A Method for Accurate Ballasting of an Autonomous Underwater Vehicle

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Abstract

Use of autonomous underwater vehicles (AUV's) has transformed the way in which marine related data is collected. AUV's allow for unmanned underwater data collection in remote and hostile environments and can greatly reduce the expense and resources required for such data collection, compared to the use of manned vessels and remotely operated vehicles (ROV's). The Tethys-class AUV developed by the Monterey Bay Aquarium Research Institute (MBARI) has allowed for longer duration missions for use in spatial and temporal studies of the euphotic zone. With mission durations extended from days to weeks, more careful attention must be paid to vehicle weight and balance during pre-deployment buoyancy and trim adjustments, or ballasting, to minimize energy use. When an AUV is incorrectly ballasted it must generate lift to offset that trim imbalance resulting in a drag penalty which decreases range and could induce control problems. Ballasting issues are further complicated by frequent payload changes as various instruments are added and removed. We have developed a quick yet accurate method to determine the vehicle's current center of gravity (CG), center of buoyancy (CB) and righting moment; these values can be applied to the vehicles onboard configuration information and for the addition of trim weights to achieve the desired trim. Essential components of this procedure include development of a means for accurately locating the longitudinal CG and CB of the vehicle, in addition to using hydrostatics to

derive the righting moment. In this paper we will look at a method to accurately ballast an AUV.

Introduction

It is human nature to strive for knowledge and understanding of the world we inhabit. In our efforts to acquire information we are often driven to exploration of distant and hostile environments, to which we can travel only at great expense [6]. The costs and technical challenges associated with keeping humans alive in these harsh and distant environments have led to an increase in the use of robots as alternatives. For oceanographic studies, remotely operated vehicles (ROV's) are unmanned vehicles which can be operated safely from a ship and allow for collection of sensory data, video footage as well as sampling capabilities. The use of ROV's however, does have its limitations as this vehicle is attached to the ship via a cable tether. Additionally, ROV's require a fully staffed ship which can also be costly. Exploration of the oceans interior presents additional challenges, in that it is difficult to communicate information without the need for wires.

With the limitations of the ROV's a new type of robot the autonomous underwater vehicle (AUV) has been developed to overcome the necessity for a pilot or a cable tether. AUV's have the ability to function with little to no human supervision, and relay information and communication wirelessly via satellite upon surfacing. Autonomous robots used in exploration activities are highly dependent on their ability to sense and respond to their environment. An exploration robot must accomplish its goals in a previously unmapped environment with unpredictable disturbances and threats [6].

Propeller-driven autonomous underwater vehicles (AUVs) have predominantly had endurance cycles of about one day [2], in which they are able to collect a variety of data for use in oceanographic research. These vehicles can be equipped with a variety of sensory and sampling capabilities, which can be used for ocean floor mapping, water sampling, tracking and following of organisms, tracking and mapping of upwelling fronts, thermoclines, and phytoplankton blooms, in addition to many other applications.

The Monterey Bay Aquarium Research Institute (MBARI) has developed a 110kg propeller-driven Tethys-class long range AUV [1] which has the ability to complete longer missions, ranging from weeks to months without requiring the attendance of a ship. To achieve this, the long range AUV, uses a buoyancy engine to allow for neutral buoyancy and a shifting mass to provide additional pitch control; with neutral buoyancy there is a reduction in power needed to travel as the AUV does not have to resist buoyancy to maintain its depth position.

Frequent additions and modifications made to the configuration of MBARI's AUV have caused changes in the performance of the vehicle due to shifts in the center of buoyancy and center of gravity of the vehicle. To allow for successful long duration deployments, AUV's require optimization to achieve efficiency with a limited on-board power supply. Longer deployments can accumulate more extensive and continuous sets of data, this longer range also increases the demand for efficiency in the AUV's power consumption. In an effort to improve the capabilities and performance of the long range AUV we have addressed the issues in hydrostatics through modifications in the ballast and trim procedure. The question we seek to answer is can an improved ballasting procedure increase the range and improve the dynamic control of MBARI's long range AUV?

Methods

To develop an improved ballast and trim procedure for the LRAUV there must first be an understanding of the vehicles features and the existing test-tank ballast and trim procedure and the impact it has on the long range vehicle's performance. The Tethys-class long range AUV is equipped with redundant systems for vertical plane and pitch control. These systems include vertical elevators (actuated horizontal fins), a movable centrally located mass, made up of the vehicles battery supply —62 laptop batteries, which compose about a third of the vehicles total weight—, and a buoyancy engine which is capable of displacing oil from the interior of the pressure hull to an exterior bladder, for visual representation, refer to Fig. 1.

The AUV's current ballast and trim mission uses the vehicles on board sensory information such as a depth sensor, accelerometer, and an inertial measurement unit to determine the vehicles pitch angle and is then programmed to adjust the mass shifter until the desired pitch angle is achieved; for the existing ballast and trim mission the desired pitch angle is zero. Additionally, the vehicle is commanded to a certain depth and will adjust its buoyancy engine until it can come to rest at that depth in neutral buoyancy. Although the vehicle is capable of self-ballasting, the physical location of the center of gravity (CG) and center of buoyancy (CB) as well as the righting moment — the length of the separation between CB and CG) — are not known.

To accurately locate the physical position of the center of gravity and buoyancy in the X and Z axis, the use of the hydrostatic moment equation for pitch (see Fig. 9) and a balance tool specifically designed to weight the AUV in order to measure the center of gravity has been created. To design this tool the first consideration was the format which would be used. A single knife-edged vehicle support could be used but is not entirely practical as this vehicle has a mass ranging from 110kg to 160kg depending on configuration. Additionally, the vehicles contains a number of finely calibrated instruments which could be damaged if the vehicle were to impact the ground, thus an alternative format with more support was ideal. A two-scale design would offer the additional support with as much accuracy as the knife-edge format but also lead to a new format decision, whether to use hung (See Fig. 2) or floor scales(see Fig. 3). Both format types were considered and a thorough analysis of major parameters such as cost, capacity, resolution and material was performed.

The determining requirements for the scales was done by looking at the goals we hoped to accomplish with this measurement device. Since the AUV has a capacity ranging from 110kg to 160kg, a two scale configuration would require scales which exceeded the 80kg demand. We also wanted to be able to accurately measure the center of gravity to within a millimeter. Through a moment calculation I was able to determine the desired resolution to be ±100 grams, (see Fig. 4 for full calculation). The cost of the scale was also a major consideration as the long range AUV lab has a project budget to comply with, desired cost was to be less than $1000 per scale. After an extensive search and comparison of scales, it was determined that the hung scales which met the capacity and resolution requirements did not meet the cost requirements and ultimately the decision was made to use floor scales. With the selection of floor scales as our format a more thorough search was conducted to determine the best features at the most affordable cost. The result of our comparison yielded a fair number of scale options that met the criteria and of those, the most inexpensive scale which met all of the desired design requirements was the Adam GBK260A. This scale has a load Capacity of 150kg with a resolution of ±5 grams (much finer than the desired resolution) at a retail cost of $399 each.

Once the scale had been selected more careful attention had to be paid to supporting the vehicle on the scale. The design for supporting the vehicle went through a number of material and overall shape changes. These changes were made first to make the balance design fast and simple to set up and use with an accurate and reproducible contact point. Secondly, to fit the vehicle support to the scale's pan dimension requirements, and lastly to select materials that could be easily machined (in house) while also being robust enough to handle the load, impact and possibly corrosive conditions. The final design was constructed of 8020 aluminum tubing as well as 1" UHMW sheeting with 1-1/4" stud-mounted ball transfers to allow for adjustment of the vehicle (See Fig. 5).

As mentioned, this tool is used to measure the moment between the scales and is used to determine the longitudinal center of gravity (in the X-axis). The use of this balance set up can be used not only to determine the vehicles center of gravity but also its center of buoyancy along the X-axis. The way in which the center of buoyancy along the X-axis is measured is as follows: the vehicle will be placed in the test tank and will run its normal self-ballast and trim mission, once this mission is complete the vehicle will be neutrally buoyant and have a zero pitch angle. This means the center of gravity and center of buoyancy should be coincident along the X-axis. The vehicle is then placed onto the vehicle supports on the scale balance and from the measured masses, and the fixed distance between the vehicle support contact points, the center of gravity can be calculated. Being that the center of gravity value is the same as the center of buoyancy following the self-ballast and trim, the center of buoyancy is now known. With this value we can then place the vehicle back into the test tank and command it to induce specified pitch angles and using the distance that the mass is shifted (extracted from mission data) we can then also determine the vehicles righting moment. To accompany this procedure and measurement balance setup, I have created a spreadsheet which takes input from the user for all the required measurements and outputs the locations for Xg, Xb and Zg. See Figure 6 and 7 to view the entire written procedure and spreadsheet.

The measured values from this tool can be used to determine pre-deployment dynamics as well as to calculate the location of additional trimming weights in order to achieve a neutrally buoyant and well ballasted vehicle. The values can additionally be applied to developing a more accurate solid (3D computer animated design) model which will more efficiently calculate the new center of gravity of the vehicle given future changes in configuration. The center of gravity and center of buoyancy measurements as well as the solid model calculations can also be applied to the improvement of the existing ballast and trim mission structure as well as on board simulation accuracy which could result in more efficiency during a given flight. Further improvements to ballast and trim mission may be necessary to make this process faster, more accurate and more automated.

Results

The resulting product of this project is essentially the balance design (see Fig. 8) including the scale selection sheets, the vehicle support design and a fast, accurate and repeatable procedure to locate center of gravity and center of buoyancy locations and derive the righting moment using the written procedure and the excel calculation sheet.

The application of these results can be directly implemented into the vehicles on board and currently outdated configuration file which gives the vehicle its preliminary data to reference from for its onboard simulation. Additional applications as mentioned previously are to assess any troublesome pre-deployment vehicle dynamics, strategically add weights to compensate for the vehicles trim as well as to implement these values into the solid (CAD) model in order to more accurately predict the effect of vehicle configurations. The application of these values could prove to benefit a number of oceanographic research applications through potentially improving the vehicles dynamic control and energy efficiency, the vehicle in theory would have the ability to travel a longer range, as well as having improved control near bottom surfaces. In addition, the improvement of the ballast and trim through real-time software applications can assist in anomaly detection as the behavior of the vehicle would become more predictable.

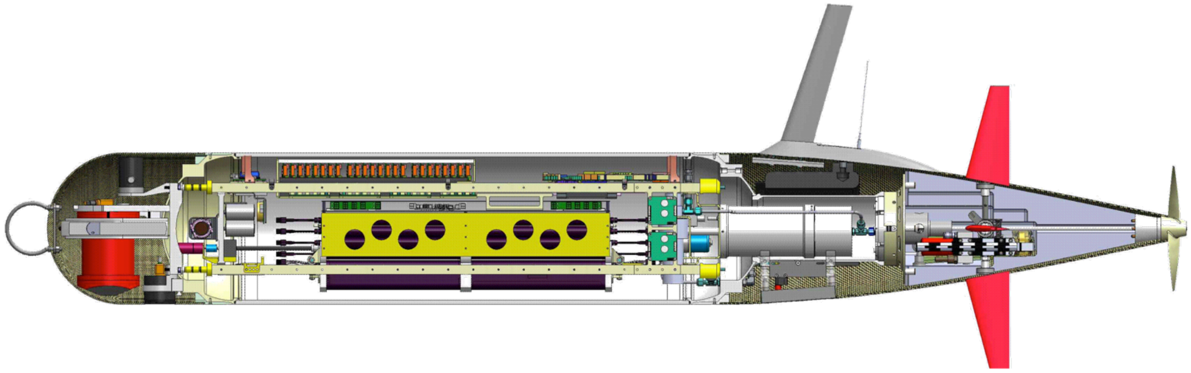


Fig 1: Cross sectional view of MBARI's LRAUV

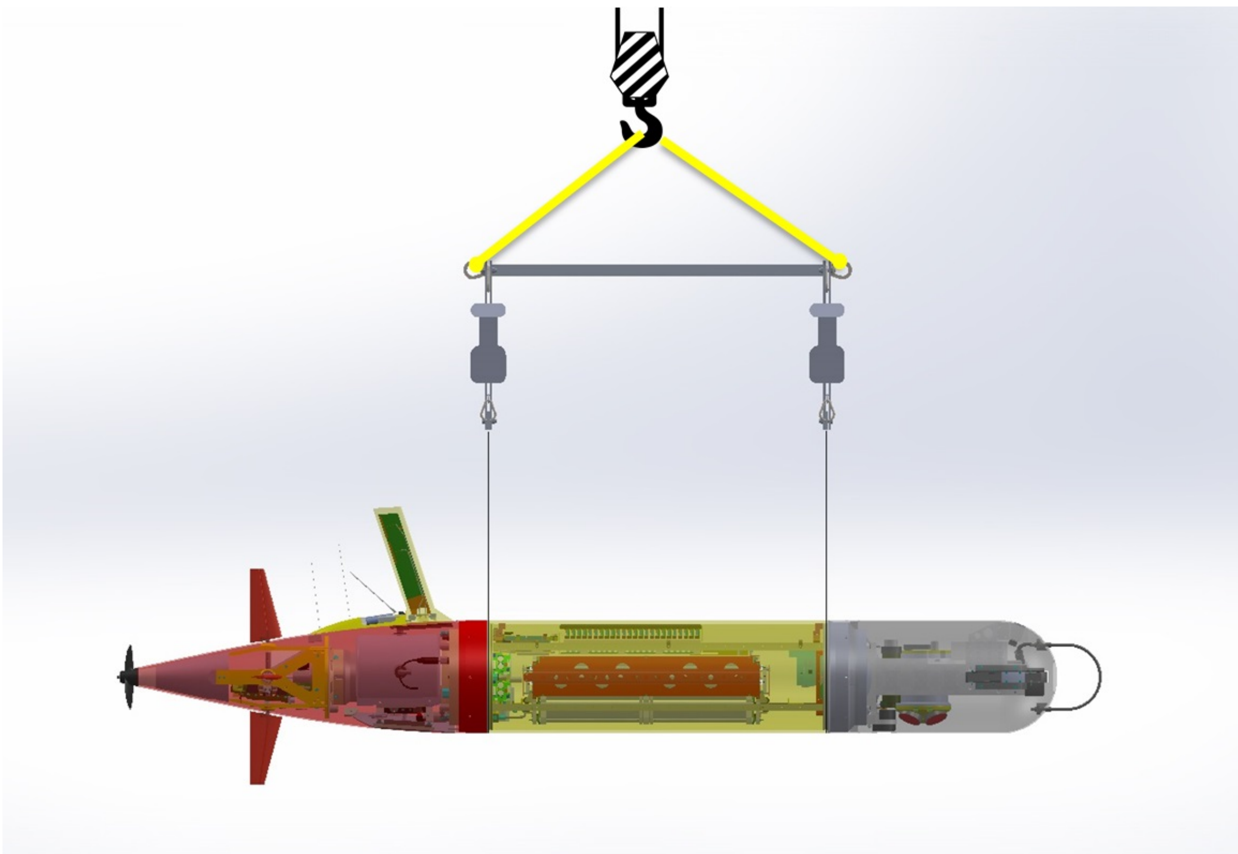


Fig 2: MBARI's LRAUV on a dual hung scale design to measure center of gravity

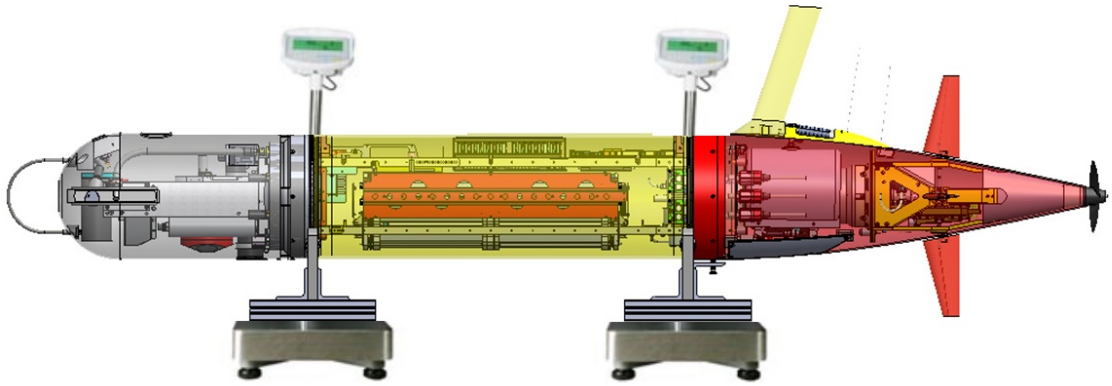
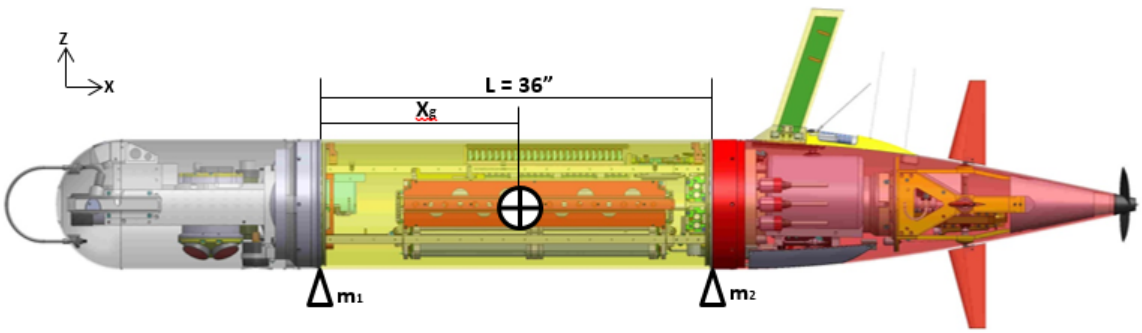


Fig 3: MBARI's LRAUV on a dual floor scale design to measure center of gravity

Scale Resolution



- X_g in this case is the distance from the point at which m_1 is weighed (the seam at which the nose and pressure hull meet) to the center of gravity (CG).
- If the CG is centered in the pressed hull (at 18" from either seam) this would mean that the weight at the two scale positions (m_1 and m_2) would be half of the total weight of the vehicle.
- If the total vehicle weight is 110kg (m1 + m2 = 110 (kg)), this would mean that if CG is centered in the pressure hull each scale will read 55kg.
- If the CG is then shifted by 1/32" (0.03125") along the x-axis, we can calculate the desired scale resolution as follows:

Total length: $L = 36"$
Shifted CG distance: $X_g = 18.03125"$
Total mass: $M_{total} = (m1 + m2) = 110$ kg

$X_g(M_{total}) = L*m_2$
$m_2 = X_g(M_{total} / L)$
$m_2 = (18.03125")*(110 \text{ kg} / 36")$
$m_2 = 55.095486$ kg

Desired resolution:
55.095486 kg – 55 kg = ± 95.486 g

For scale resolution necessary to measure a 1mm (~ 0.0393701") shift in CG the desired accuracy should be ±120.298 g.

Fig 4: Calculation showing scale resolution required for sub-millimeter precision.

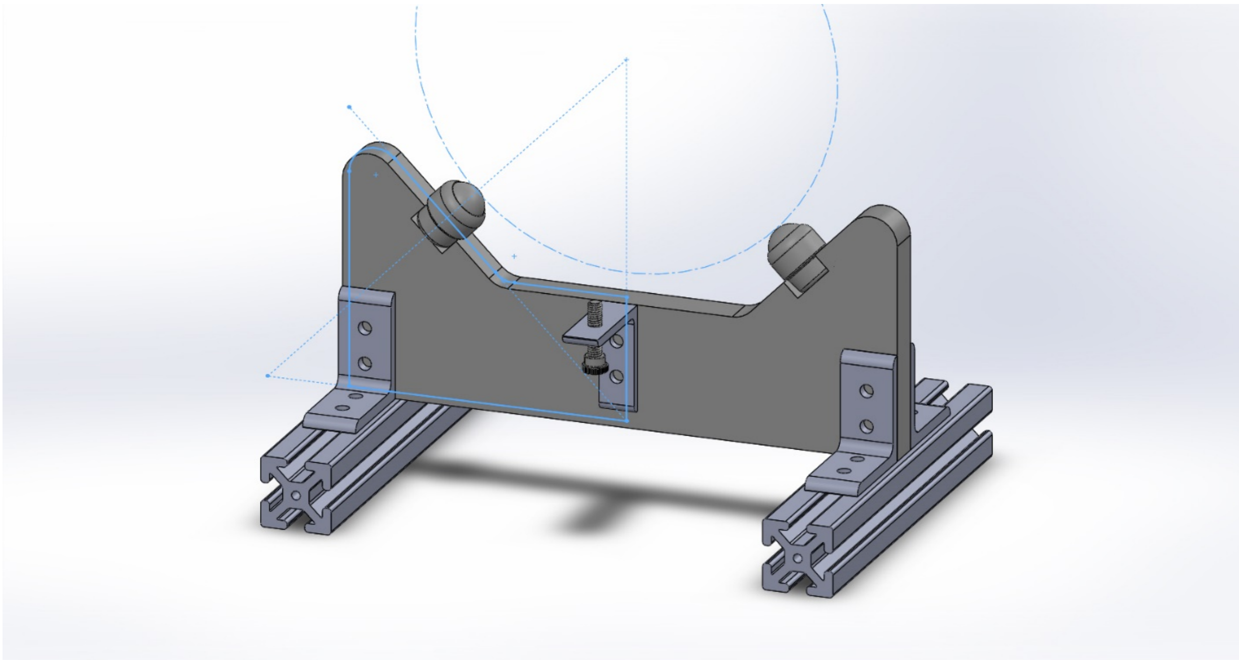


Fig 5: LRAUV Support Chock assembly, used to support the LRAUV on the floor scales

Procedure for locating Xg, Xb and Zg of an AUV
For Long Range Vehicle:

- **Finding Xb**

1. Run ballast and trim mission in test tank.
2. After ballast and trim is complete, remove LRAUV from tank and place on scales.
   - The LRAUV should be positioned on supporting chocks which are lined up at known locations on the vehicle; In this case we will use the pressure hull seams.
3. Using the measured weight values from the scales, the center of gravity along the X-axis (Xg) can be calculated.
   - If the distance from the point at which the scale chock at the forward side of the vehicle to Xg is desired we can calculate this

     Xg = (m2 / (m1 + m2)) * L

     Where m1 (the forward scale mass) and m2 (the aft scale mass) are the measured masses of the LRAUV at the two scales and L is the total distance between the scale chocks.
4. This value calculated for Xg is equal to the center of buoyancy along the X-axis (Xb) following the ballast and trim.

- **Finding Xg'**

1. Since we have measured and calculated Xg and acquired Xb for the vehicle at a zero pitch angle, we can use this information to determine the new location of the center of gravity (Xg') along the X-axis once the mass is shifted to produce a given angle by accounting
2. We can calculate the value of Xg' using the following equation:
   - Xg' = (mbat / mtotal)Xshift + Xg

     Where mtotal = (m1 + m2) total vehicle mass, mbat = the shifted battery mass

- **Finding Zg (Assuming Zb is set as an origin at zero.)**

1. We will place the LRAUV back in the tank and command it to hold defined pitch angles.
2. Using the hydrostatic equation for pitch:

   Mhs = – (ZgW – ZbB)sinΘ – (Xg'W – XbB)cosΘ cosΦ

   In steady state Mhs = 0

   W = mg (weight), B = ρVg (buoyancy), Θ pitch angle, Φ roll angle.
   - Setting this equation up to solve for Zg we get:

     Zg = ((B / W)Xb – Xg')cotΘ cosΦ

   Since the LRAUV is neutrally buoyant W = B, which then gives:

   Zg = (Xb – Xg')cotΘ cosΦ

Procedure | Calculations

Fig 6: LRAUV Procedure write up for locating Xg, Xb and Zg.

	A	B	C	D	E	F
1	**Calculation sheet:**					Input
2	With Test Tank Ballast and Trim mission complete:					Output
3						
4	**Scale Values**					
5	**Aft** Scale Reading	58.66	kg			
6	**Fore** Scale Reading	47.725	kg			
7	**Total** Vehicle Mass	106.385	kg			
8	**Measured Distance**					
9	**Distance** Between AUV Scale Supports	94.1	cm			
10						
11	**Finding Xg**					
12	X-location of **Center of Gravity**	51.8861306	cm	Note: This value is the distance from the Aft scale location to Xg.		
13	**Finding Xb**					
14	X-Location of **Center of Buoyancy**	51.8861306	cm	(Xg = Xb)		
15						
16						
17	Using Test tank Pitch angle command and Mass shift values:					
18						
19	**Shifted** (Battery) **Mass**	40	kg			
20	**Distance Shifted**	0	cm			
21	Commanded **Pitch angle**	0	ϴ°			
22	**Roll angle** (if any)	0	Φ°			
23						
24	**Finding Xg'**					
25	**X-Location of CG** after Shifting mass	51.8861306	cm			
26						
27	Given Neutral Buoyancy:			Hydrostatic moment is Zero at Steady State		
28	**Finding Z_g**			(Assuming Zb is set as an origin at zero.)		
29	**Z-location of CG** (Neutral Buoyancy)		cm	This value is only true Given Nuetral Buoyanc		
30						
31						
32	**Alternative:** Given Any Buoyancy:			Note: This process to find the righting moment is		
33	**Finding Z_g**			necessary if Vehicle is not able to achieve Neutral		
34	Volume of water displaced		m^3			
35	Water Density		kg/m^3			
36	Gravity	9.80665	m/s^2			
37	Bouyant Force	0	N			
38	**Z-location of CG**		cm			
39						
40						

Procedure | Calculations

Fig 7: LRAUV Procedure calculation sheet inputting values to output location of Xg, Xb and Zg.

Fig 8: LRAUV Procedure application using Vehicle supports and scale system.

These equations can be expanded to yield the nonlinear equations for hydrostatic forces and moments:

$$
\begin{aligned}
X_{HS} &= -(W - B)\sin\theta \\
Y_{HS} &= (W - B)\cos\theta\sin\phi \\
Z_{HS} &= (W - B)\cos\theta\cos\phi \\
K_{HS} &= -(y_g W - y_b B)\cos\theta\cos\phi - (z_g W - z_b B)\cos\theta\sin\phi \\
M_{HS} &= -(z_g W - z_b B)\sin\theta - (x_g W - x_b B)\cos\theta\cos\phi \\
N_{HS} &= -(x_g W - x_b B)\cos\theta\sin\phi - (y_g W - y_b B)\sin\theta
\end{aligned}
\tag{4.3}
$$

Note that the hydrostatic moment is stabilizing in pitch and roll, meaning that the hydrostatic moment opposes deflections in those angular directions.

Fig 9: Hydrostatic moment equations, Pitch is denoted as Mhs. These equations are from the referenced Timothy Prestero Thesis

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