sin\theta\ [8]$$

$$\ddot{y} = \left(\frac{motor\_thrust}{mass} - \frac{k_u}{mass}(\dot{x}\sin\theta + \dot{y}\cos\theta)^2\right)\sin\theta + \left(\frac{k_u}{mass}(\dot{x}\sin\theta + \dot{y}\cos\theta)^2\right)\cos\theta\ [9]$$

$$\ddot{\theta} = \frac{(motor\_torque) r_{motor}}{I_{vehicle}} - k_{rotational}\dot{\theta}\ [10]$$

In these equations, there exist two previously undefined terms: motor_thrust and motor_torque. These two terms, unsurprisingly, refer to the motor forces and torques, respectively that are imparted to the vehicle. Using the equations above in an ODE45 computation simulation, the six dimensional phase space: $[\dot{x}, \dot{y}, \dot{\theta}, x, y, \theta]$ was calculated by solving the input matrix:$[\ddot{x}, \ddot{y}, \ddot{\theta}, \dot{x}, \dot{y}, \dot{\theta}]$. This simulation showed that as an open loop system the vehicle was by nature over damped. With this in mind it was determined that a simple proportional only control law was all that was required for heading and position control. The control laws which replace the motor_thrust and motor_torque terms became:

$$\text{motor\_thrust} = K_P(\sqrt{(X_G - x)^2 + (Y_G - y)^2} \text{ [11]},$$

$$\text{motor\_torque} = K_H\left(\text{atan}\left(\frac{Y_G - y}{X_G - x}\right) - \theta\right) \text{ [12]},$$

where K_P and K_H are the proportional gains.

The work done on this simulation and control are currently being implemented into a better control process in the next version of *Virgil*'s software, alongside a position estimation process which will help smooth out the jumpy sensor data in the path planning operation.

C. Relevance to Undergraduate Education

In addition to being a valuable contribution to the project as a whole this simulation work constitutes a multidiscipline pursuit revolving around *Virgil*. The simulation and computation work were submitted by members of the project team to both mathematics and engineering professors as part of course work. It was only though the cooperative effort between these two different areas of the college that these results were possible. This serves as a continued testament to the fundamentally interdisciplinary nature of this type of undergraduate project.

VI. Conclusions and Future Work

The *USV Virgil* and the Olin Field Robotics Laboratory are entering into the next level of technical depth and capabilities with the successful testing of *Virgil* as an unmanned vehicle. The work that has been completed to date in the transition from *Circe* to *Virgil* has continued to show that unmanned surface vehicles can play a critical role in an undergraduate engineering education through their accessibility, scalability and fundamentally interdisciplinary nature.

Future work for the *USV Virgil* and the Field Robotics Laboratory include the addition of a vision system to the vehicle for carrying out visual based survey missions of river banks as well as beginning to lay the foundation for a third vehicle which will be larger and capable of obstacle avoidance in order to transition from testing at Lake Waban to a more challenging site such as the Charles River. Other work is also in progress to implement higher fidelity navigation via the SHARPS acoustic ranging system.

Acknowledgment

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