"N.O.A.H" - The Navel Orange Autonomous Hauler

Final Report

Submitted on April 14th,
2022

Group Name: “N.O.A.H”

Approximate Vehicle Weight: 2 lbs.
Projected Cargo Weight: 140 grams
Predicted Performance Score: (900)

Abstract

The goal of this project is to create a fully self-contained boat that can autonomously navigate around a half stadium shaped pond from the right bottom side to the left bottom side while carrying a provided navel orange of unknown exact weight and size. The start position is chosen randomly from a set of 8 indexes along the horizontal starting line. The sub goals are to complete this path as fast as possible, construct the boat with under eighty dollars in materials (including other fees), and to make the method of navigation as reliable as possible. The boat must also be able to complete this task a minimum of two times without recharging or replacing consumable items such as batteries and without human intervention once an individual run has started. The timeline of the project is from January 14th to April 15th. This report analyzes and documents the problems & solutions associated with the challenge, the design processes & methods, the unexpected hurtles overcome, and the conclusions drawn following the completion of the project.

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Summary

The attributes documented in this report pertain to the engineering and logistics aspects of the project. This includes an analysis of the mathematical model chosen to represent the challenge, a geometrical and materials analysis of the product hardware design, the onboard electrical systems design, software control systems theory & design, testing and data collection, and manufacturing processes. Additionally, planning, organization, and execution of the project is reviewed

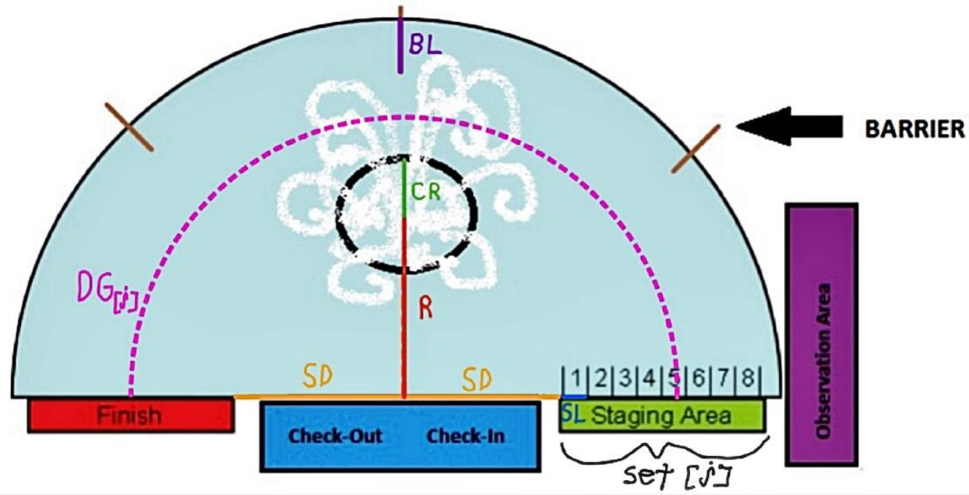
Introduction

The concepts utilized in this project report include, but are not limited to: mathematical control theory, force analysis, buoyancy calculations, electrical system design, manufacturing techniques, open & closed loop control systems, mechatronics, and quantitative data evaluation. The target audience is persons of technical and engineering backgrounds interested in learning more about autonomous systems or product design. The purpose of the report is to document the engineering processes and methods used as well as evaluating the project organization and conclusions drawn to provide the reader with information that may aid in the development and testing of other similar embedded products.

Methods, Assumptions and Procedures

The units used throughout this report are metric for distance & dimensions, imperial for weight, and both radians & degrees are used for angular measurements. Additionally, longitude and latitude are utilized in the form of decimal degrees as opposed to degrees minutes seconds.

The first step in the overall solution design was to create a geometric model of the problem. A diagram provided in the project outline was used as a base image for visual representation adding additional visuals digitally as needed. An assumption made by the provided diagram was that the pond is a semicircle while it is actually a half stadium shape. Three algorithms were derived, one to solve for "$\mathrm{DG}_{[\mathrm{i}]}$" representing the distance of the path given the starting position index "i". The second solving for "$\Delta\mathrm{D}_{[\mathrm{i}]}(t)$" representing the total distance that should be traveled given the starting index and a value of time since the start "t" assuming we are traveling at "$\mathrm{V}_{\mathrm{max}}$" which is the maximum stable velocity to be obtained through testing. The third algorithm solves for "$\Delta\theta_{[\mathrm{i}]}(t)$" the positive change in target bearing from the initial bearing given the starting index and time since start. Figure 1 below shows the modified diagram, formulas, and assumptions.



Assuming:

$$R = SD$$

BL does not intersect $DG_{[8]}$

$V_{\max} =$ maximum stable velocity

Then:

$$DG_{[i]} = \left(\frac{4\pi \cdot SD + 2i \cdot SL - SL}{4}\right)$$

$$\Delta D_{[i]}(t) = (t \cdot V_{\max})$$

$$\Delta\theta_{[i]}(t) = \left(\frac{\Delta D_{[i]}(t)}{DG\,[i]} \cdot 180\right)$$

Figure 1: Geometric model of the problem

After forming a model of the problem, the mechatronics were decided on. This includes the sensors and actuators used to control the boat according to the computational model. A jet thruster powered by a single 390 sized standard brushed dc motor was chosen for propulsion. The thruster was chosen for increased efficiency due to being ducted and thrust vectoring abilities. The motor was chosen over a BLDC (brushless dc) motor to reduce the cost of both the motor and ESC (electronic speed controller). The motor controller chosen was a generic 20-amp PWM (pulse width modulation) controlled H-bridge made by Readytosky. This ESC was selected for its low-cost, sufficient rated current, and onboard 5-volt buck converter. The battery picked was a 2s 2200mAh Li-Po (lithium polymer) with a discharge rating of 50c. This battery was chosen for its low cost and high discharge rating. The battery capacity was approved by calculating the time till depletion at the max current draw of the motor plus overhead for other electronics and ensuring there would be ample time for two runs. A basic PWM controlled hobby servo was chosen for steering the output of the jet thruster for precise computer-controlled steering. To obtain absolute heading, needed for the computational model, a three-axis magnetometer was chosen for its affordability. In later testing both the magnetometer and a, in theory, more accurate nine axis IMU (inertial measurement unit) were evaluated independently. The magnetometer was ultimately chosen due to unreliability from excessive drift of the IMU's internal gyro. Initially the IMU alone was to be used for navigation. Out of fear of compounding error it was decided to use a Neo-6M GPS module in addition to the magnetometer for more precise positioning. The microcontroller selected as the main computer was initially the Texas Instruments MSP430F5529LP as it would be provided at no cost; however, it was eventually changed to the ESP32 based Node32s. This controller was chosen over the TI board as double precision 32-bit floating-point math was required for the GPS positioning to be accurate enough. The GPS way points were generated using Google Earth and a custom python script was used to parse the resulting ".kml" files to obtain the information in the format needed. Below in Figure 2 is an example of a way point path.

Figure 2: Waypoint Path

After deciding on the initial hardware, the first step in the construction process of the boat hull was to choose a method of manufacturing. The method chosen was 3D printing using a FDM (fused deposition modeling) style printer. This method was chosen over construction by hand using materials such as foam to achieve a higher level of geometrical precision and density control, additional contributing factors included a team member owning a 3D printer of this type and that they have extensive experience with CAD (computer-aided design) modeling. Figure 2 below is renders of the CAD design. The following Figure 3 is the design with dimensions.

Figure 3: CAD Design

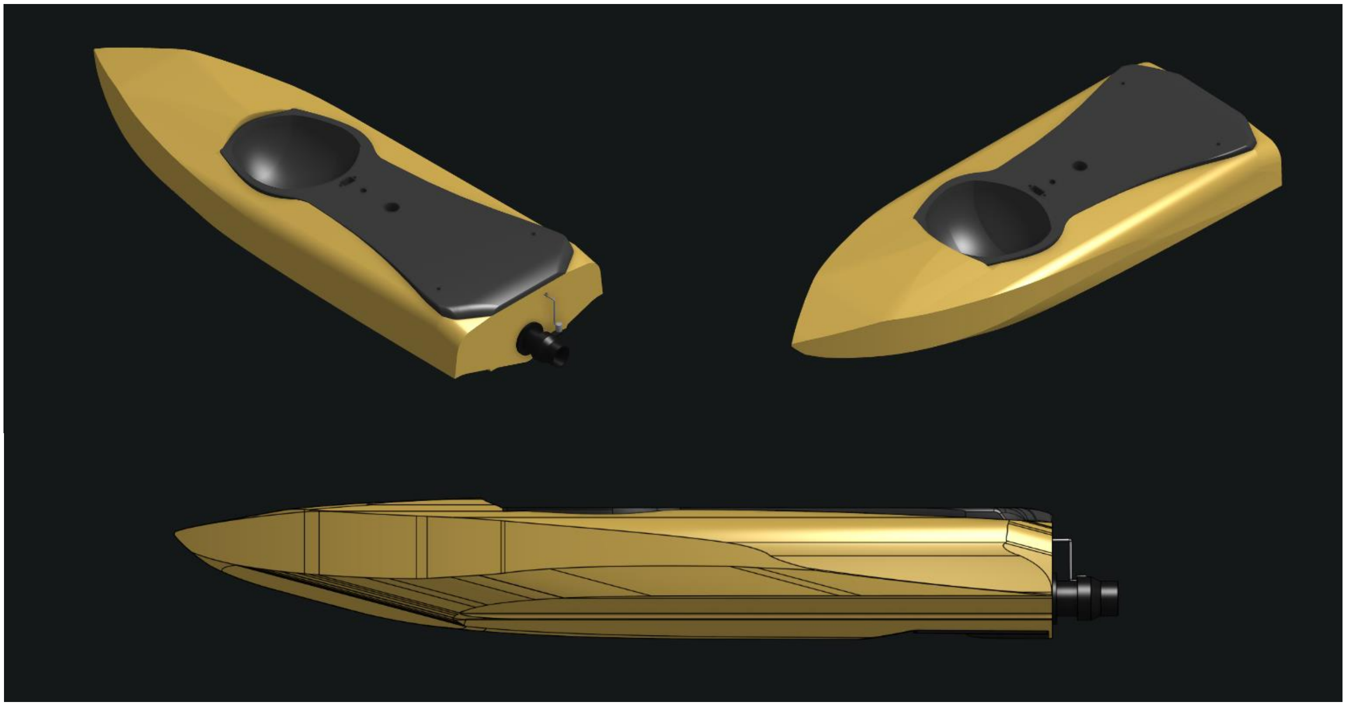
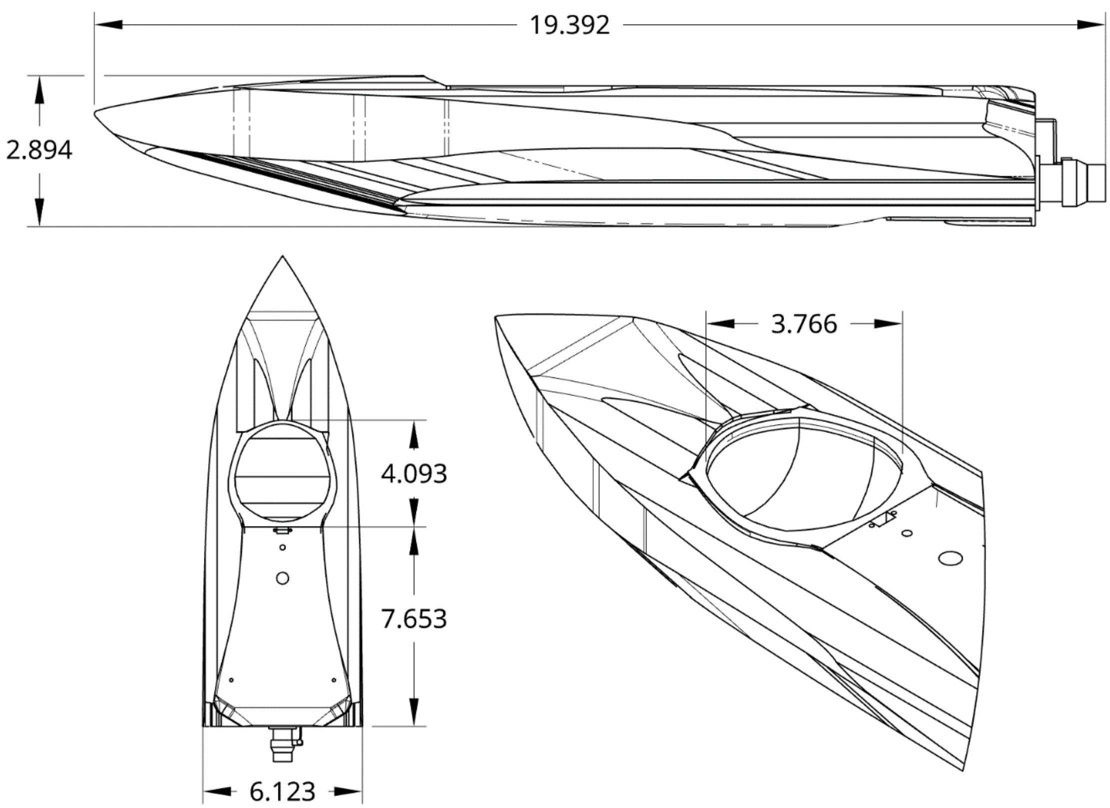
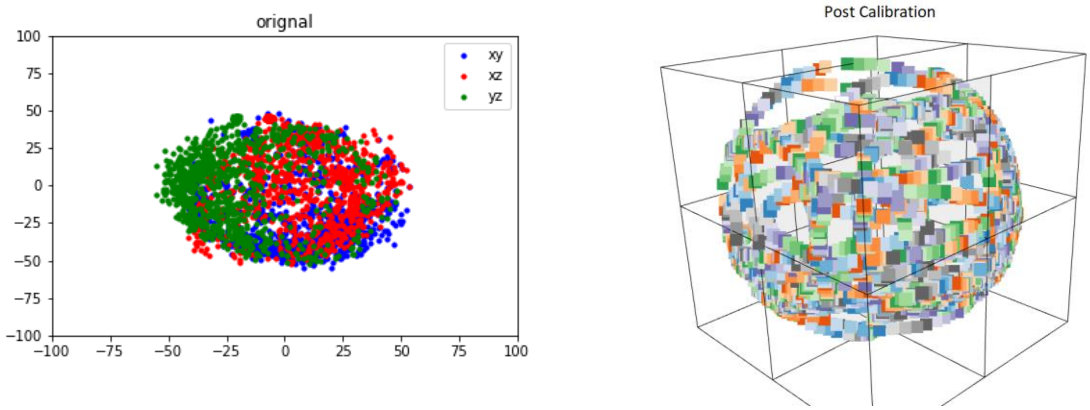


Figure 4: Design Dimensions



After deciding on a manufacturing process the type of plastic filament to be used was selected. The chosen plastic was PLA (polylactide). This plastic was picked for its low cost, ease of printing, and ability to be post processed. We chose to use both gold and black filament to represent UCF as color did not significantly affect cost. The first step in the CAD design process was to evaluate the requirements of weight capacity and buoyancy of the hull. The formula "$SA = \left(\frac{F_b}{997 \cdot g \cdot h}\right)$" was used to calculate the required surface area "SA" given the height of the water line "h" and required force of buoyancy "F_b" and acceleration due to gravity "g" to support the weight of the components and orange plus overhead for the weight of the final hull design. This surface area was used to constrain the design of the bottom face which was then used to create the layout of components inside the boat. The formula "$\mathrm{x} = \left(\frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}\right)$" was used to find positions for the internal components that would most closely balance the boat from left to right and keep most of the weight behind the center point. Keels were added to the bottom of the hull to help with steering control and maneuverability. The holder for the orange was constructed by creating two circles one the diameter of an average large navel orange and the other of an average small navel orange. These two circles were split into arcs and joined by two other arcs created from a circle with the diameter of an average navel orange. This was all done to ensure an orange anywhere within the typical size range would fit tightly. Silicone was used to create watertight seals around the openings and Velcro to mount components. The magnetometer was mounted on double sided tape for a more stable mount than Velcro. A button and LED were implemented on the main cover for status indication and interaction like starting the race; and everything was wired together using standard header pins and jumpers for affordability and modularity. The servo and thruster were connected by a steering rod made from a paperclip and passed through a watertight linearly compliant gasket created from a silicone caulking tube cover. The motor speed controller five volt regulated output was used as the main power supply for the control board, sensors, and servo. The magnetometer was calibrated during testing and will be prior to the competition. The method of calibration accounts for both soft and hard iron distortion. This is accomplished by taking a large set of samples over the course of a minute of each axis while rotating the vehicle around its center point. This must be done for every new environment and will account for electromagnetic and ferromagnetic disruption onboard the vehicle that is stationary relative to the sensor as well as off the vehicle in the environment. This is necessary to counteract the disturbance in the local magnetic field caused by the surrounding factors. These disturbances present themselves in the form of nonlinear transformations in each of the magnetometer's axis magnitude readings. This is a problem for finding heading because the way we convert the sensor axis data into angular displacement is with the trigonometric operator "atan2". This function gets the angle in radians from the "x axis" to the compound vector described by the "x" and "y" axis component vectors. When a nonlinear transformation is observed this results in a non-circular field which provides incorrect heading estimations. The solution is to find the average maximums and minimums of each axis over the calibration period and use those to compute scale factors to be applied to each axis as well as offsets for each axis. This compensated data more closely approximates a circular field allowing for greatly improved heading approximation. The effect of the calibration is shown in Figure 4 below.

Figure 4: Magnetometer Calibration Data



After all the hardware was completed, the software was developed. The navigation algorithm went through many iterations and testing before coming to the final design. The final version of our navigation algorithm is as follows: get GPS position, compute distance to the next way point, if the distance is less than the defined tolerance set the new target as the following way point, if the distance is greater than the tolerance compute the target azimuth angle between north and the target waypoint, use the calibration adjusted magnetometer readings to determine the vehicles absolute heading and find the error from the heading to the target azimuth, lastly, update a steering PID controller which adjusts the servo in order to close the heading error. This runs continuously from the start until the last waypoint is confirmed to be in tolerance range.

Results and Discussions

The results of our boat are quite satisfactory. The GPS positioning accuracy is impressive but the magnetometer distortion, even with calibration, leaves more to be desired. The overall build quality of the boat is good. Water resistance was initially a concern due to the jet thruster requiring holes in the hull of the boat, but the silicone proved to work well. The maneuverability of the boat hull is impressive due to the keels and optimal low drag surface area. The method through which we determined our predicted scoring was in degrees around the pond the start being zero and the end being one hundred and eighty. The test data recorded is shown in Table 1 below. The following, Table 2, shows the cost analysis for the project.

Table 1: Test Data

Test Number:	Distance:
1.	15 degrees
2.	45 degrees
3.	90 degrees
Average:	50 degrees

Table #: Cost Analysis

Item	Qty Purchased	Cost	Qty Used	Net Cost	Purchase Location
Node32s	5	$30.99	1	$6.20	Amazon
Jet Thruster	1	$5.73	1	$5.73	AliExpress
Motor	4	$4.13	1	$1.03	AliExpress
Motor Controller	1	$3.30	1	$3.30	AliExpress
Battery	1	$16.90	1	$16.90	Amazon
Momentary Switch	10	$13	1	$1.30	Tayda Electronics
LED	100	$3	1	$0.03	Tayda Electronics
XT60 to JST plug	1	$1.76	1	$1.76	AliExpress
Paper Clip	1	$0.00	1	$0.00	Sidewalk outside
Neo-6M GPS	1	$5.30	1	$5.30	AliExpress
Gold PLA Filament	1 kg	$18.69	389 grams	$7.27	Amazon
Black PLA Filament	1 kg	$20.99	139 grams	$2.92	Amazon
Caulk Tube Cover	35	$13.06	1	$0.37	Amazon
Socket Head Screws	1200	$28.99	20	$0.48	Amazon
Countersunk Screws	510	$14.99	2	$0.06	Amazon
Magnetometer	1	$10.99	1	$10.99	Amazon
Perfboard	100	$15.49	1	$0.15	Amazon
Velcro	30 ft	$19.97	5 in	$0.28	Amazon
10k ohm resistor	100	$4.00	1	$0.04	Tayda Electronics
JST Connector	460	$11.99	1	$0.03	Amazon
Servo	6	$26.99	1	$4.50	Amazon
Jumper Wires	120	$6.79	20	$1.12	Amazon
Total:		$277.05		$69.76	

Conclusions

There are several conclusions that can be drawn from this project regarding the hardware used, algorithms used, and testing. One of the largest conclusions is that using an IMU to determine heading of a water vehicle is usually very inconsistent. While sensor fusion of magnetometer and gyroscope data to get heading and then using an accelerometer and gravity to account for tilt can be very accurate on flat land with vehicles that primarily move in one axis at a time; it is not nearly as accurate on water. The bobbing around that the water causes results in the gyro drifting and ultimately corrupting the magnetometer readings leading to inaccuracies. Another conclusion is that the floating-point precision constraints on your processor is very important when working with GPS coordinates in decimal degree form. A difference in a few decimal places can decide whether your navigation system works at all. A conclusion regarding the use of a magnetometer for absolute heading is that calibration makes all the difference in accuracy. Lastly, while a more technically advanced system may be more consistent after being developed it will still be difficult to make work and my not be better than a simpler solution.

Recommendations

It is recommended to anyone using a magnetometer for navigation to do the proper calibration procedures. Calibration is the most important thing for getting accurate positioning data. It is also important to ensure that your processor has sufficient accuracy to complete the computations you need. In our case the need for 32-bit precision was extremely important. The navigation would never have worked with the 16-bit precision of the previous micro controller. For designs specifically using GPS and a magnetometer it would probably be beneficial to add an accelerometer for integrating to get change in position in between GPS updates. This would significantly improve the smoothness of this method. Using wireless telemetry could be quite useful as well. The inability to see what data the sensors were reading while testing made it very hard to debug strange behavior. Another possible design approach would be differential steering using two motors without a thrust vectoring control servo. This would allow for more precise adjustments of heading without the need to move forwards along the instantaneous heading as much.

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