MIT 2.S01 Introduction to Autonomous Underwater Vehicles

Lecture 8: Hydrostatics

Supun Randeni
Mike Benjamin
Mike Sacarny

MIT Sea Grant AUV Lab
MIT Marine Autonomy Lab

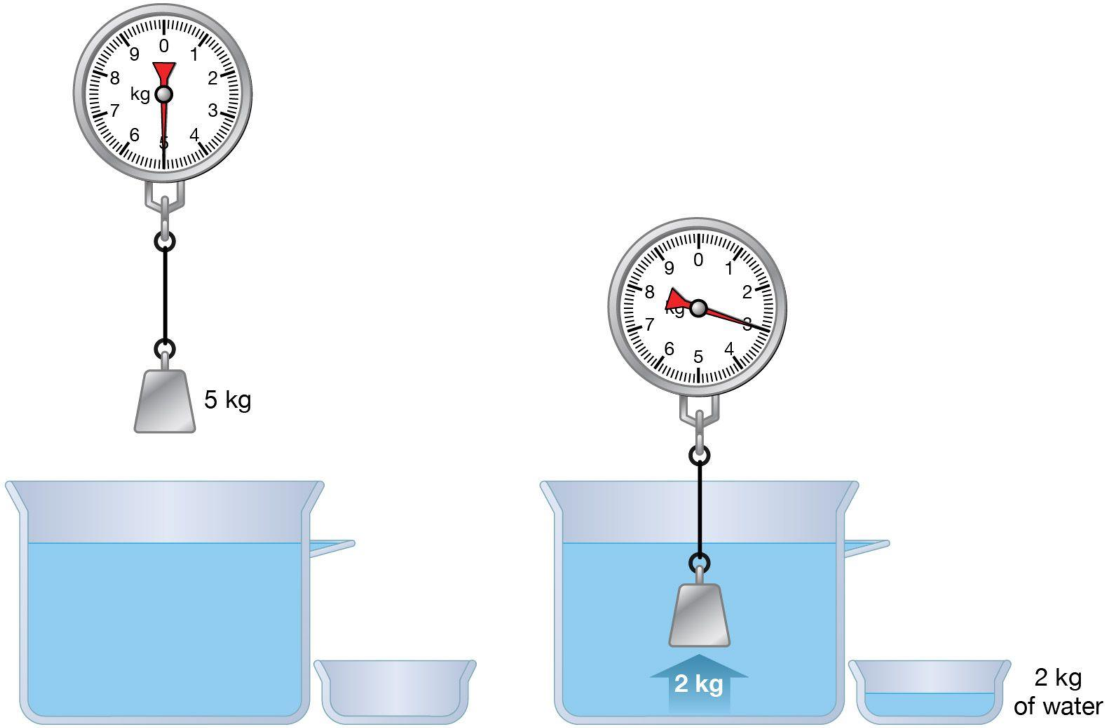
Archimedes' Principle

"An arbitrary shaped body immersed, either partly or fully, in a fluid will experience the effect of a net positive vertical force originating from the fluid pressure (depth dependent). This vertical force is called buoyancy and is equal in magnitude to the weight of the displaced fluid."

Displaced mass (kg) = volume displaced (m^3) x density of the fluid ($kg\ m^{-3}$)

Buoyancy force (N) = volume displaced (m^3) x density of the fluid ($kg\ m^{-3}$) x gravitational acceleration ($m\ s^{-2}$)

$= V \rho g$

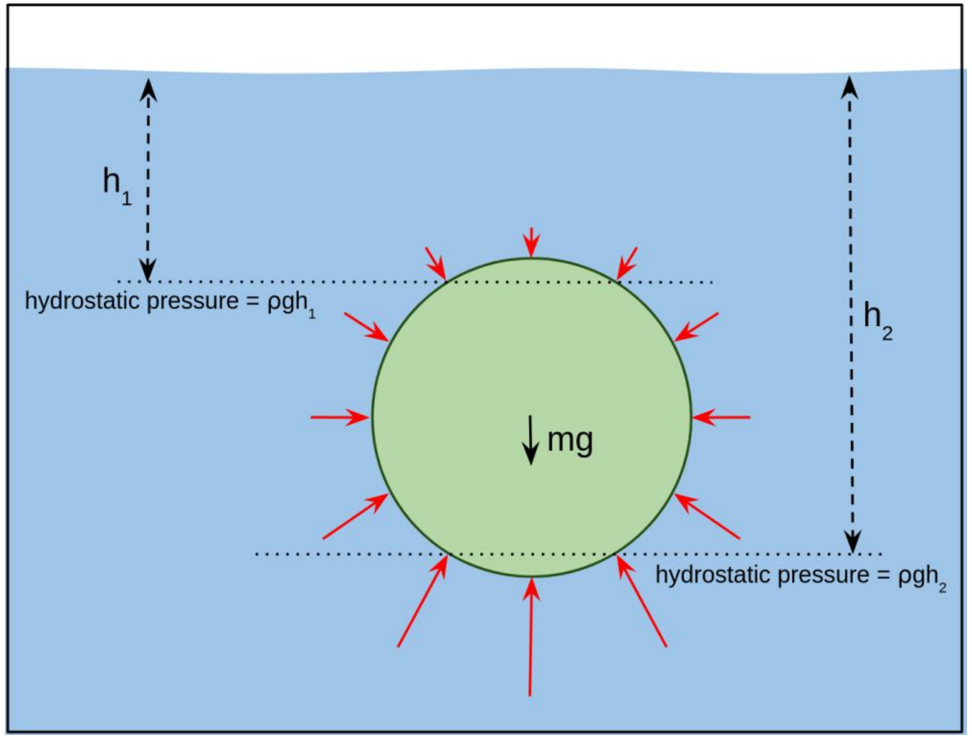


Hydrostatic pressure

The hydrostatic pressure is the pressure exerted by a fluid on an immersed object, caused due to the force of gravity.

hydrostatic pressure = fluid density x gravitational acceleration x water height

$= \rho g h$



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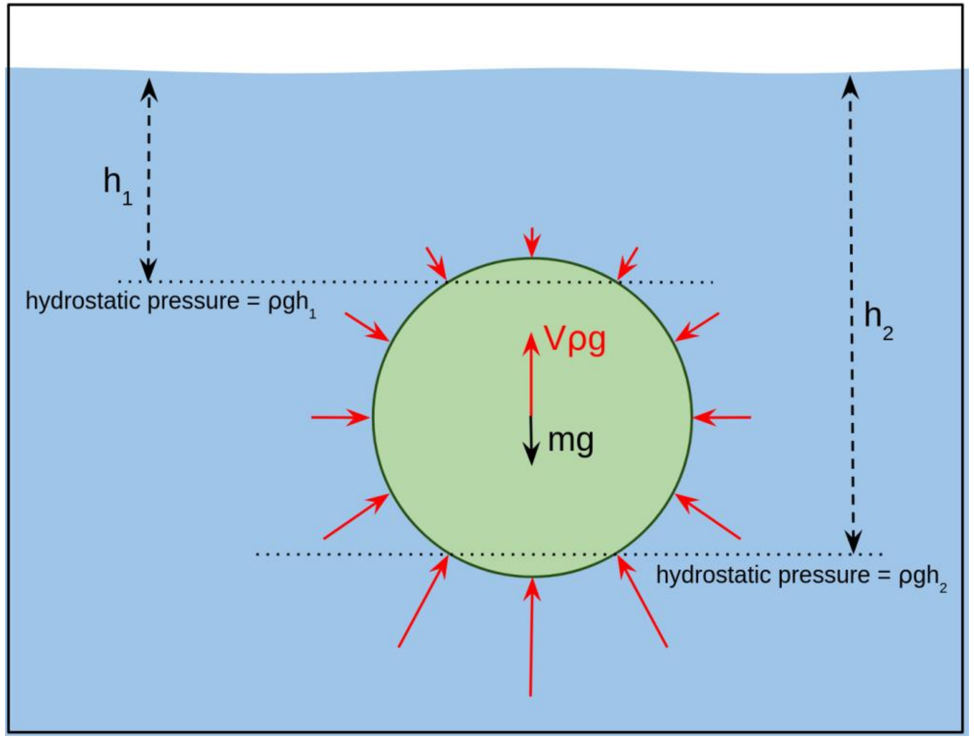
$= \rho g h$

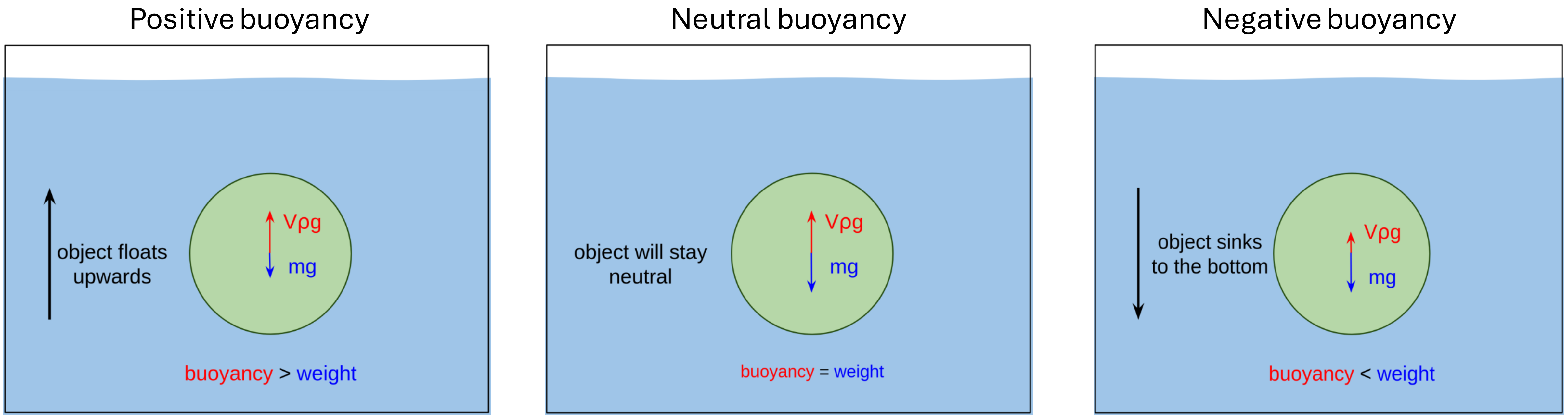
The buoyancy force

- The hydrostatic pressure acting on the body varies along the vertical axis, with the water height.
- The lateral components of the hydrostatic force cancel each other out, since they are equal and in opposite directions.
- Due to the hydrostatic pressure difference in the vertical axis, the vertical components of the hydrostatic force creates an upwards resultant force, i.e., the buoyancy force ($V\rho g$).



Weight and buoyancy

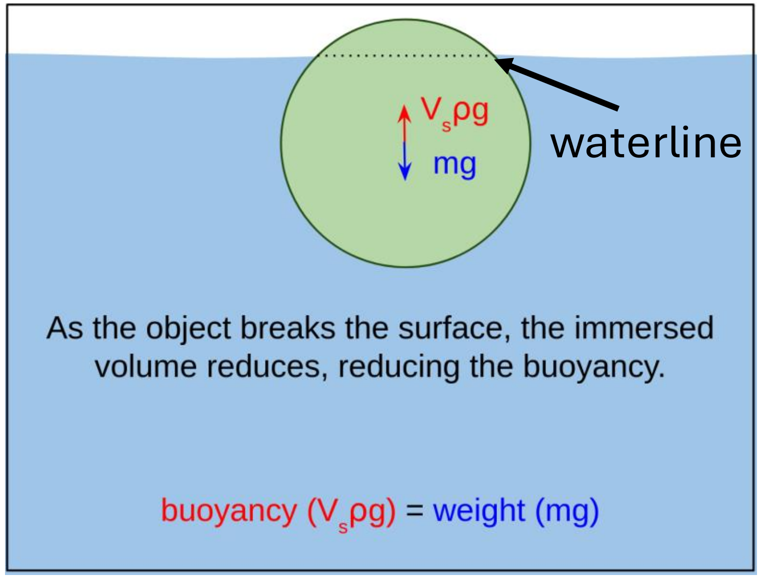
- If the buoyancy is larger than the weight of the object, it will float upwards.
- If the buoyancy is equal to the weight, it will stay natural in the water column.
- If the buoyancy is smaller than the weight, it will sink to the bottom.



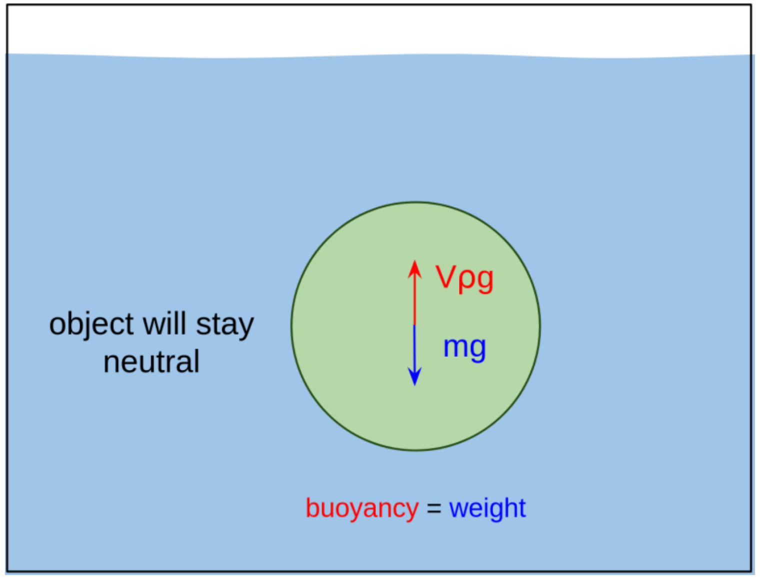
Weight and buoyancy

- If the buoyancy is larger than the weight of the object, it will float upwards.
  - When at surface, object will stick out of the water until the immersed volume (i.e., the buoyancy) reduces until buoyancy is equal to the weight.
- If the buoyancy is equal to the weight, it will stay natural in the water column.
- If the buoyancy is smaller than the weight, it will sink to the bottom.

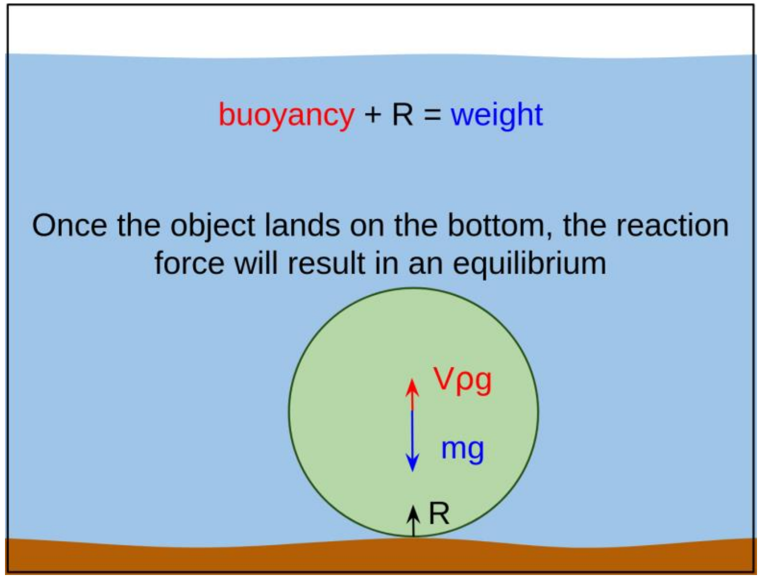
Positive buoyancy



Neutral buoyancy



Negative buoyancy



Center of buoyancy and center of gravity

Center of gravity (C_g):

- The point where the gravitational force (i.e., the weight) acts upon.

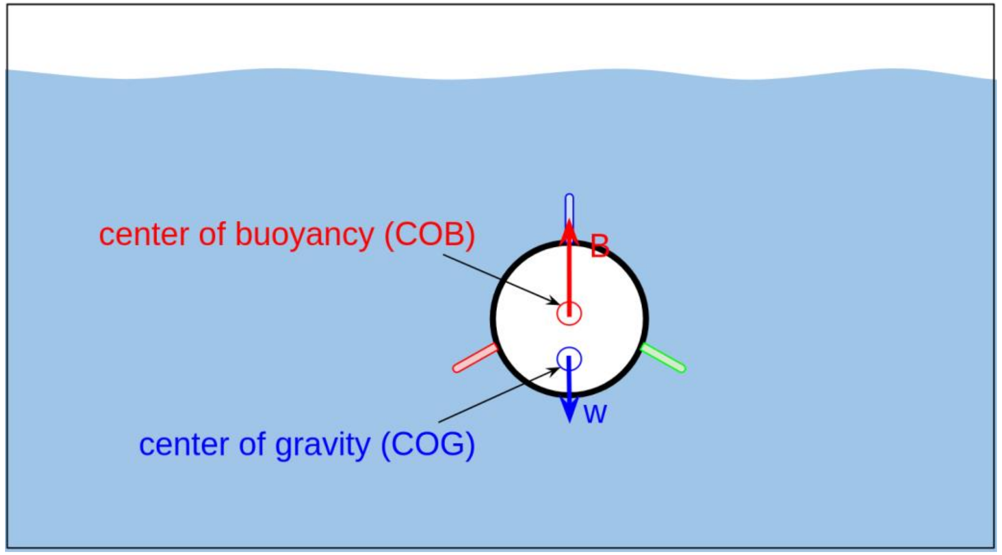
- The position of center of gravity:
  - Longitudinal center of gravity (LCG) - longitudinal distance from origin to C_g
  - Vertical center of gravity (VCG) - vertical distance from origin to C_g
  - Transverse center of gravity (TCG) - transverse distance from origin to C_g

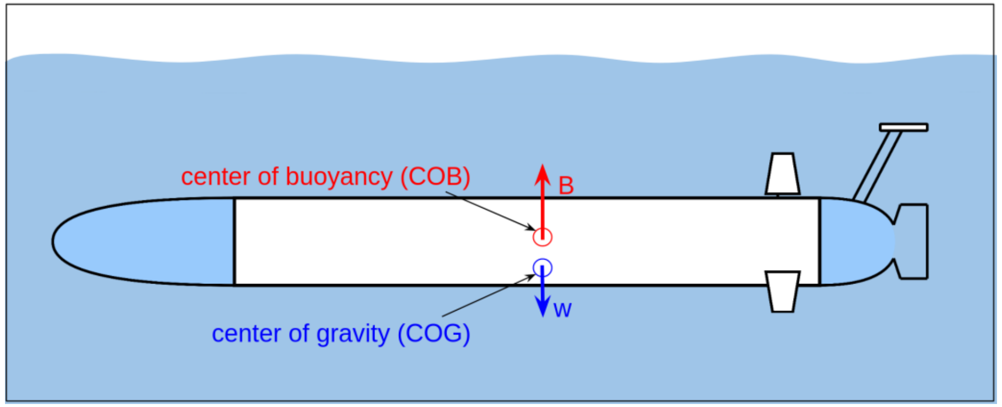
Center of buoyancy (C_b):

- The point where the buoyancy force acts upon. I.e., the center of gravity for the volume of water which a hull displaces.

- Varies with the shape of the non-free-flood hull.

- The position of center of buoyancy:
  - Longitudinal center of buoyancy (LCB) - longitudinal distance from origin to C_b
  - Vertical center of buoyancy (VCB) - vertical distance from origin to C_b
  - Transverse center of buoyancy (TCB) - transverse distance from origin to C_b

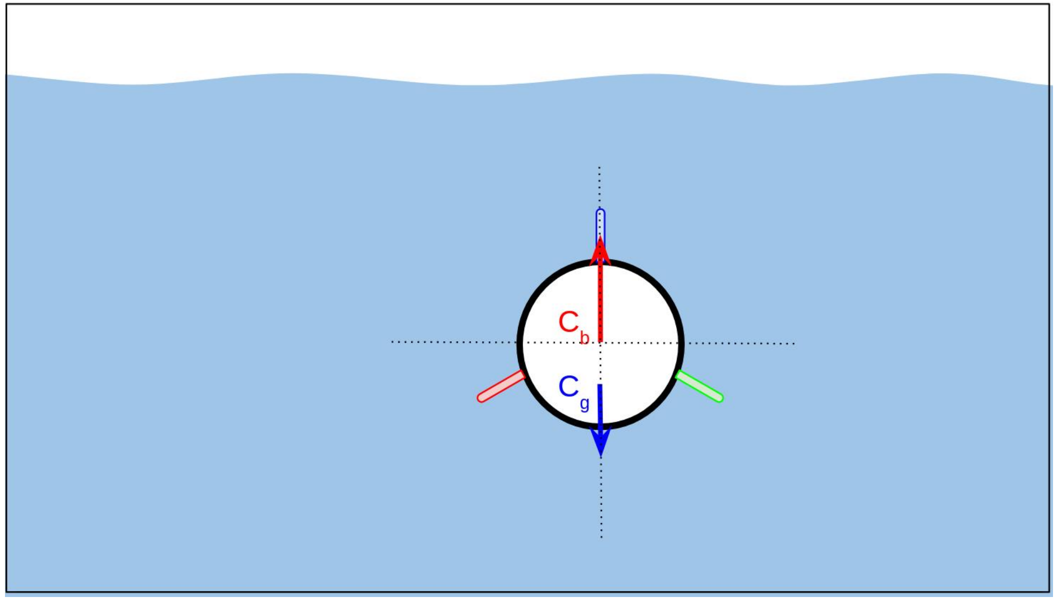


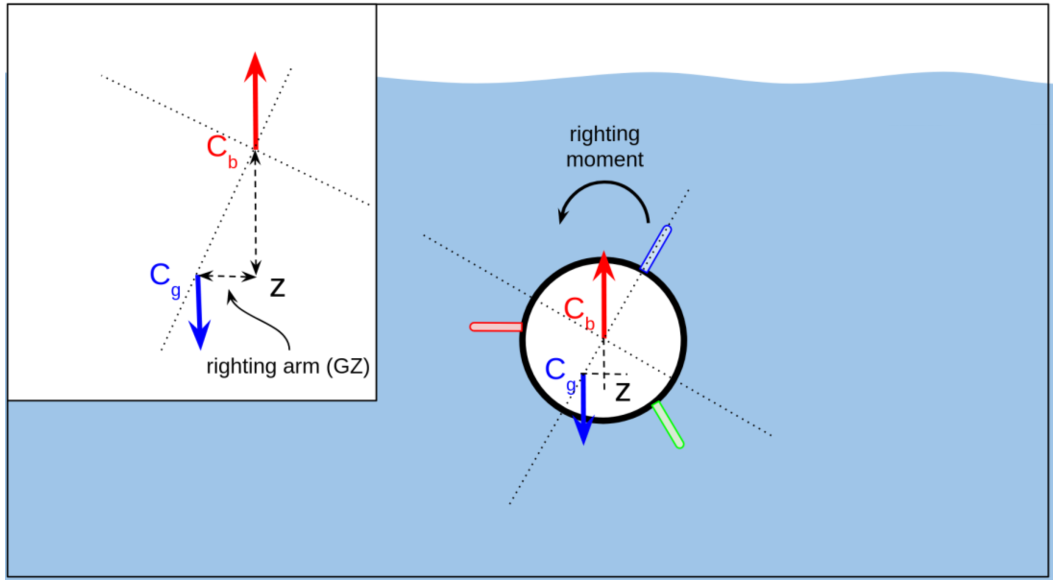


Submerged transverse stability of an AUV

Positive stability:

- If the center of buoyancy is above the center of gravity (i.e., VCB is above VCG), the AUV is in positive stability condition.
- If the AUV inclined due to an external force, a righting moment will be created to return the vehicle to its original position.

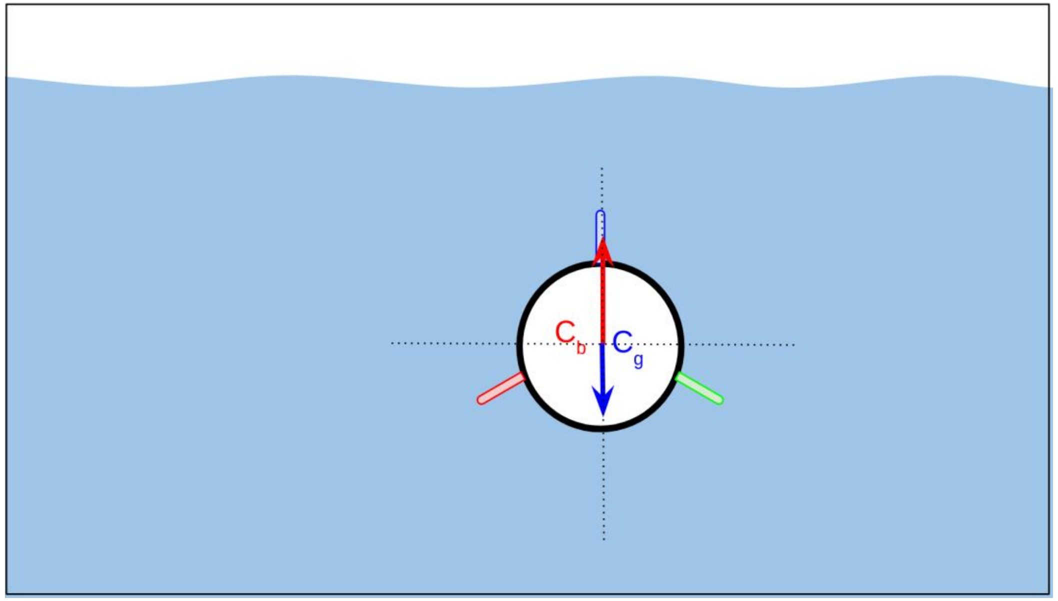


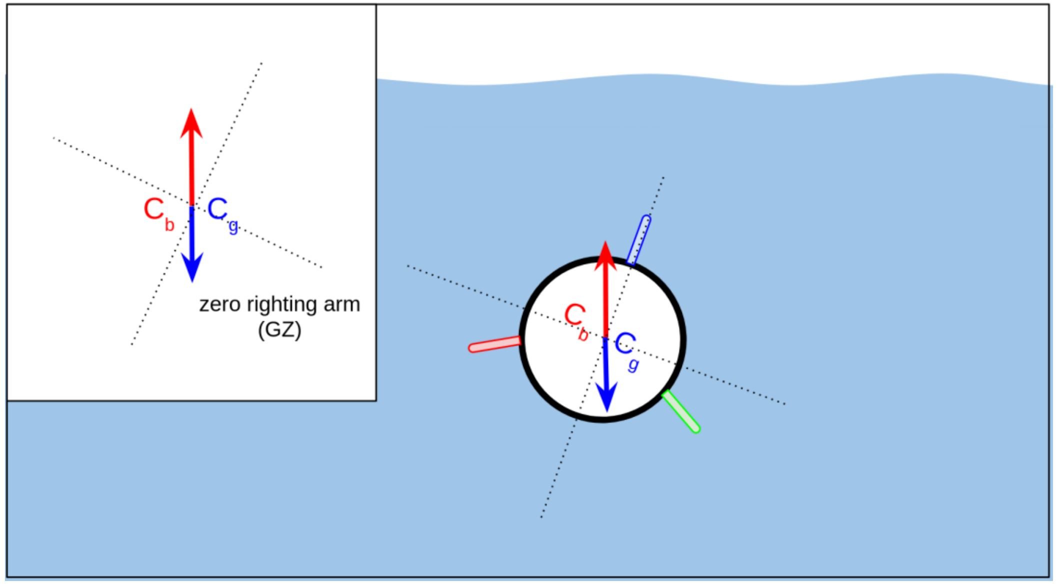


Submerged transverse stability of an AUV

Neutral stability:

- If the center of buoyancy and the center of gravity are in the same vertical position (i.e., VCB and VCG are equal)
- If the AUV inclined due to an external force, no righting arm is created. It will stay in at the same roll angle.

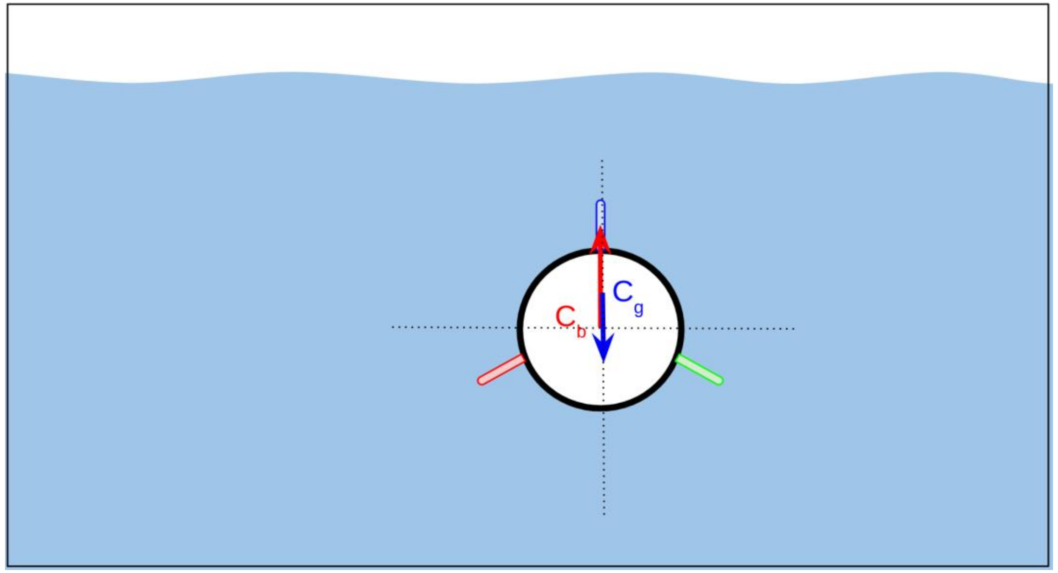


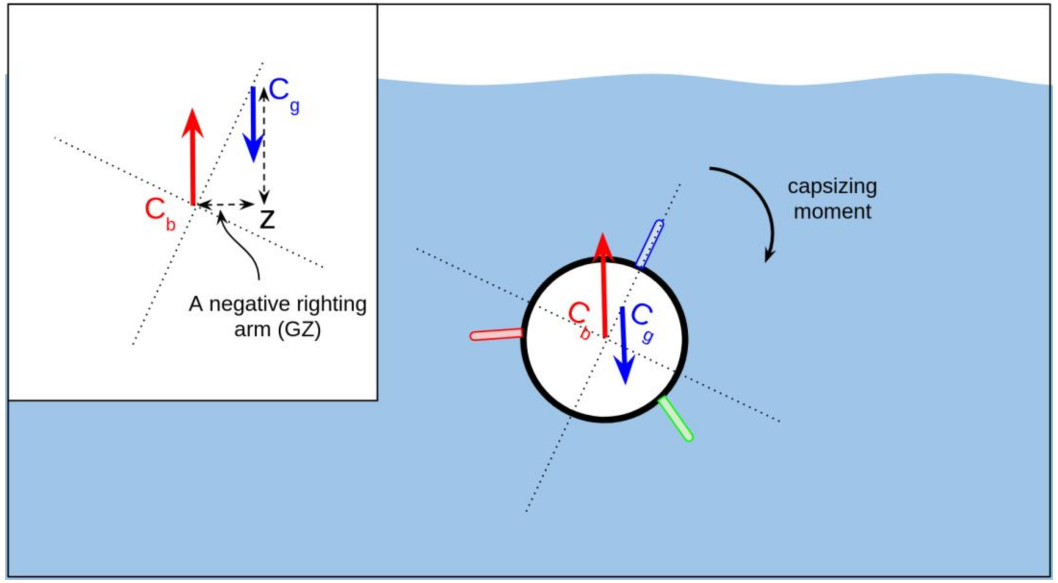


Submerged transverse stability of an AUV

Negative stability:

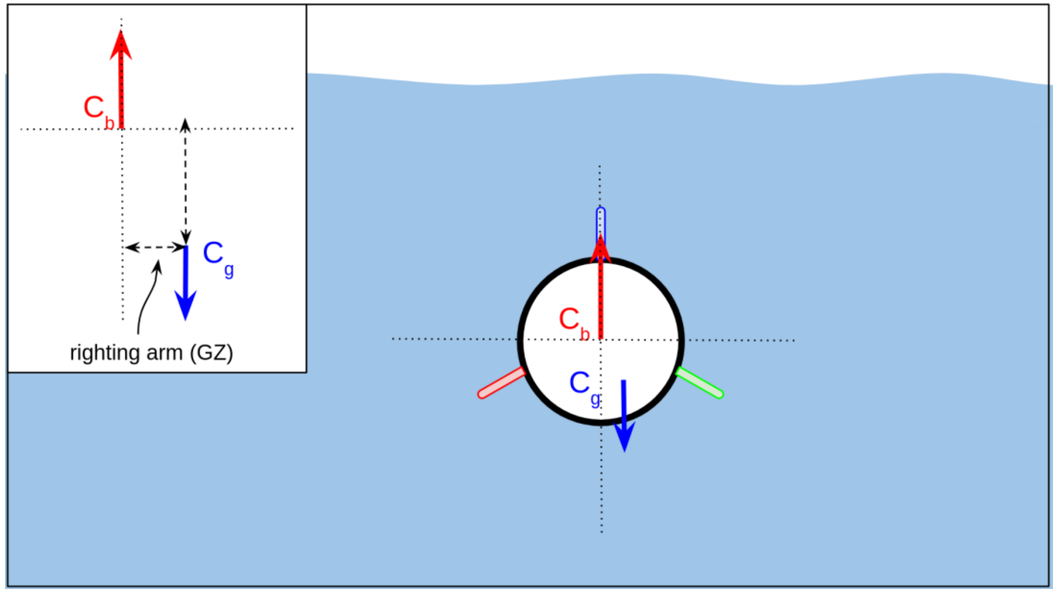
- If the center of buoyancy is below the center of gravity (i.e., VCB is below VCG), the vehicle is negatively stable.
- A small inclination can result in the AUV turning upside down due to the capsizing moment.

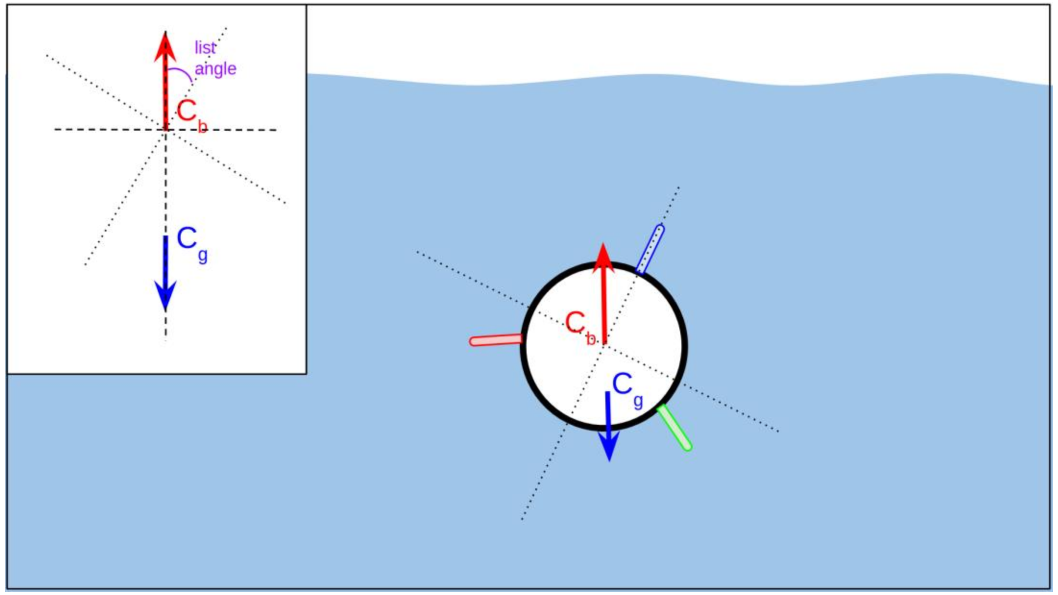




List angle

- If the transverse center of gravity (TCG) is not equal to transverse center of buoyancy (TCB), a negative righting moment will be created.
- Righting moment will result in a permanent steady-state roll angle, called the list angle.
- Some AUVs are ballasted to have a list angle that counteracts the propeller torque.



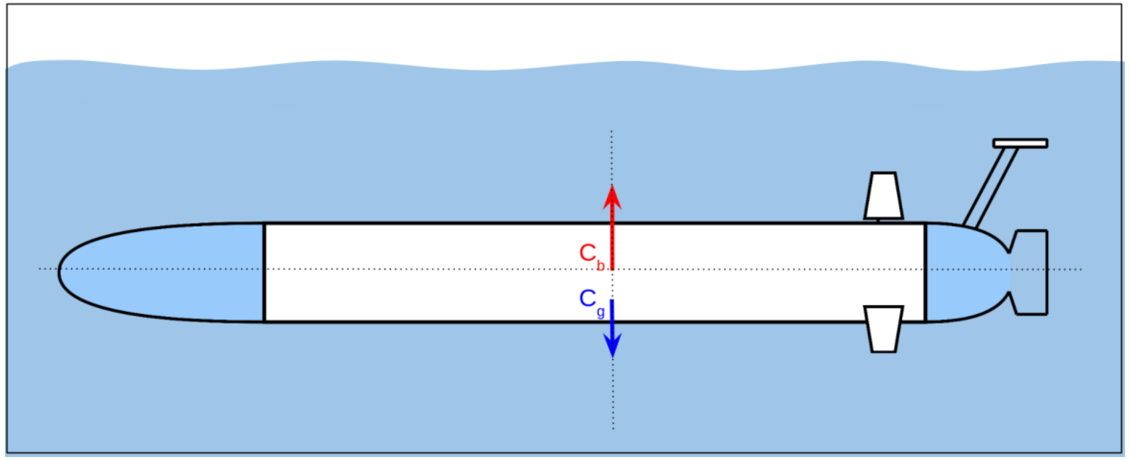


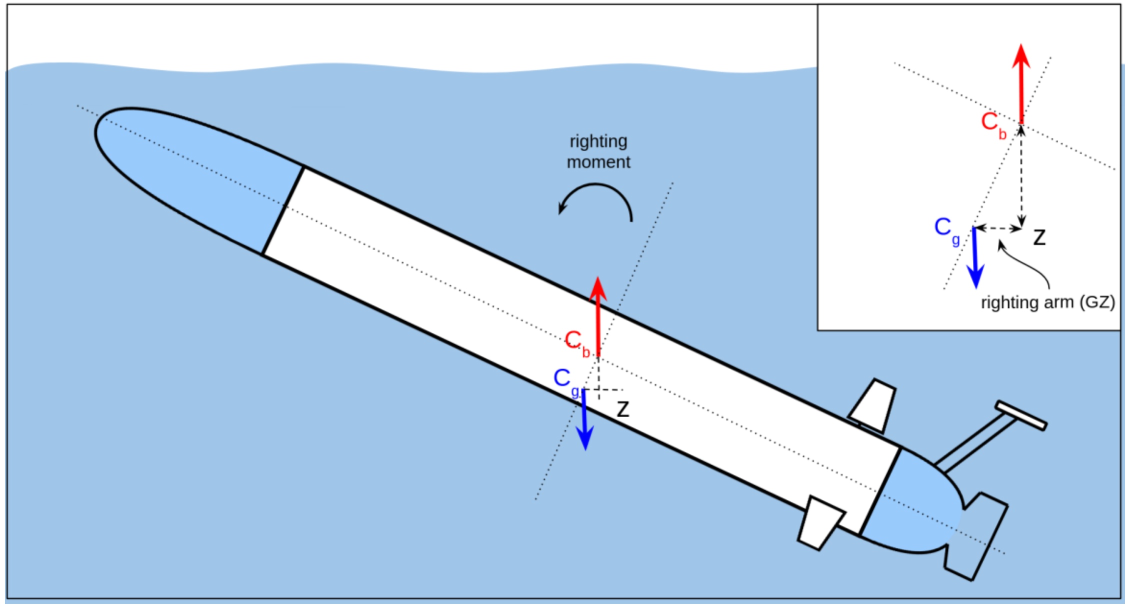
Submerged longitudinal stability of an AUV

Similar to the transverse stability, the position of VCB and VCG will result in a positive, neutral or negative longitudinal stability.

The figures show the positive stability condition:

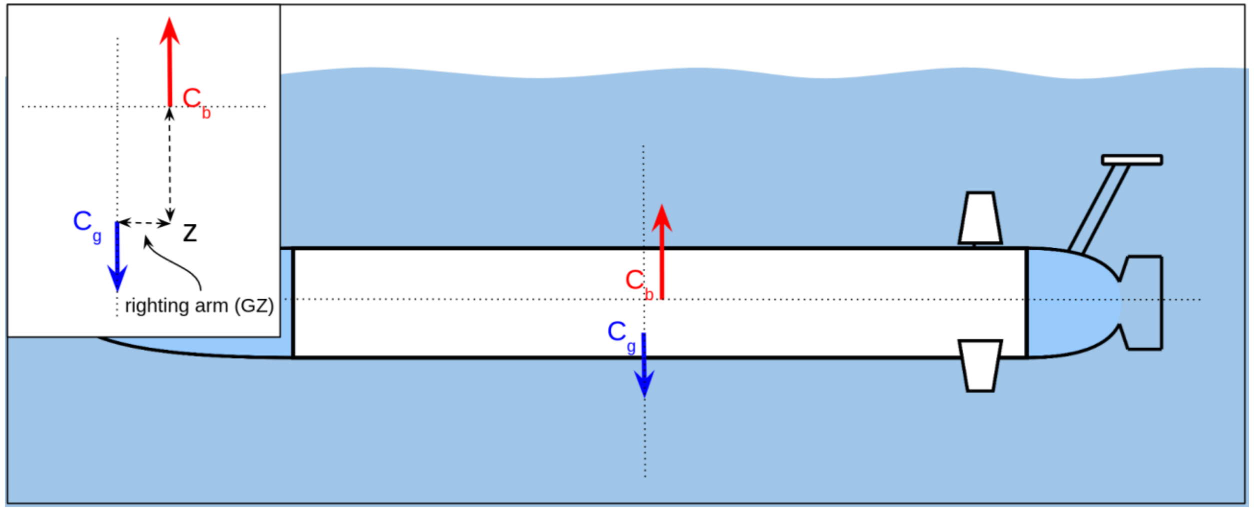
- The VCB is above VCG
- If the AUV inclined due to an external force, a righting moment will be created to return the vehicle to its original position.

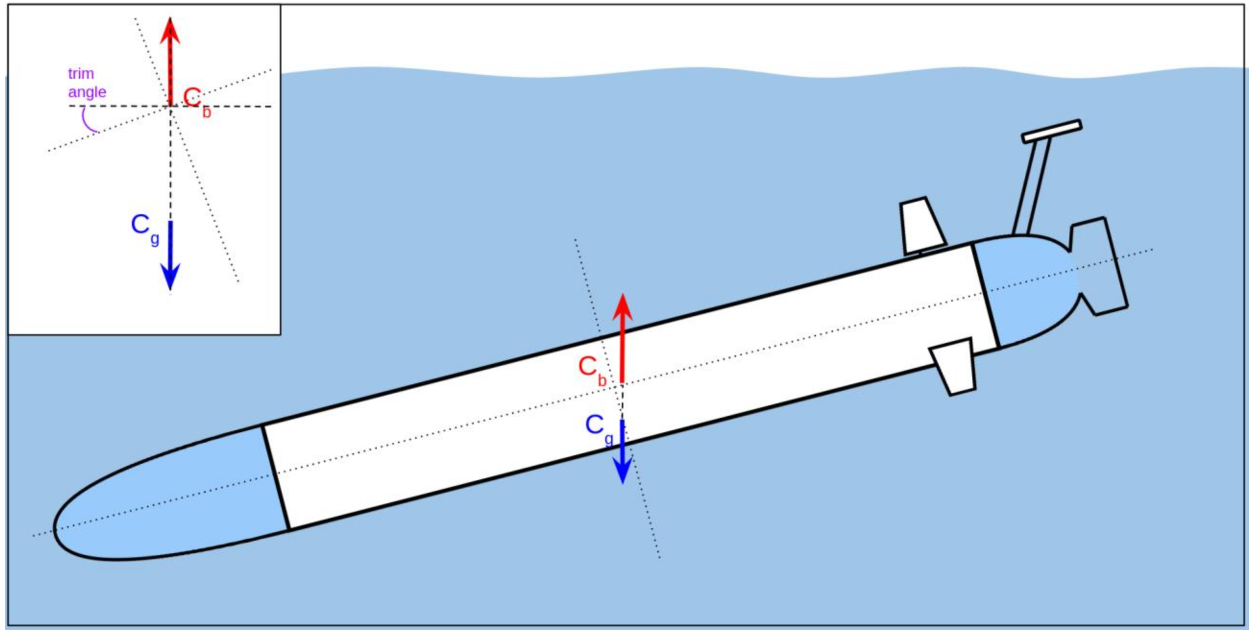




Trim angle

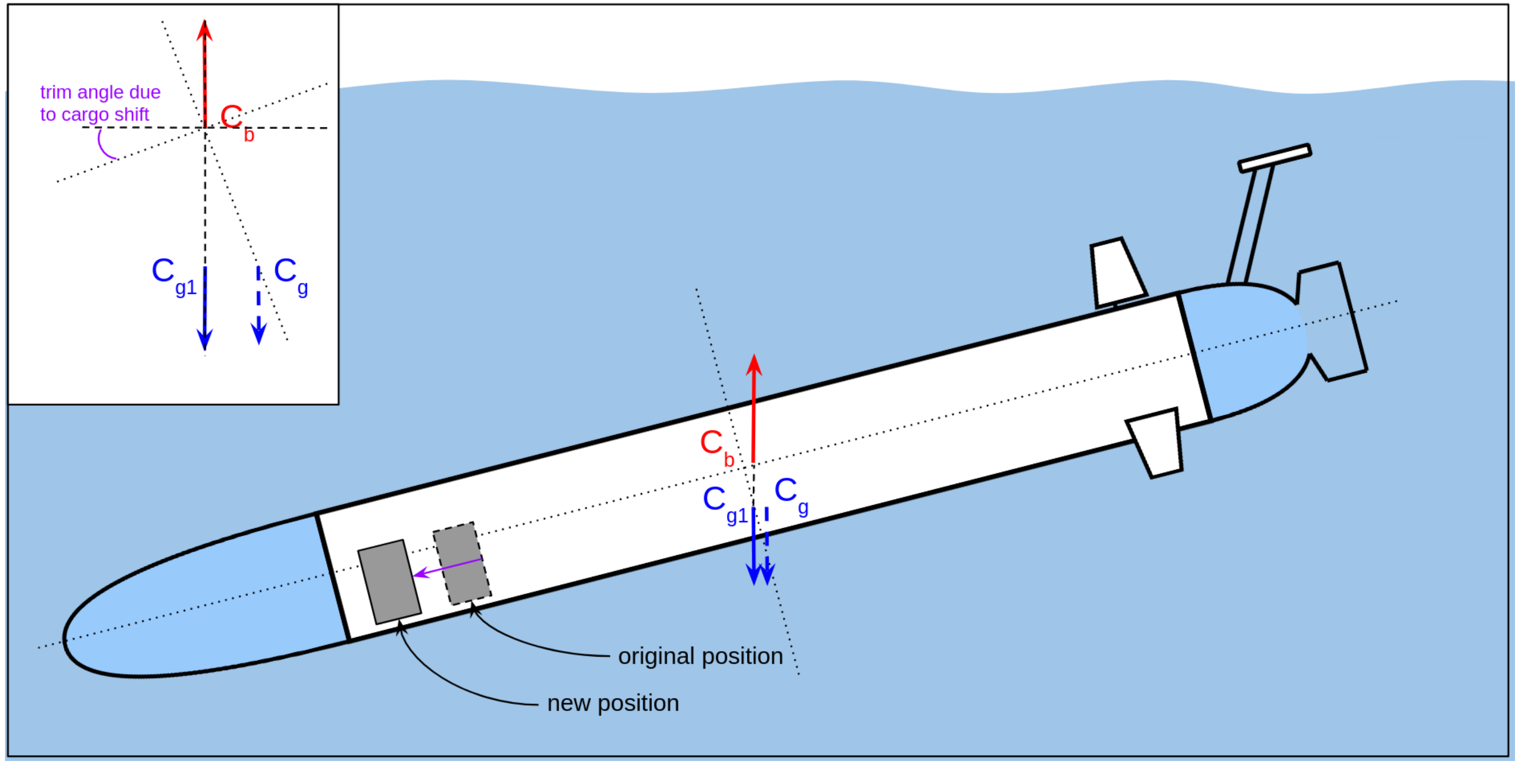
- If the longitudinal center of gravity (LCG) is not equal to longitudinal center of buoyancy (LCB), a negative righting moment will be created.
- This righting moment will result in a permanent steady-state pitch angle, called the trim angle.
- Most torpedo-shaped, small AUVs need to be ballasted with a small trim angle (nose down), to support the initial dive.





Mid-mission cargo shifting

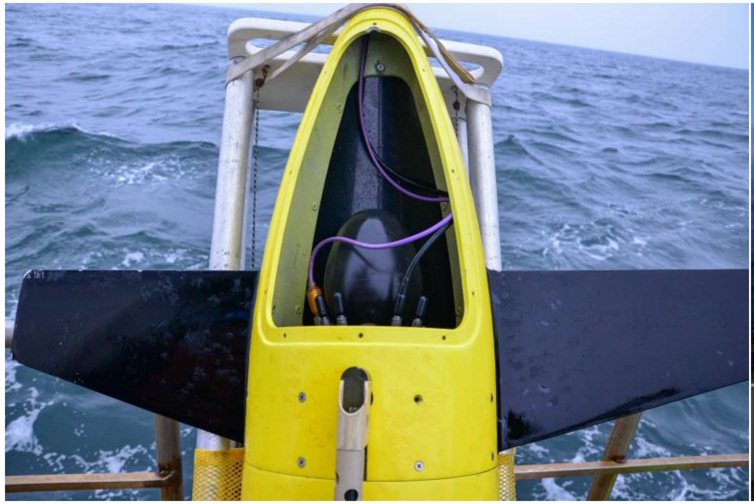
- If hardware equipment are not properly secured, they may shift due to the motion of the vehicle.
- Such weight shifts will result in unintended trim and list angles.
- This may result in mission failures or vehicle loss.

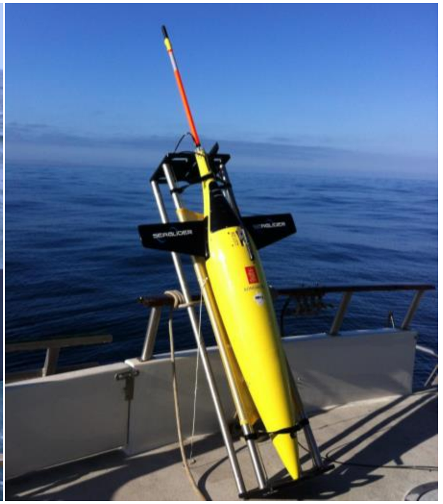


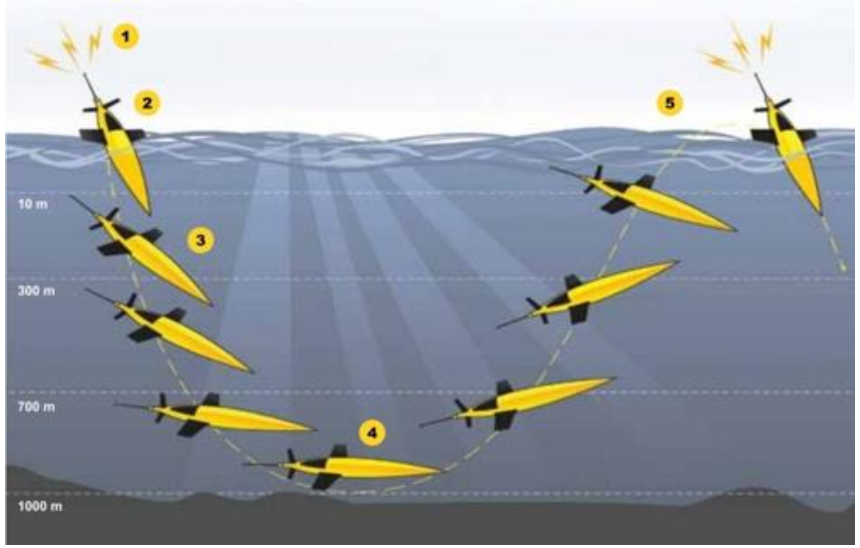
Buoyancy engines and variable ballast tanks

- Buoyancy engines can actively control the buoyancy of the vehicle.

- Types of buoyancy engines include:
  - Inflating/deflating oil bladders.
  - Pump-based variable ballast tanks.







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- Types of buoyancy engines include:
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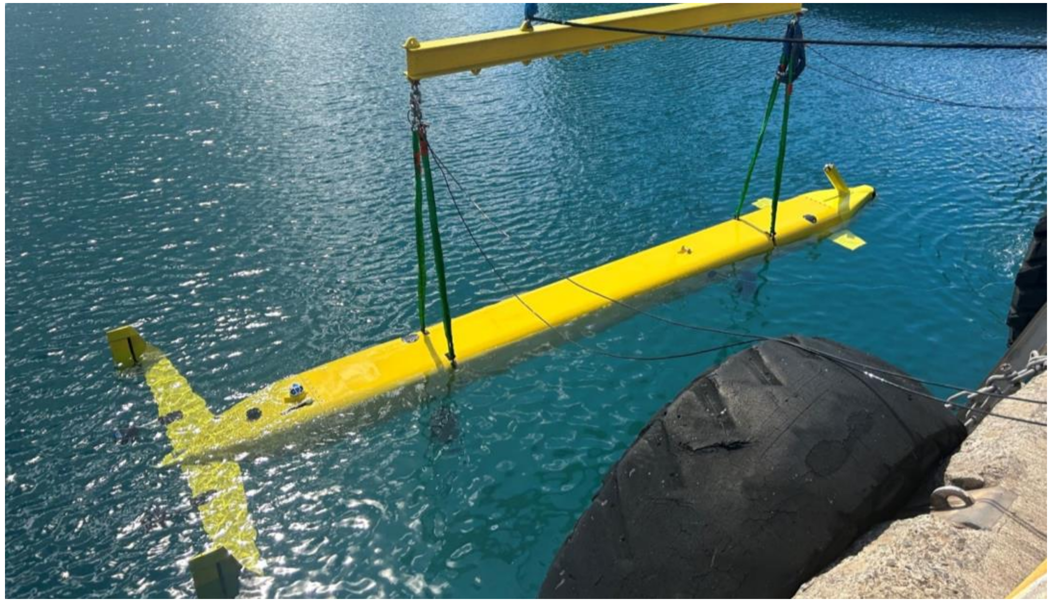
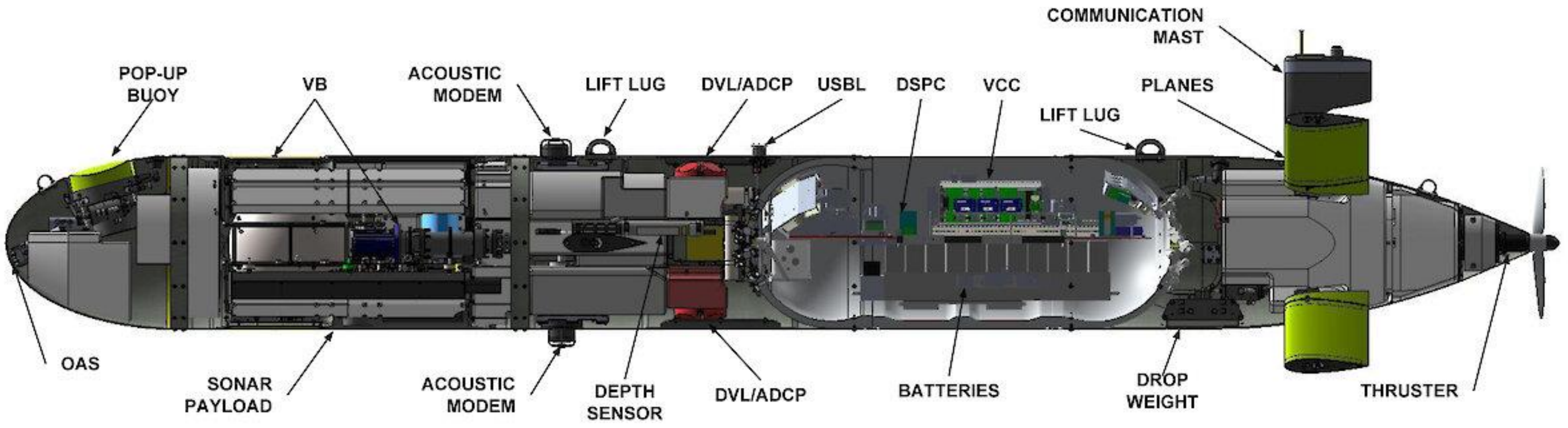
- Buoyancy engines can be used to:
  - Use gliding as a propulsion method
  - Land UUVs on the seabed
  - Park underneath ice-shelfs
  - Stay in the mid-water column without propulsion



Drop-weights

- Drop-weights are primarily a safety feature.
- In emergency situations, the drop-weight can be released to make the vehicle positively buoyant.
- The drop-weight release can be triggered acoustically by a human operator, or by the vehicle's autonomy system.



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