Glider Advancements in Efficiency: Enhancing Factors Necessary for Ocean-Wide Flights

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***Abstract*—The Slocum Glider is an instrument of efficiency and getting more out of less. When looking at getting the most distance out of a single battery, it is important to consider many different variables. Horizontal speed and flight path planning can both play a part in being able to achieve flight across ocean basins. With the ability to change a glider's velocity, a pilot could determine the quickest speed to fly the glider trans-ocean without depleting the battery. In other words, the pilot could choose the optimal pitch angle for a specific mission. Different pitch angles travel at different speeds while consuming battery power at different rates. One mission may carry great importance on speed rather than energy while another mission would rather go slow-and-steady in order to save as much power possible. Through enabling a pilot to change the speed of a glider through pitch angle, shorter missions can be done much more quickly while longer missions can conserve more energy while flying at a slower pace.**

Additionally, having a flight path that utilizes the currents in the ocean is a method used today to make gliders run efficiently. Making sure all instruments are reading properly is crucial to being able to navigate these currents. The key to this accurate navigation is a properly calibrated compass. Compass calibration can be complicated and frustrating but new methods of calibration have been able to remove a lot of the error that is associated with the compass. One comparison deals with a calibration of hanging a glider with ropes versus a calibration using a wooden tilt cart. Having the glider travel on the correct course between waypoints can cut miles off the overall trip that may add up and waste battery.

Keywords—Battery Consumption; Pitch Angle; Compass Calibration; Autonomous Underwater Gliders;

I. Introduction

Slocum gliders are autonomous under water vehicles that rely on bouyancy changes to slowly move through the ocean within the upper 1000m. Along the way, the gliders sample ocean parameters including temperature, salinity, and in some cases biological measures of phytoplankton occurance, abundance, and health. These gliders are designed in such a manner as to emphasize energy efficiency. By using simple changes in density, the glider is able to travel long distances with minimal power. Since the inception of Autonomous Underwater Vehicles (AUVs), multiple improvements have been made on the design and engineering of the instrument. In 2009, Rutgers University did what has never been done and sent a glider across the Atlantic, starting off the coast of New Jersey and ending at the coast of Spain. Since then, trans-ocean glider deployments have become a common goal in research. The current global glier flights are organized unde the umbrella of the Challenger Project. This project seeks to navigate along the path of the HMS challenger in the late 1800s on the first circumnavigation for science. Legs have been identified in each basin that together will track the path of this improtant science mission. In the South Atlantic, the glider 'Challenger' completed two legs from South Africa to Ascencsion Island and from Ascension Island to Brazil. In July of 2015 the glider was deployed on a mission that extends approximately 6500 kilometers from Ubatuba, Brazil back to Cape Town, South Africa. The current available battery power flying with default parameters will allow for only approximately 7000 kilometers of flight. There is potential to recover the glider, re-battery and deploy from Tristan da Cunha (37.1167° S, 12.2833° W) but this will require a boat trip of at least a month, which is cost and logistically prohibitive. Thus achieving optimum battery life and flight efficiency is critical to completing this mission. As the limits of glider travel are being pushed, designs need to be optimized in order to gain the most out of the increasingly important glider voyages.

A Slocum Glider is a very efficient machine as it currently stands however there is room for improvement. Battery consumption and currents all deal with the efficiency of a glider. Through glider engineering, we can manipulate these factors internally by improving pitch angle and compass precision. Data from previous glider missions along with our

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own test models can provide the support necessary to prove what advancements will revolutionize the efficiency of the glider. Gliders have the potential to accomplish unimaginable feats without any need to physically change the vehicle.

II. PITCH ANGLE OPTIMIZATION

The glider consumes a variable amount of energy at different pitch angles and different pitch angles led to different horizontal speeds. It has been determined that the most optimal pitch angle to use for the Slocum Glider is about 26 degrees up and down. However, not all glider missions are the same. One glider could be collecting data for a few weeks in the Gulf of Mexico while another is traveling transatlantic for a whole year. Flexibility in speed would lead to getting the most use out of a fully charged glider. Adjusting the glider to a steeper pitch angle would lead to shorter long-distance voyages while maintaining enough energy onboard as a precaution. Here we present steps we have taken to optimze glider flight for the required energy efficiency to cross an ocean basin.

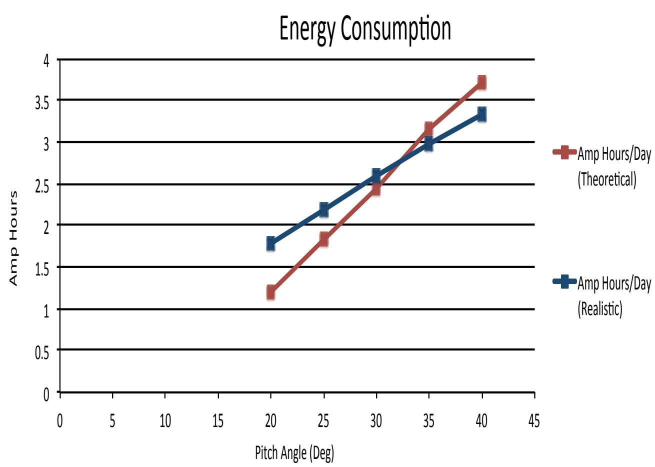

Fig. 1. The energy consumed by the Slocum Glider in Amp Hours at different pitch angles (degrees). The red line shows the theoretical Amp Hours/Day while the blue line shows the realistic Amp Hours/Day.

First, we focused on the rate of energy consumed at a range of pitch angles (Figure 1). Originally, we looked at energy consumption theoretically: using simple trigonometry and the comparison of the number of yos (consequtive upcast and downcast) to amp hours. After that, we computed a realistic trend showing the amp hours per day at different pitch angles using data gathered from the Slocum Glider. The realistic trend shows a smaller slope compared to the theoretical trend, illustrating that measured energy consumption is consistent with theory.

Taking the data retrieved from the Slocum Glider, another trend was calculated to estimate the number of spare days of battery life would be left if completing a 6000 kilometer voyage at different pitch angles (Figure 2). The linear trend indicates that a smaller pitch angle would lead to many more spare days compared to a steeper pitch angle.

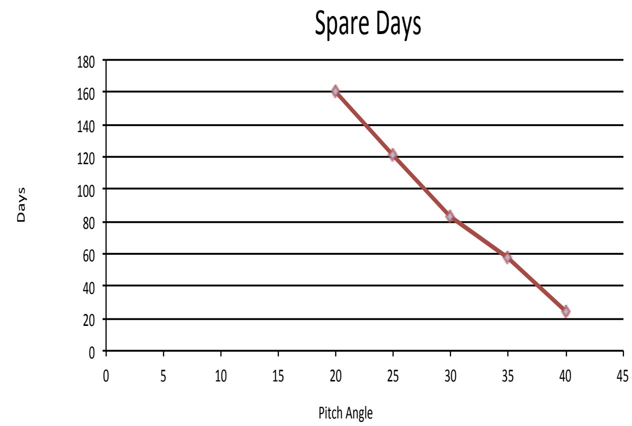

Fig. 2. The spare days of energy left at different pitch angles (degrees).

Next we looked at the horizontal velocities of the glider at different pitch angles. Figure 2 is based on information in Jeffery Sherman's paper, *The Autonomous Underwater Glider "Spray"*. The information describes where the maximum horizontal velocity and maximum range lie on the pitch angle scale. For ocean-wide deployments, the information concerning the horizontal velocity is most essential. According to the Sherman's equation, the maximum horizontal velocity occurs at a pitch angle of about 36 degrees, recommending to remain below it. The range maximized at around 19 degrees, recommending the glider remain above that angle. This window between 19 degrees and 36 degrees is the recommended range that a pilot should consider when flying a glider.

The equations designed by Sherman are derived from the following variables:

ρ	Fluid Density;
u	Horizontal Velocity;
E_0	Energy;
x	Range;
B	Buoyant Force;
C_D	Drag Coefficient;
A_D	Cross Sectional Area of Hull;
U_0	Characteristic Velocity;
X_0	Characteristic Range;

The following equations (1) (2) below describe how to calculate the characteristic velocity U_0 and the characteristic range X_0:

$$U_0 = \left(\frac{2B}{\rho A_D C_D}\right)^{.5} \quad (1)$$

$$X_0 = \frac{E_0}{.5\rho A_D C_D u^2} \quad (2)$$

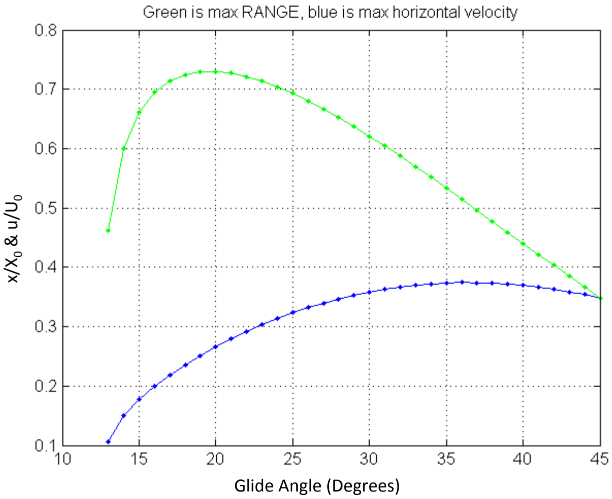

Fig. 3. The ratio between the range of the glider x and it characteristic range X_0 as well as the ratio between the horizontal velocities u and charateristic horizontal velocities are indicated at different pitch angles (degrees).

Comparing this with the information concerning energy consumption, our directive is to find the most optimal pitch angle that allows us to fly fast but safely. With so much spare energy stored in the glider, a pitch angle of 30 degrees may fair for a better transatlantic voyage for RU29.

III. COMPASS OPTIMIZATION

Finally we looked at energy saving opportunities within the glider hardware and software. Given the optimal flight parameters it is important that the glider logic efficiently navigate along its intended path. Deflections from its intended path could lead to energy loss in frequent rudder adjustments. Therefore, the distance traveled on a given day can be optimized with a more precise, properly calibrated compass. With a 6000-kilometer voyage, a simple 5% compass error could lead to a distance error of 300+ kilometer. In order to achieve a more precise compass, effective methods of calibration must be developed and implemented.

Rutgers University generally calibrates Slocum Gliders with a hanging apparatus (Figure 4). This method allows the glider to be rotated in 3D space while suspended, making the calibration process easy and generally effective.

Fig. 4. The hanging apparatus allows the glider to freely move in 3D space with ease. Object such as a tree is required to hang the apparatus.

However, in an environment with limited options to hang a glider (such as tree-less Antarctica), we developed a tilt cart that can be used in many more environments prior to deployment (Figure 5). While testing, the tilt cart prototype did have some issues in rolling the glider, which caused a few errors in our calibration trials. The tilt cart expressed much more error than the hanging method however I hypothesize that if a better method to roll the glider in the tilt cart or a more flexible calibration software was available, the tilt cart could prove to be a very effective method of calibration in the future.

Fig. 5. The tilt cart prototype designed to rotate the glider in 3D space without the necessity of an object to hang the glider from. Limitations in pitch angle exist at about 40 degrees and there is difficulty in rolling the glider in the wooden cradle.

Effective methods in calibration would not be as beneficial without an effective working compass. With both the True North Technologies Revolution Compass and the PNI Corperation TCM3 Compass models at our disposal, we put them to the test to see which model performed better in the hanging apparatus (Figure 6 & 7). Surprisingly, the results from our data show that the earlier TCM3 performed nearly 54% better than the newer Rev compass. More interesting was the errors calculated from the Rev compass as the trends resemble sine curves. We hypothesize that this error could be corrected with a more advanced calibration software however this software is not yet available to us to be tested.

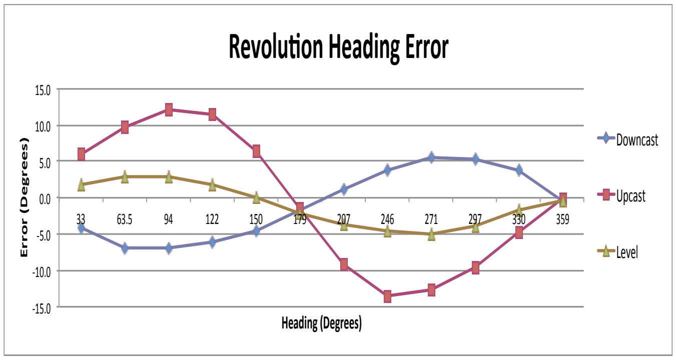

Fig. 6. The Revolution compass error (degrees) rotated around 360 degrees while pitched up 26 degrees, pitch at a level 0 degrees and pitched down at 26 degrees.

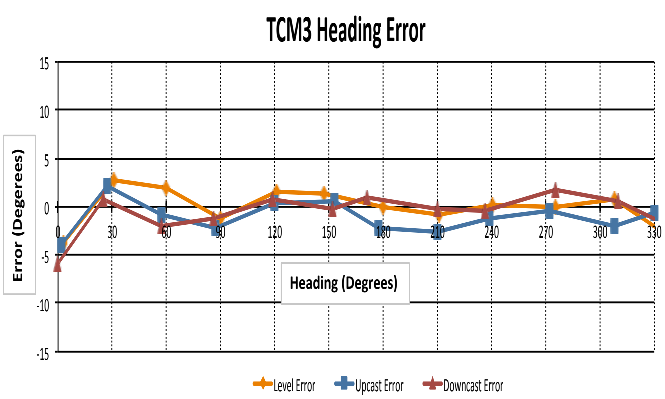

Fig. 7. The TCM3 compass was tested exactly like the Revolution compass by rotating the glider 360 degrees while being pitched up 26 degrees, down 26 degrees and kept level.

As a way to combine our different methods and compasses, we mixed-matched different calibration trials to present each comparison (Figure 8). The first comparison shows how the replacement Revolution compass performs better than the used, original Revolution compass with a 1.1 degree difference in error. The hanging apparatus was our control as our method of calibration. Next, the comparison between the tilt cart and the hanging apparatus provided some insight on how effective our prototype faired. With the replacement Revolution compass as our control, the tilt cart presented 1.3 degrees more error than the hanging method on average. This chart also includes the comparison between the TCM3 and Rev compass from previous.

Type of Compass/Calibration Method	Average Error
RU30 Original Rev Compass/ Hanging Method	4.9
RU30 Replacement Rev Compass/Hanging Method	2.8
RU30 Replacement Rev Compass/Tilt Cart	4.1
RU23 TCM3 Compass/Hanging Method	1.5

Fig. 8. The chart includes the amount of error present when testing a glider with different compasses (Original Rev Compass, Replacement Rev Compass and TCM3 Compass) with different calibration methods (Hanging Apparatus and Tilt Cart).

IV. Disscussion

The optimization of the Slocum Glider is within the ability to change the speed of the glider and pinpoint the best route available. These capabilities depend on the accuracy of the compass and pitch angle of the AUV.

Combining what we know about the horizontal speed of the glider and the rate of energy consumption used at a range of pitch angles allow the pilots to calculate the most efficient way of flight for the specific mission. A glider pilot should decide between the window of 26 and 36 degrees and compare it with the energy consumption at those angles. Any angle between 19 and 26 degrees would be an interesting range to test to see how the glider moves at such low angles. This window enacts as a possible speedometer for the pilot to use in order to operate the instrument for the mission at hand.

Once a pitch angle is agreed upon as the best choice for a mission, the most optimal route must be planned upon as well. A precise compass will allow a pilot to accurately direct the AUV into a favorable waters. For a voyage that is ocean-wide, the smallest compass error could lead to significant distance off course. As of now, the best mode of calibration is through the use of a hanging apparatus however a tilt cart could move in as a substitutable mechanism quite soon. The compass models themselves have shown that the TCM3 performed better than the Rev compass. The solution for the issues with the tilt cart and the Rev compass lies in an effective software. A forgiving calibration program would allow for the glider to halt, tilt and continue moving without presenting an error could allow for a significant drop in heading error. A program to correct the sine error generated from the Rev compass would allow it to compete well with the TCM3.

With more features available to the pilot, a glider could better adapt to the huge variety of environments in the ocean present in a deployment. Control in speed as well as pinpoint compass precision are necessary for anyone operating an AUV. The Slocum Glider has the potential to be so much more efficient with only simple changes in pitch angle and calibration.

V. Acknowledgement

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VI. References

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