Ballast System Concept

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Revision 1
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Conclusions:

This report suggests a passive ballast system, and the consequent vehicle requirements. The specifics of the mechanical design, material selection, etc. are left to the M.E.

The suggested ballast system consists of 4 cylindrical containers, 6 cm in diameter and 16 cm in height. Two are located in the lower half of the nose, on either side, with the top of the container level with the top edge of the hull. They should be 16 cm (6.4 in.) forward of the section edge. The the other two should be in the lower half of the tail, 14 cm (5.6 in.) aft of the tail section edge.

These contain the trim weights, which are envisioned to be of lead, cast into disks.

It will be necessary to remove the upper hull to gain access to the weight containers.

Beware that weight and balance properties are inherently non-modular. For example, the maximum allowable static pitch angle that can be trimmed out will depend on the length of the vehicle, as this increases the lever arms. Also, any buoyancy specification for a particular section must depend on how many other sections are present, and what their buoyancies are. Consequently, the rest of this analysis assumes a single parallel midbody of length 1.81 meters (46 in.). The overall vehicle length is 374 cm.

For this ballasting system to work, the complete vehicle, excluding trim weights, must meet the following requirements:

1. The total vehicle buoyancy must be 150 ± 10 Newtons.
2. The static roll angle, ϕ_0, of the vehicle should not exceed $5°$.
3. The static pitch angle of the vehicle, θ_0, should not exceed $31°$.
4. The vertical c.g. location, z_G, must be between 5 and 10 millimeters, where the $+z$ direction is down, and zero is on the centerline.

If these requirements are met, then the vehicle can be trimmed to a negligible static roll and pitch angle, and the delta-buoyancy (ΔB) simultaneously brought down to 40 ± 10 Newtons.

We can now use the pool to measure y_G, z_G, and ΔB by the method of hanging external weights and logging AHRS, as was done previously in the harbor.

The next section justifies the above requirements.

Discussion:

The after-trim $\Delta B = 40 \pm 10$ number is based on the projected drag increase in straight-and-level flight. See Figure 1. This result is from the Gertler-Hagen equations, specialized for the steady-state, depth/pitch case in straight-and-level flight. They are not linearized.

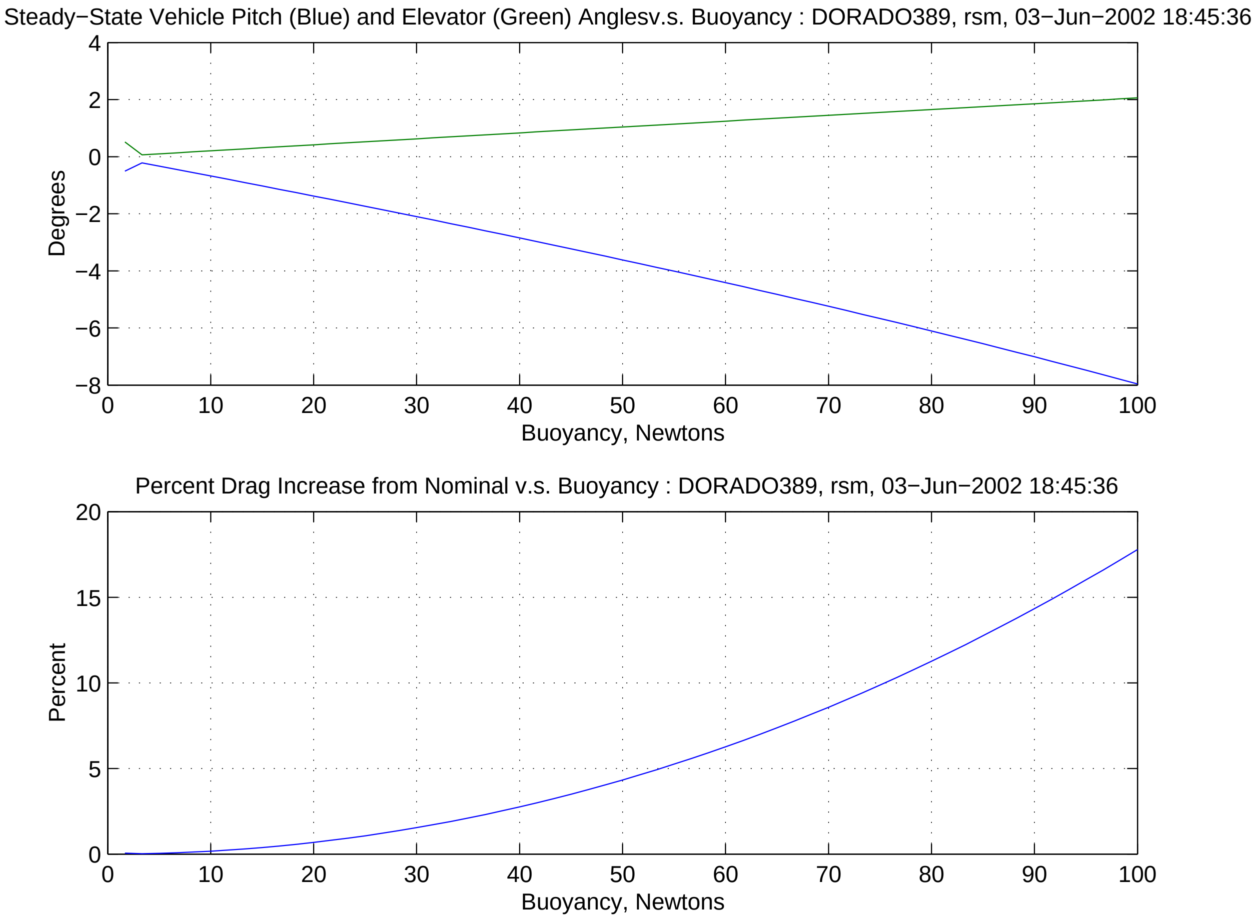

Figure 1: Attitude and Drag Versus Buoyancy

At 50 Newtons, the drag has increased by nearly 5%, prompting the upper limit of 50. The lower limit is set to 30 Newtons as a safety factor. Also, the ascent rate is 18 meters/min ($Z_{w|w|} = -560$ kg/m), assuming no forward speed and the vehicle remains level.

Figure 2 shows the increase in drag due to $x_G \neq x_B$. Presuming that the vehicle can be trimmed to within 5° of level, this is not big. Note that the minimum drag occurs at $x_G - x_B > 0$ due to the 30 N assumed buoyancy.

Figures 4 and 3 below show the effect of shifting x_B and z_B on the transient closed loop control performance.

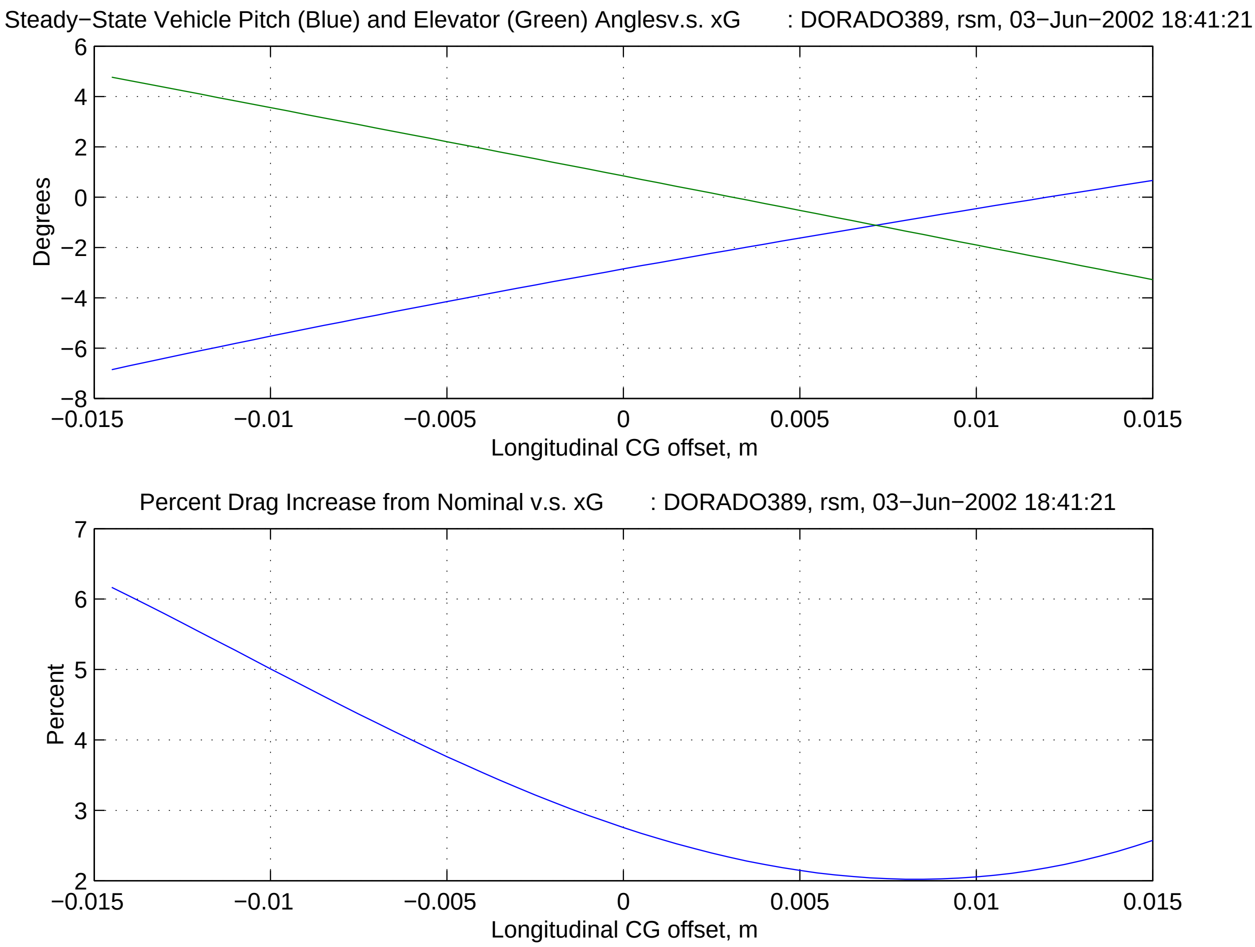

Figure 2: Attitude and Drag Versus Longitudinal c.g. (x_G) with 30 Newtons of Buoyancy

Figure 3 is a root locus on x_G, showing that the dominant poles are relatively insensitive to variation in x_G. Beware that this model was generated by linearizing the Gertler-Hagen Equations about $U = 3$ kts in straight-and-level flight. We can expect that the effect of a longitudinal c.g. offset at lower speeds will be more pronounced.

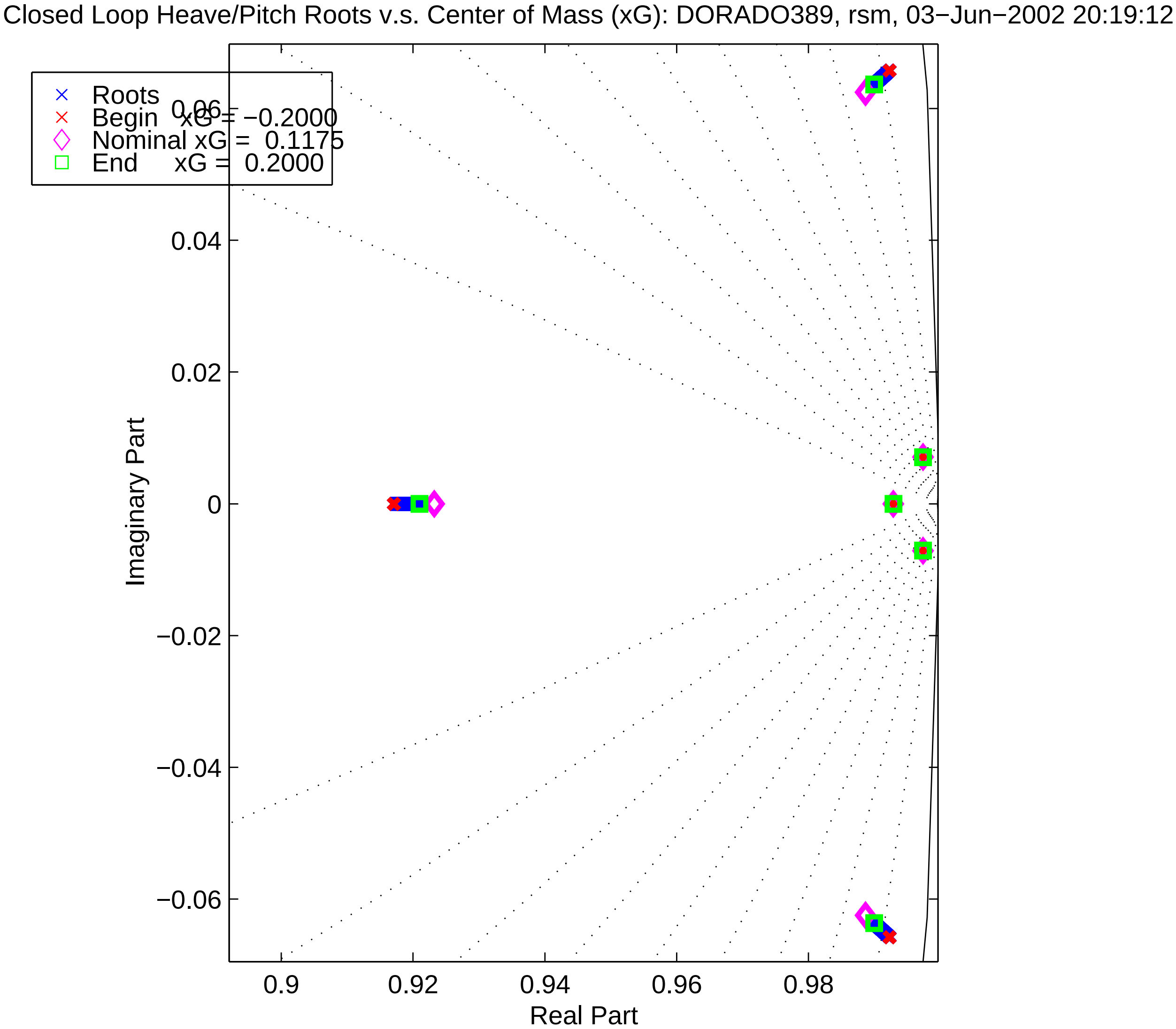

Figure 3: Closed Loop Depth/Pitch Roots Versus x_G

Figure 4 shows a similar result for variation in z_G. Interestingly, the system is unstable for very large values of z_G. This is not a problem because values of z_G that large are unrealistic, and if they were, the system could be stabilized by a gain re-design.

Measurements in the harbor have previously placed z_G at 6-7 millimeters. Thus, we will select 5-10 millimeters as a safe range regarding transient control system performance.

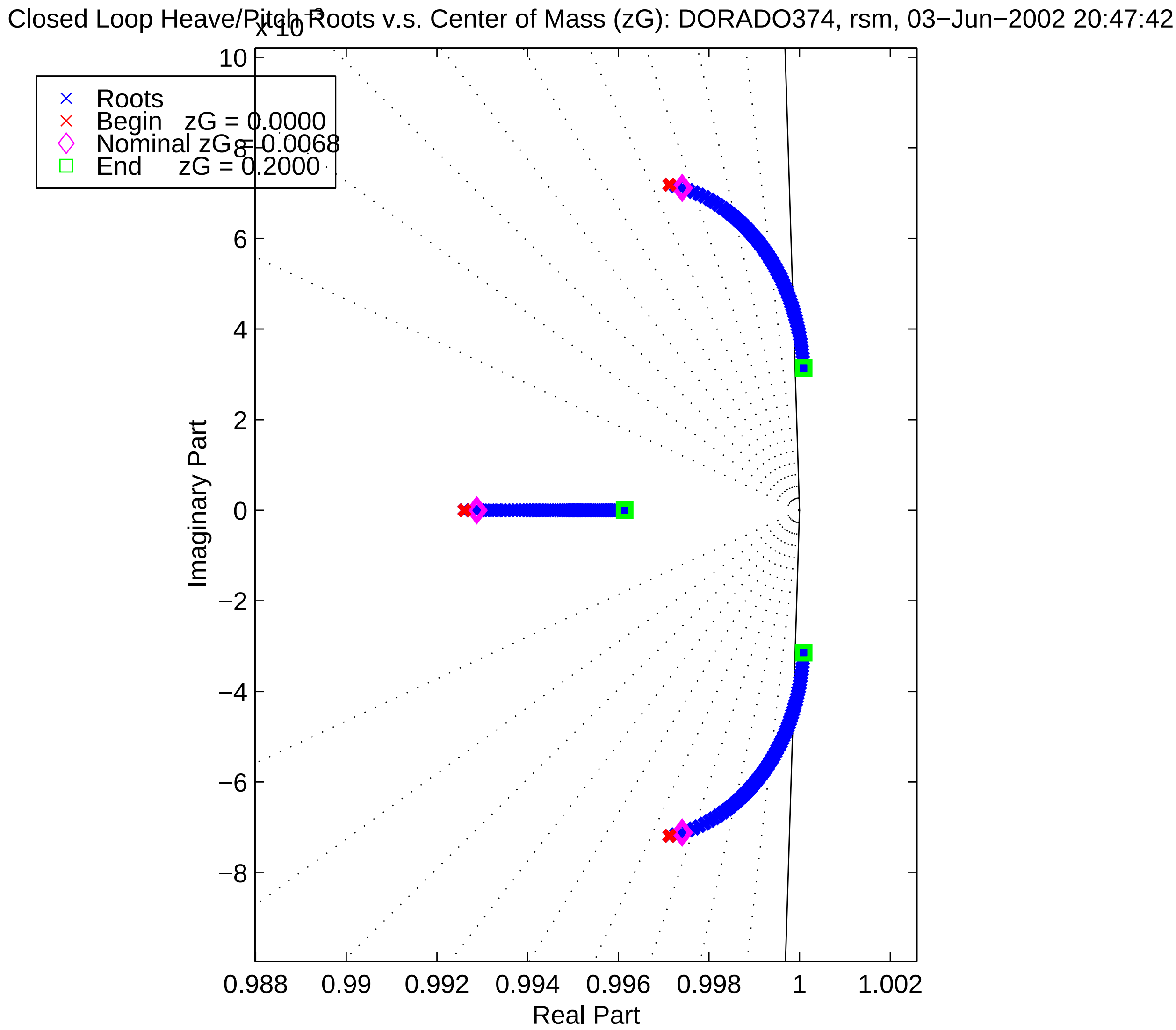

Figure 4: Closed Loop Depth/Pitch Roots Versus z_G

Passive roll stability places another constraint on z_G. It must be large enough that the prop doesn't roll the vehicle over when it starts up. Steady-state reaction torque while underway is not an issue because the propulsor stators have an angle of attack that generates an equal and opposing torque.

The size and location of the trim weights were determined by first assuming reasonable values, and then computing the subsequent maxium roll and pitch that can be trimmed out. Table shows the heights, in centimeters, of the required lead weight in each holder, given an untrimmed pitch of 31° and a roll of 5°. The weight holder in the starboard bow is empty, indicating that greater roll and pitch angles could only be trimmed out by reducing the minimum required ΔB of 50 Newtons, or adding foam instead of weights.

Also, this trim weight technique can only increase z_G (lower the c.g.) from its pre-trimmed value, which should not be a problem.

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Using Dorado374 Parameters: 46 inch midsection.
The desired (delta) buoyancy is  50.0 Newtons.
The steady-state ascent rate is  17.9 meters/minute.
The untrimmed roll angle is   5.0 degrees.
The untrimmed pitch angle is -31.0 degrees.
The total heights of the trim weights in cm are:

      Bow
  3.8    0.0
  8.7    5.0
     Stern

  (Top View)

zGNew = 0.78 cm.
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Table 1: Heights (cm) of 6 cm Diameter Lead Trim Weights