MIT MECHE

MIT 2.S01 Introduction to Autonomous Underwater Vehicles

# Lecture 7: Low-level Control Systems of AUVs

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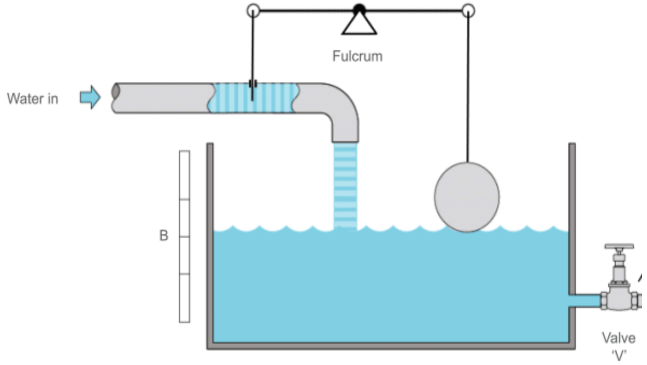
MIT Sea Grant AUV Lab

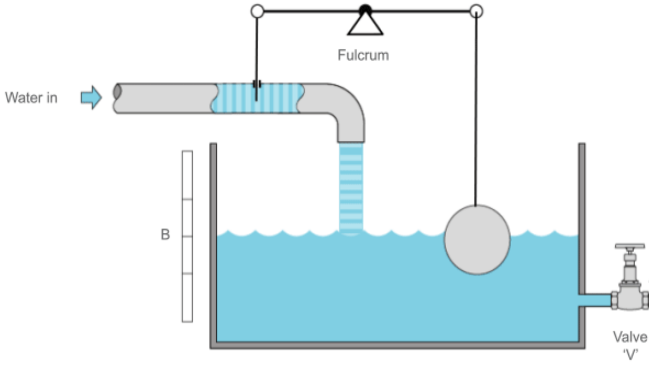
MIT Marine Autonomy Lab

# A simple mechanical controller

- The desired water level **set point** is A
- The float measures the **current water level**
- When the water level is below the set point, creating an **offset**, the inlet valve will open to re-fill the tank.
- The valve's position is proportional to the water level **offset**
- The valve will close when the level reaches back to the set point.

*Can you identify the sensor and the actuator in this example?*



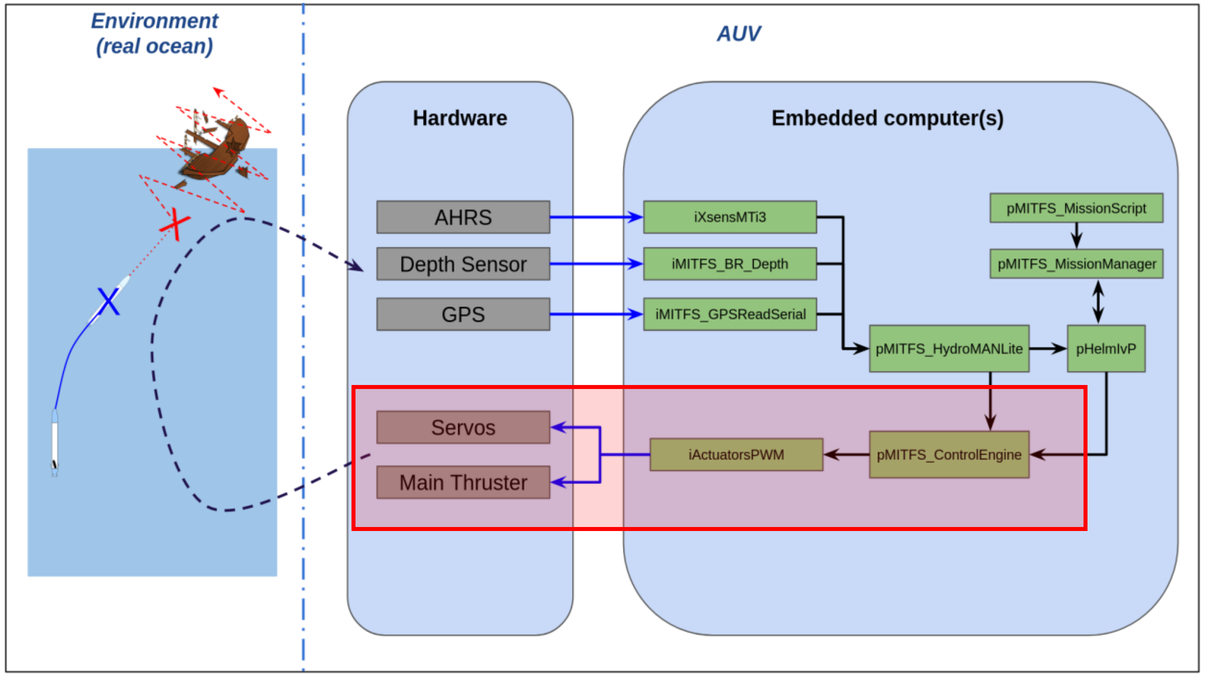



# Low-level Control System

**Navigation system estimates the AUV's:**
- current position – lat, lon & depth
- current attitude – roll, pitch & heading
- current velocity

**Autonomy system decides the course that the AUV is required to maintain to complete the mission:**
- desired heading
- desired depth
- desired speed

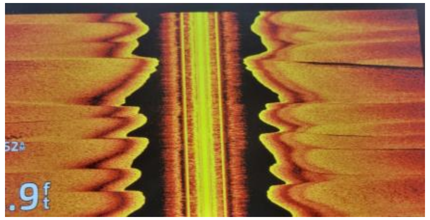
**The control system controls the actuators to maintain that course:**
- rudder
- elevators
- thruster



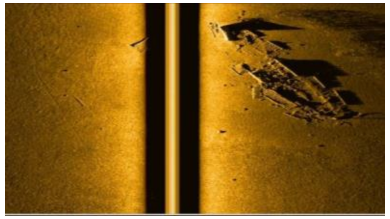
# Importance of decent control performance

- For the safety of the vehicle; e.g.,
  - To avoid hitting the seabed.
  - To avoid hitting obstacles.
  - To be able to transit to the desired location under external forces such as currents.

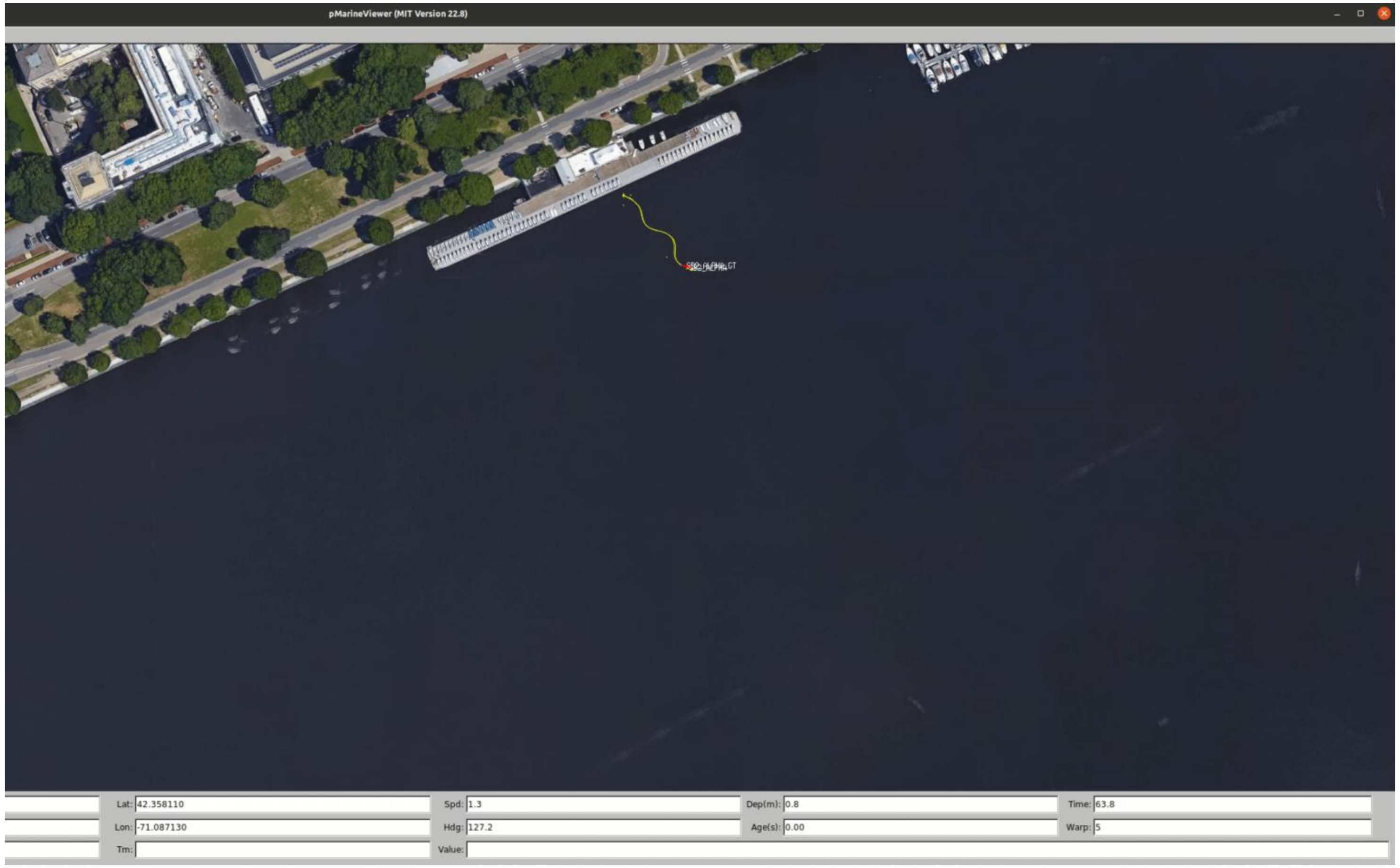
- For the quality of the collected data.



vs.



- The accepted level of control performance may vary with the application of the AUV; e.g.,
  - A vehicle conducting a side-scan sonar imaging mission needs better control performance as compared to a vehicle recording environmental acoustic data

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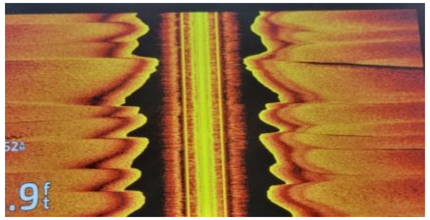

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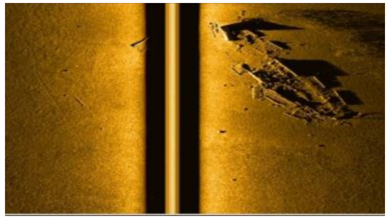

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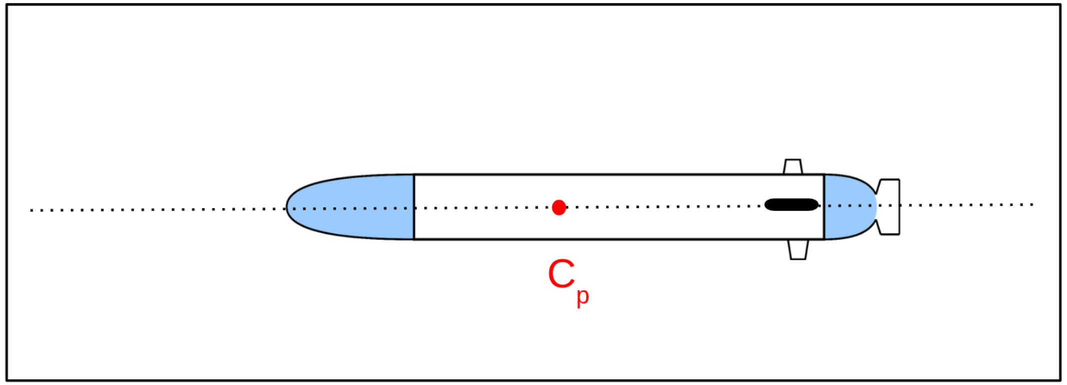
# Hydrodynamic forces generated by control surfaces

- When the AUV is stationary, there is no flow over the hull:
  - no hydrodynamic forces act on the rudder.



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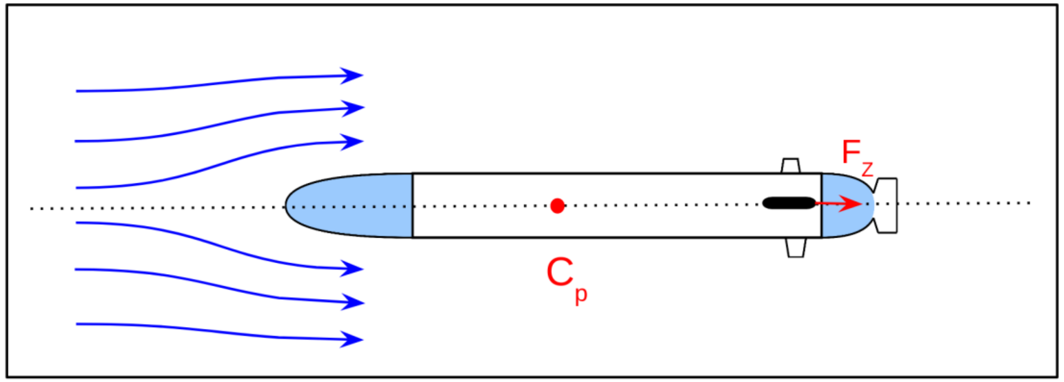
  - a drag force will act on the rudder.



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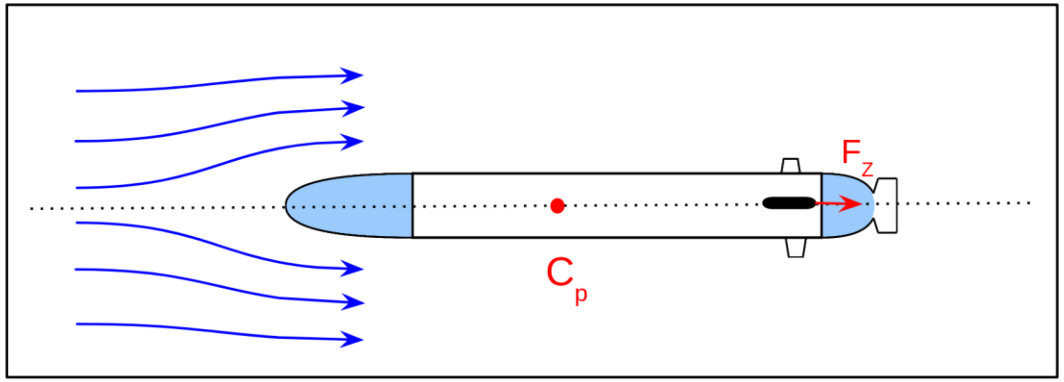
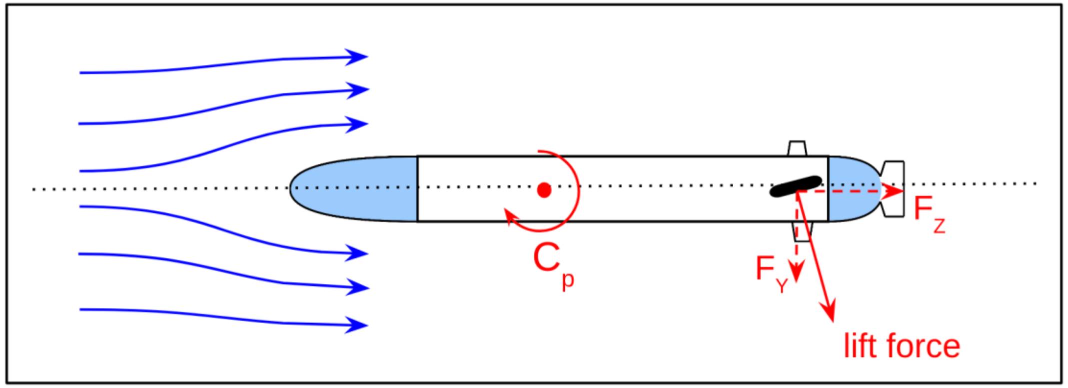
- When rudder poses an angle-of-attack:
  - a lift force is generated by the rudder
  - the lateral component of this lift force will cause the AUV to turn around its center of pressure.



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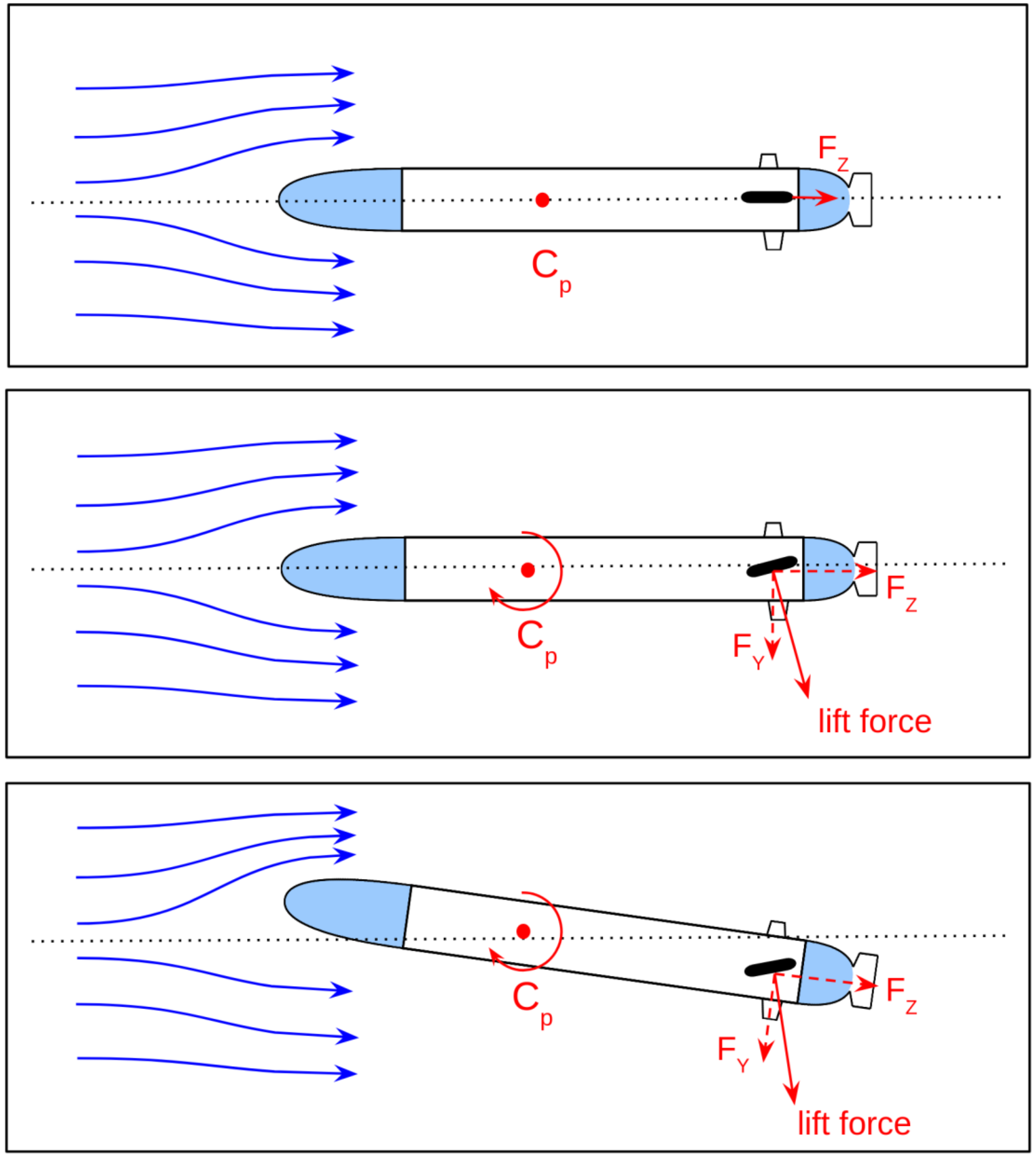
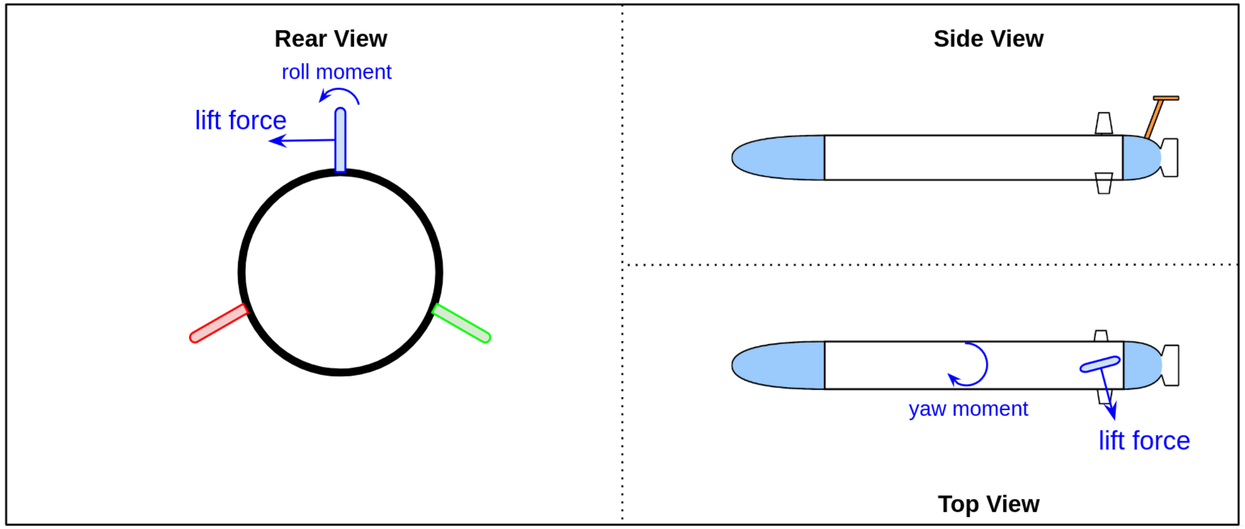
- When rudder poses an angle-of-attack:
  - a lift force is generated by the rudder
  - the lateral component of this lift force will cause the AUV to turn around its center of pressure.
- The AUV will then pose an angle-of-attack to the direction of flow:
  - This will induce further moment around the AUV's center of pressure, causing the vehicle to turn.
  - This will result in changing the heading angle of the vehicle



# Three control surface design

**Rudder-only heading control:**

- The lateral force of the rudder will also cause a rolling moment on the AUV.
- The AUV will roll while changing heading.



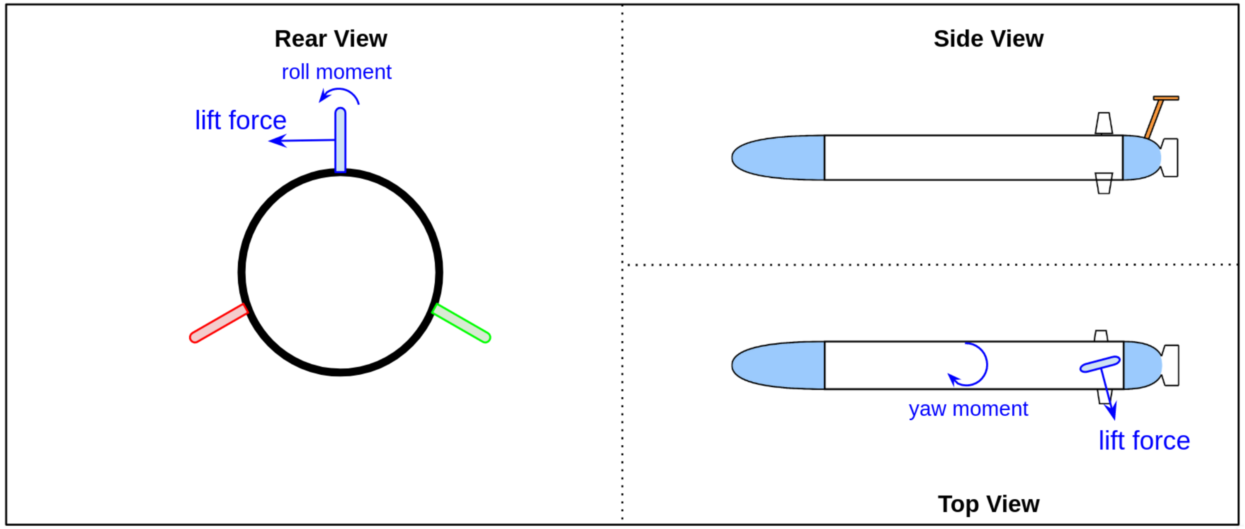
# Three control surface design

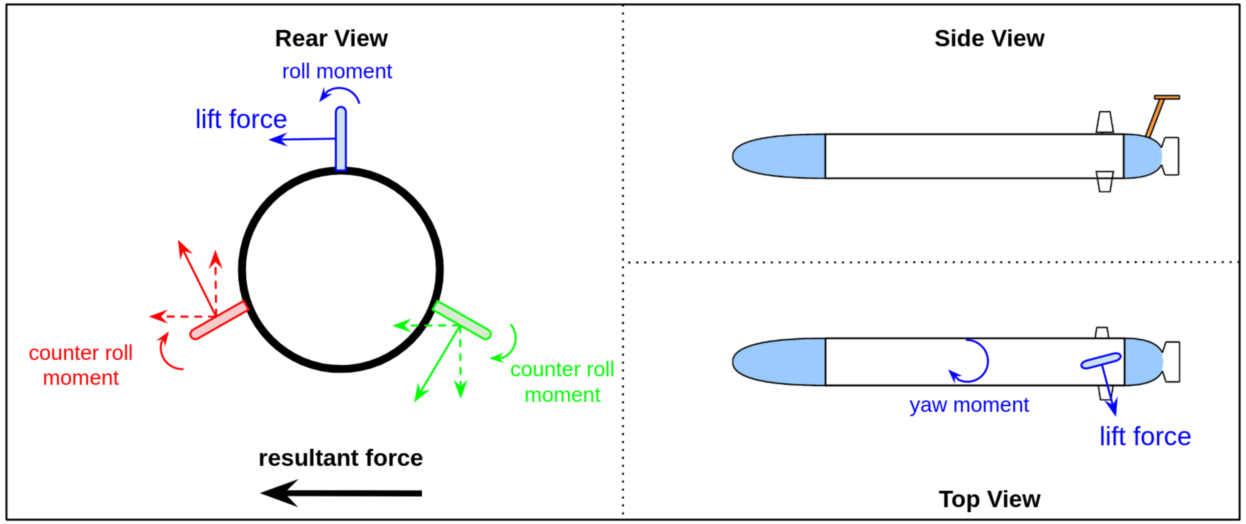
**Rudder-only heading control:**

- The lateral force of the rudder will also cause a rolling moment on the AUV.
- The AUV will roll while changing heading.

**Tri-fin heading control:**

- The port and starboard control surfaces will also engage in heading control.
- Port and starboard surfaces will provide lateral forces that supports the heading control.
- Their opposing vertical forces will cancel each other.
- Their counter roll moment will cancel the roll moment caused by the rudder.
  - typically, the heading control contribution from port and starboard surfaces are limited to 50% of the rudder so that their combined counter roll moment will be equal to the roll moment from the rudder. I.e. if rudder angle is 10 degree, the port and starboard surface angles are 5 degrees.



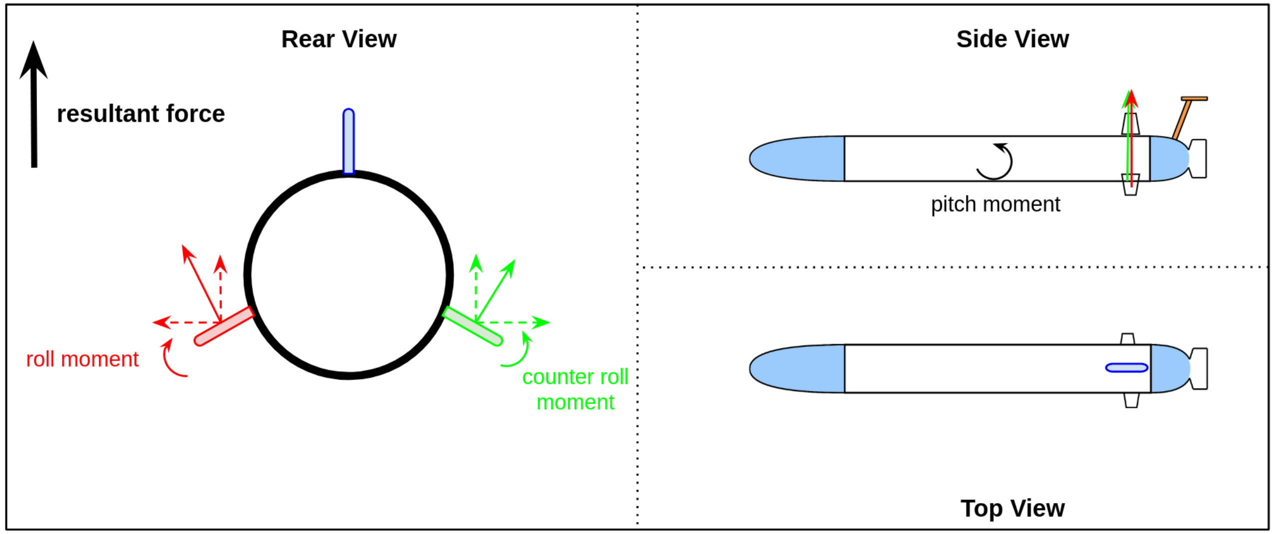



# Three control surface design

**Pitch control:**

- The vertical forces from the elevators will pitch the vehicle up/down.

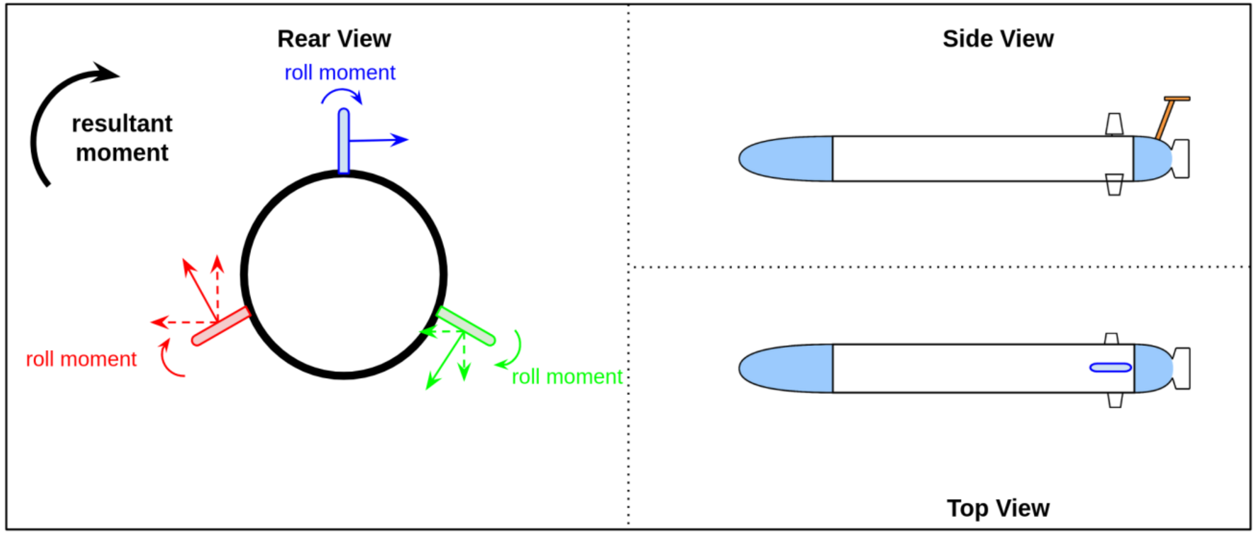
- The opposing roll moments will cancel each other.



# Three control surface design

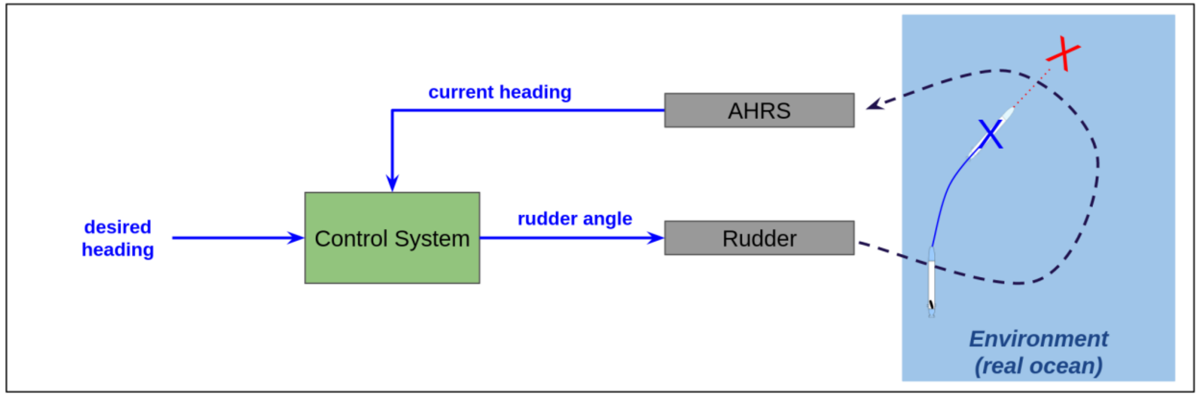
**Active roll control:**

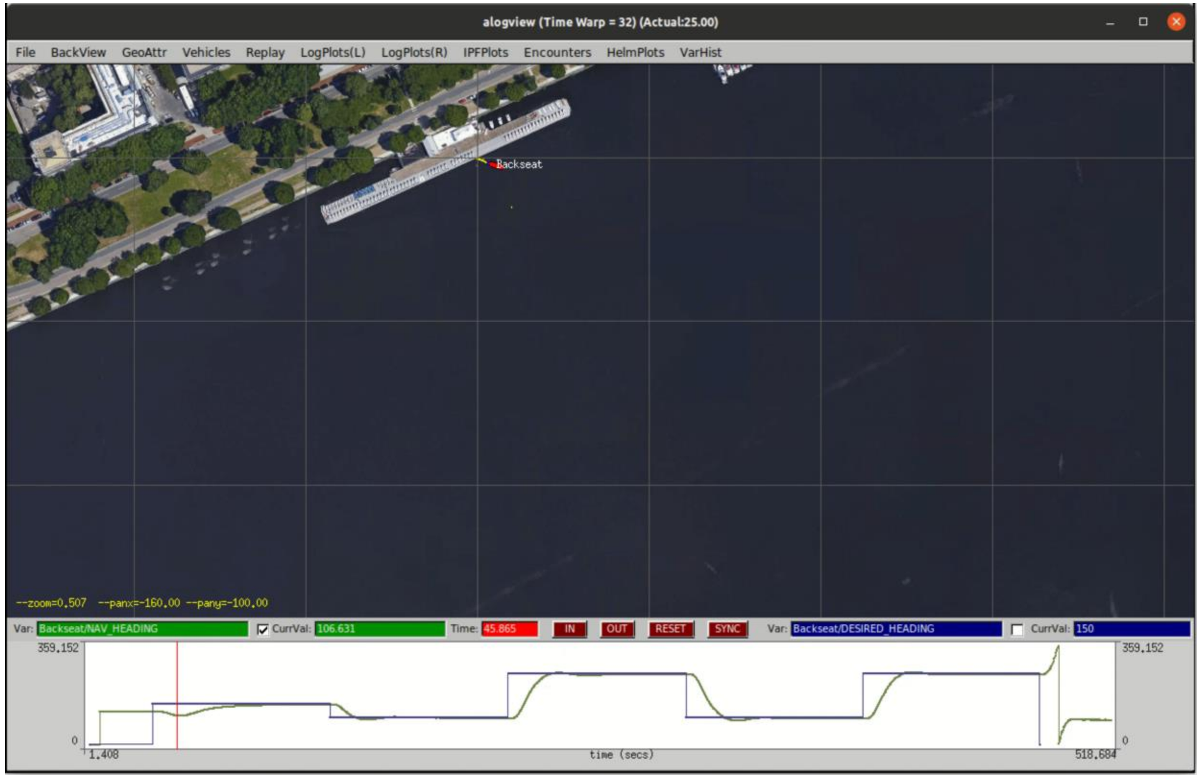
- All three control surfaces are actuated in the same direction to control the roll motion
- The opposing vertical forces of the port and starboard control surfaces will cancel each other.



# Heading control sub-system

- Control system reads the current heading and desired heading, and computes a rudder angle.

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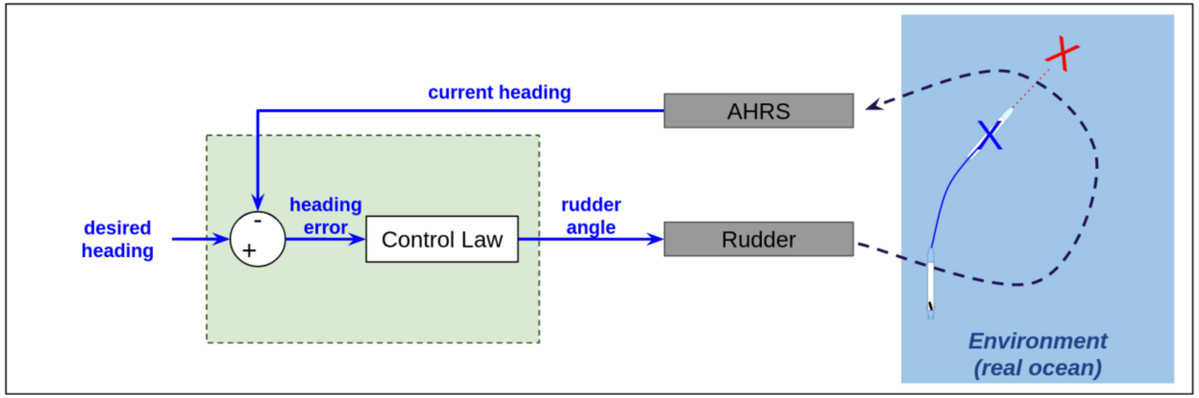
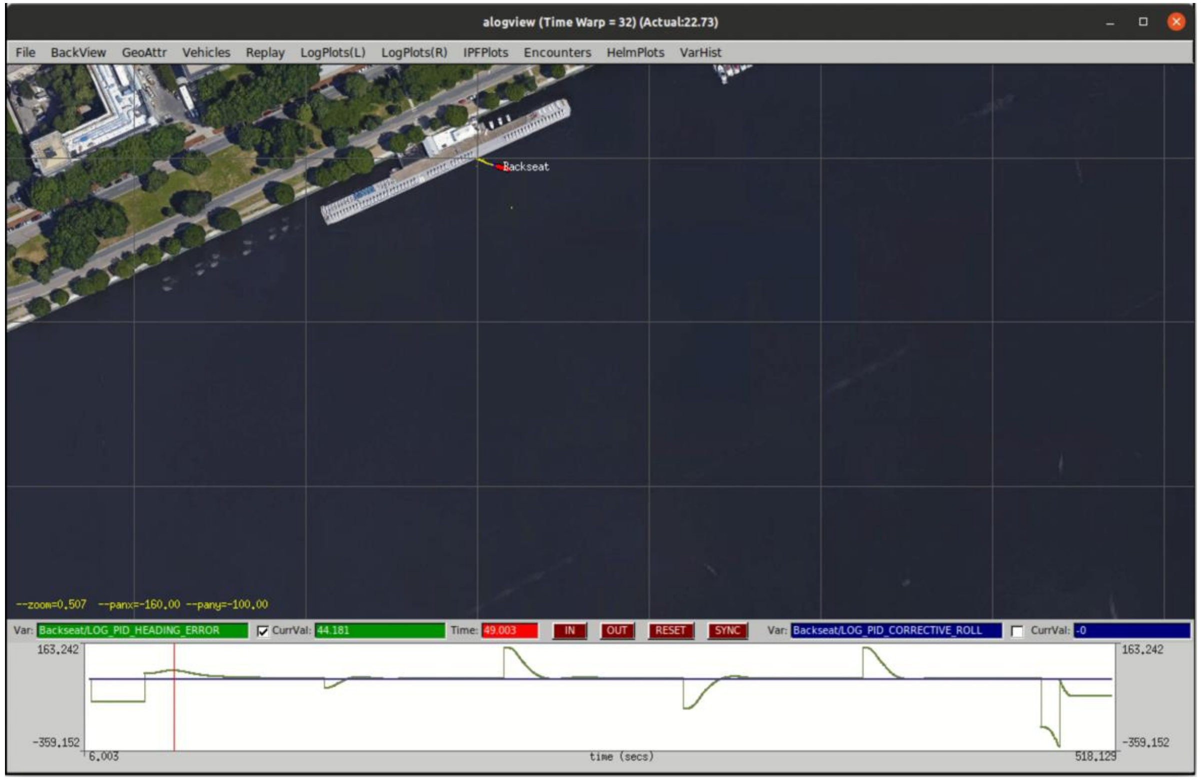
# The error

- Control system reads the current heading and desired heading, and computes a rudder angle.
- Control system first calculates the heading error, the difference between the desired and current headings.
- The control law computes a rudder angle that would minimize the heading error.

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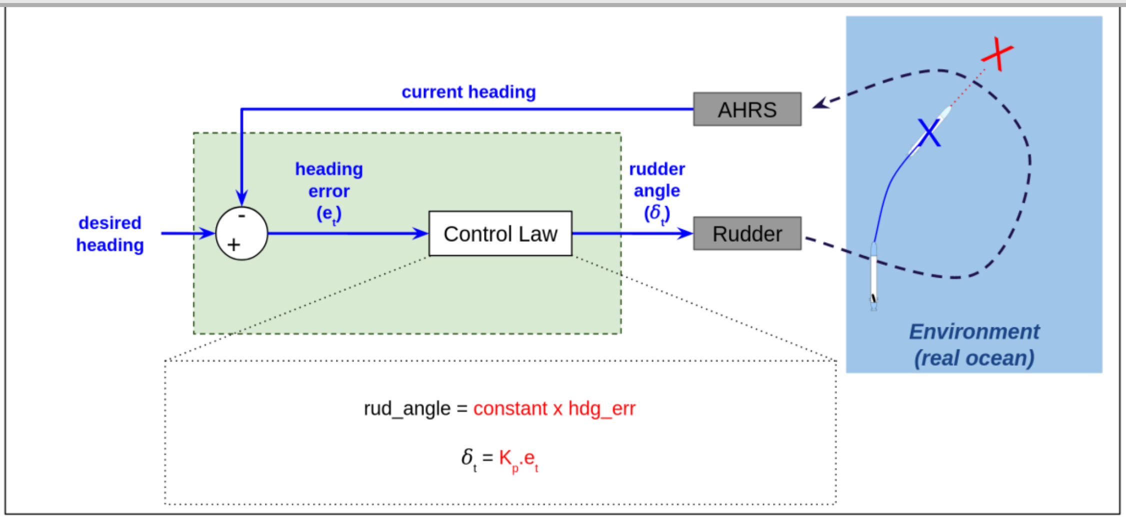
# Simplest form: the proportional (P) controller

- The error is simply multiplied by a constant called proportional-gain (Kp) to obtain the rudder angle.
- The maximum and minimum limit are applied to the rudder angle (e.g. max rudder is 20deg and min rudder is –20deg)



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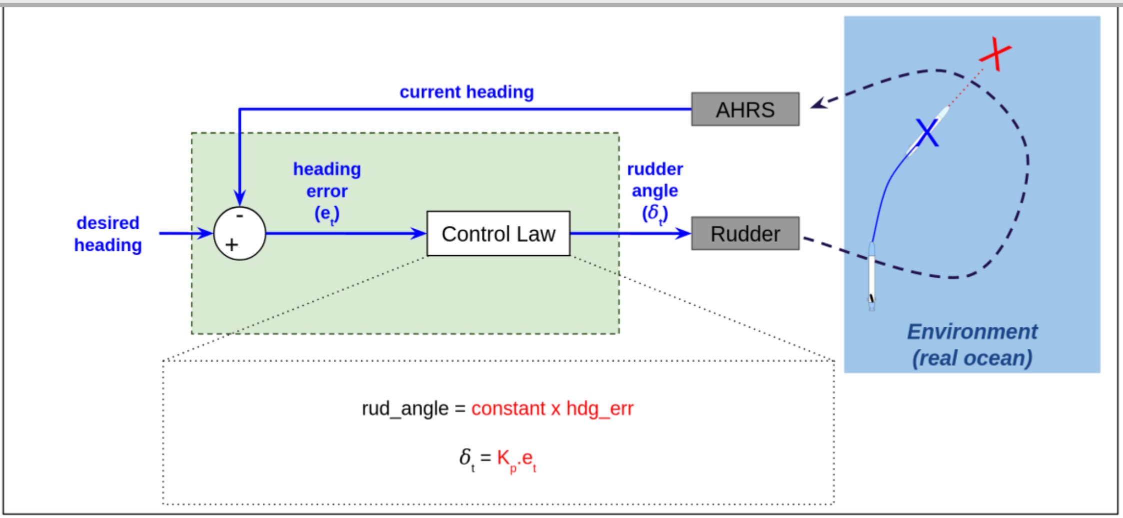
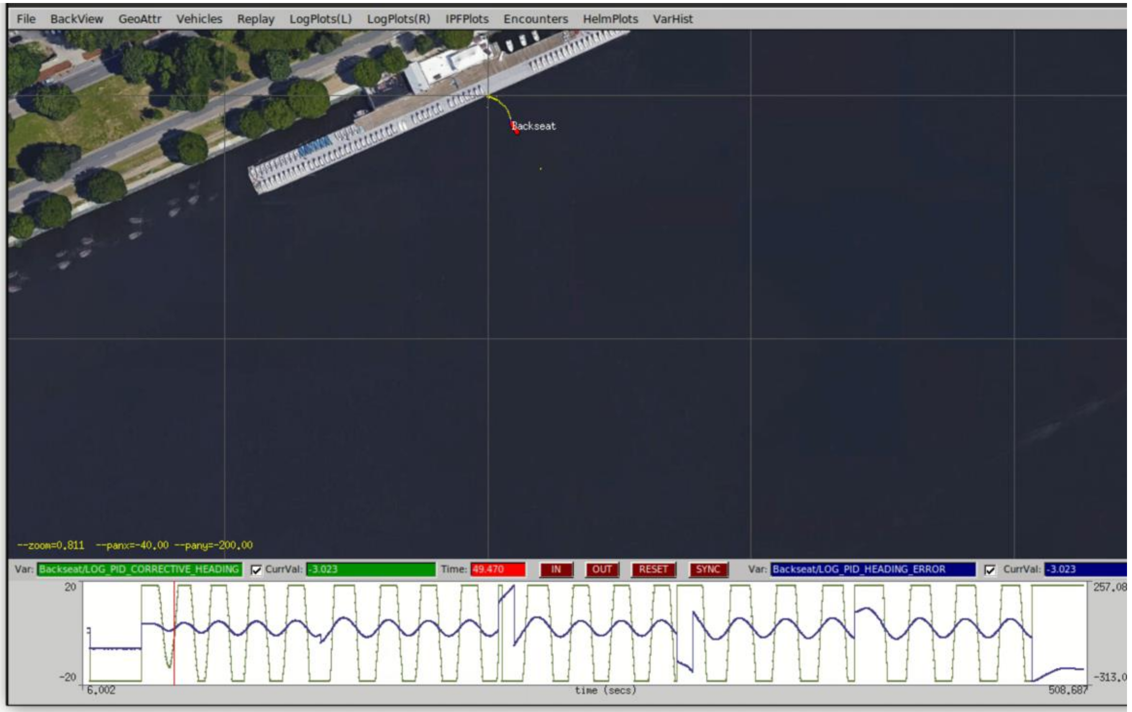
- Example A: Kp = 1.0
  - Heading steps in this mission are large (i.e., between 100 and 260 degrees).
  - Therefore, heading error is large.
  - Since Kp is 1.0, the rudder angles also become large (however, capped between –20 and 20).
  - With large rudder angles, the AUV corrects the heading so quickly, but it overshoots the desired value.
  - Once it overshoots, rudder goes to the opposite limit, AUV corrects it quickly, and overshoots to the opposite side.

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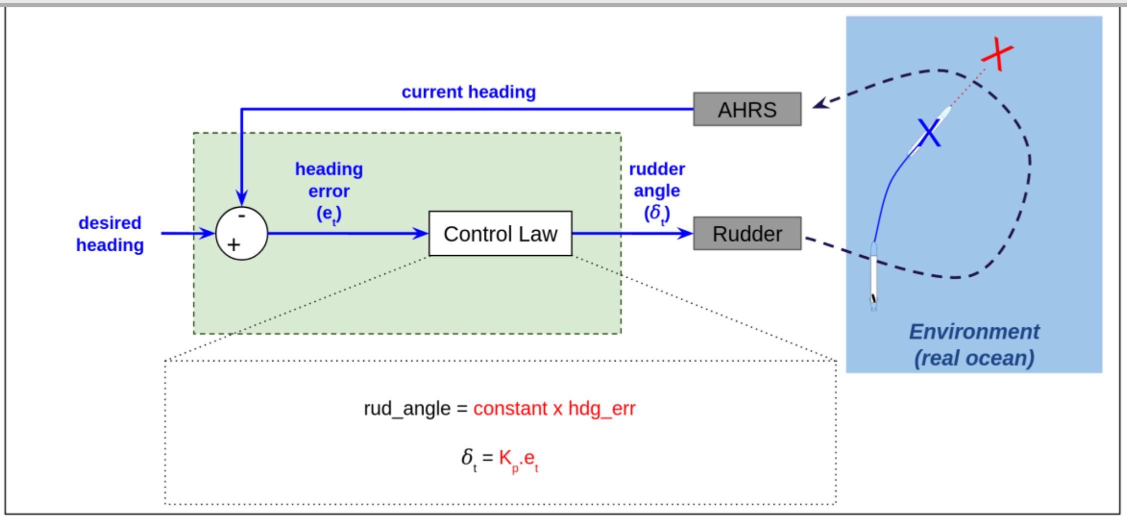
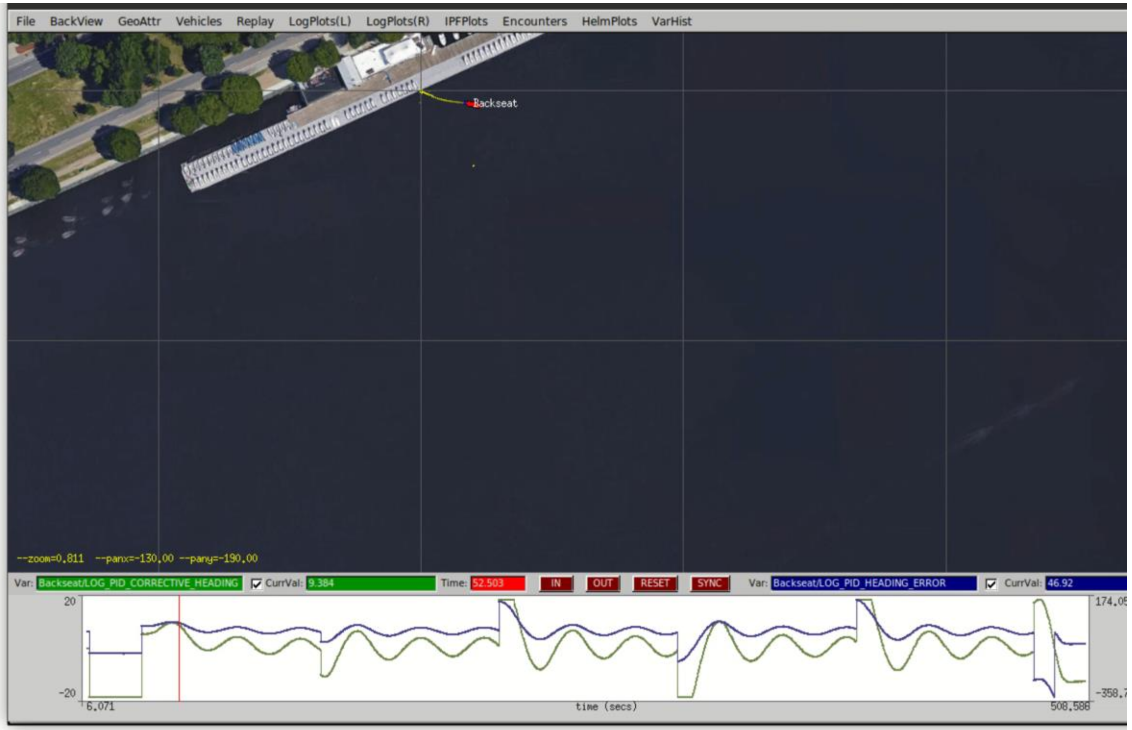
- Example B: Kp = 0.2
  - Rudder angles are relatively smaller due to smaller Kp.
  - The overshooting has been reduced, but not eliminated.

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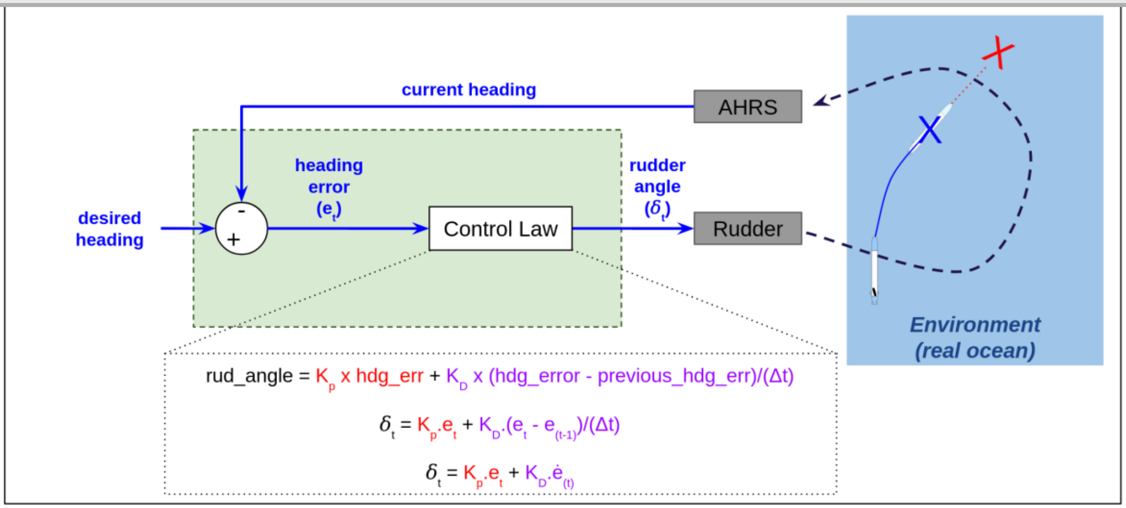
# Proportional and Derivative (PD) controller

- The rate of change of error is calculated and multiplied by a constant called the derivative-gain (Kd) to obtain the derivative term.
- The derivative term is added to the proportional term to obtain the rudder angle.
- The maximum and minimum limit are applied to the rudder angle (e.g. max rudder is 20deg and min rudder is –20deg)



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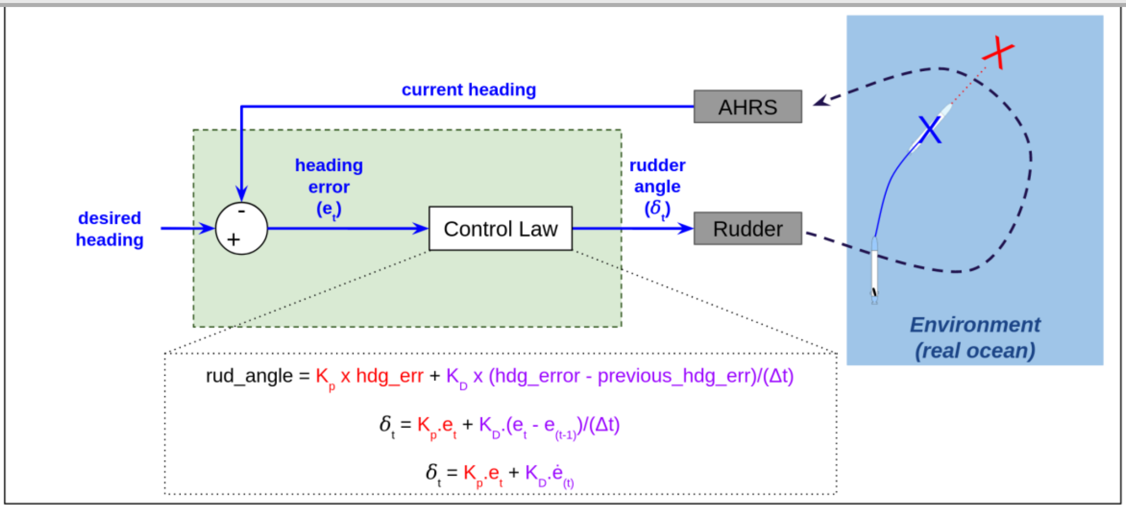
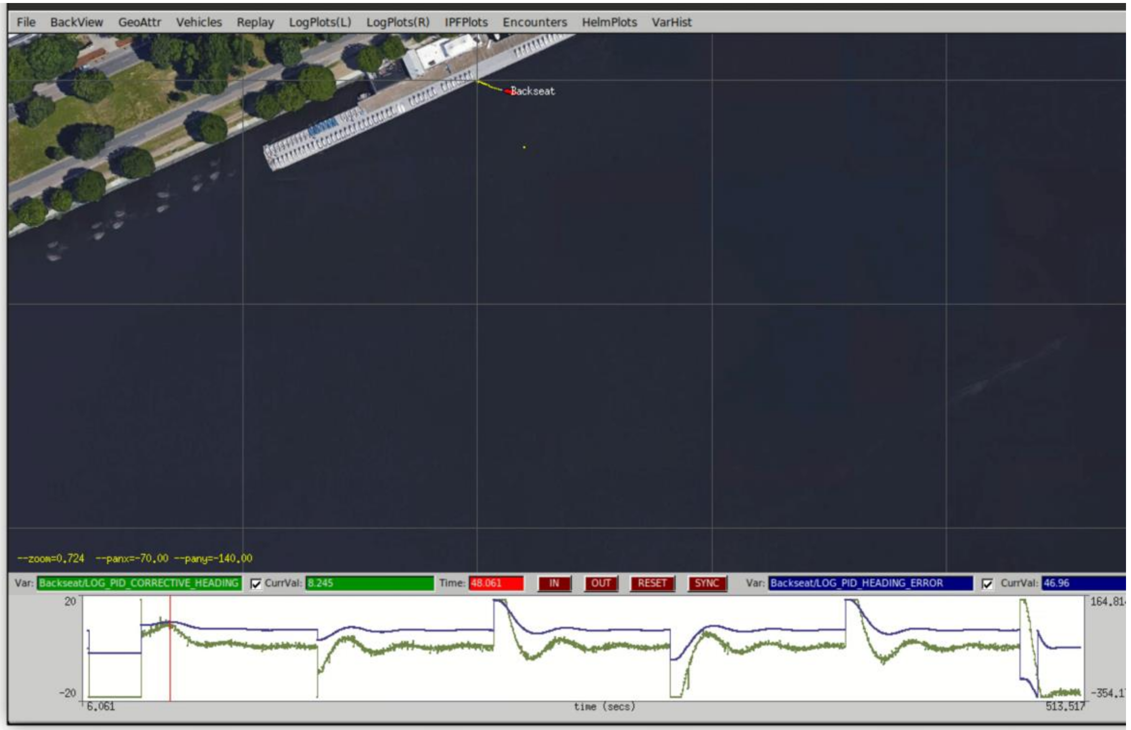
- Example C: Kp = 0.2 & Kd = 0.5
  - The derivative term reduces the rudder angle when the error rate is reducing.
  - This damps out the heading response, as the actual heading is getting closer to the desired heading.
  - Has minimized the overshooting.

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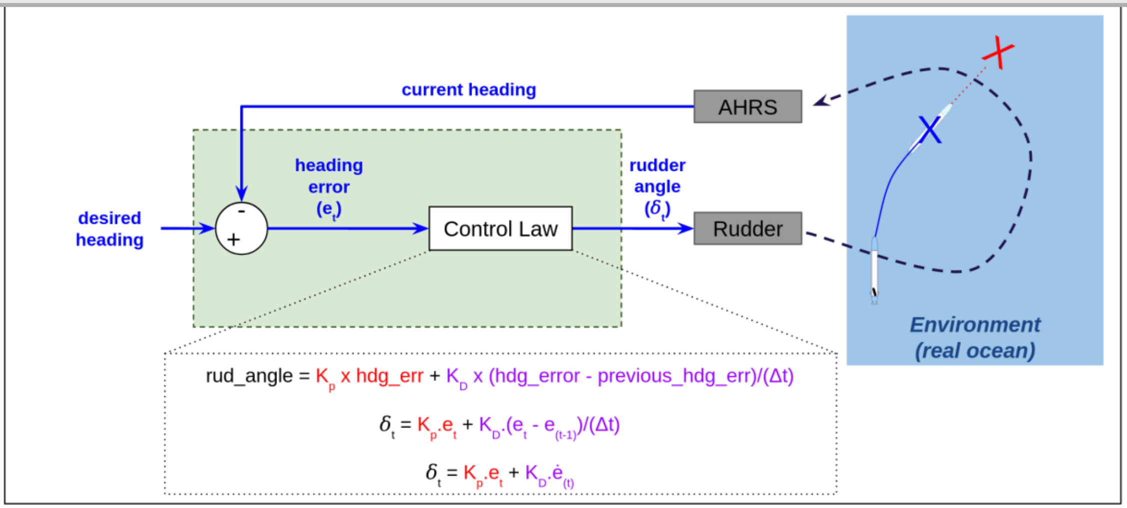
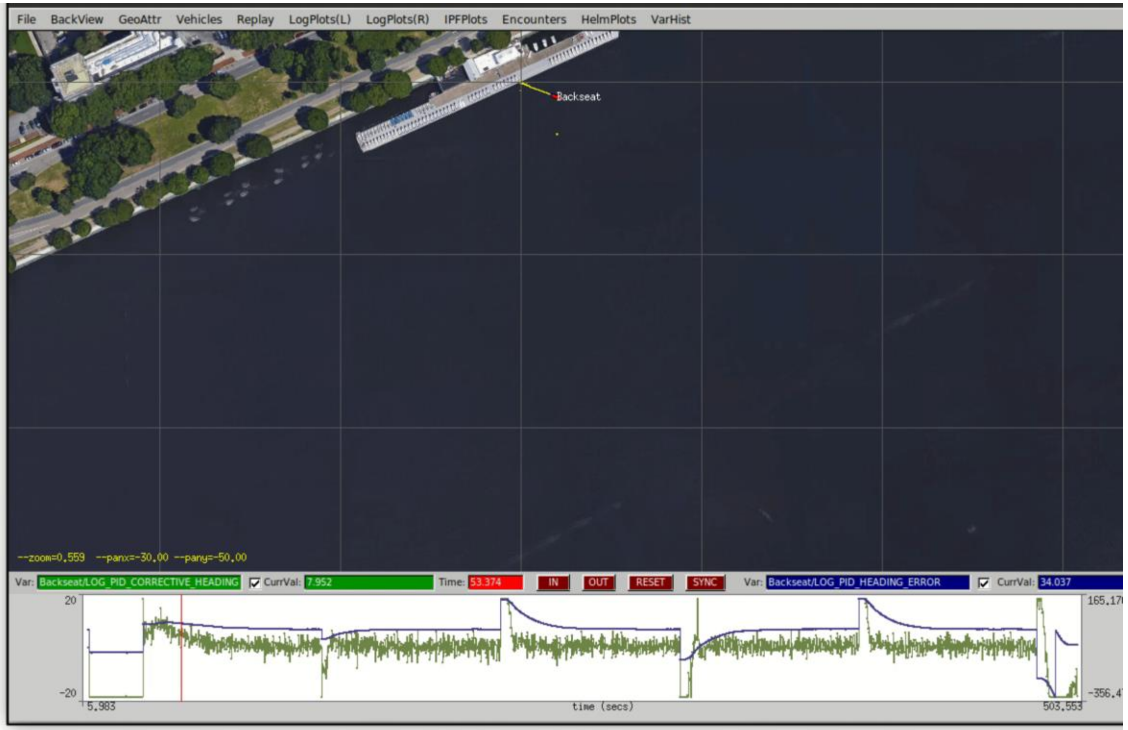
- Example D: Kp = 0.2 & Kd = 2.0
    - The larger Kd gain has heavily dampened the heading response, as the actual heading gets closer to the desired heading.
    - Overshooting is no longer observable.
    - Heavy fluctuations in the rudder response.
    - However, a steady-state error has been introduced.

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# Proportional, Integral and Derivative (PID) controller

- Previous errors are accumulated (i.e. the error is continuously being integrated).
- The current accumulated error is multiplied by a constant called the integral-gain (Ki) to obtain the integral term.
- This integral term is added to the proportional and derivative terms to obtain the rudder angle.
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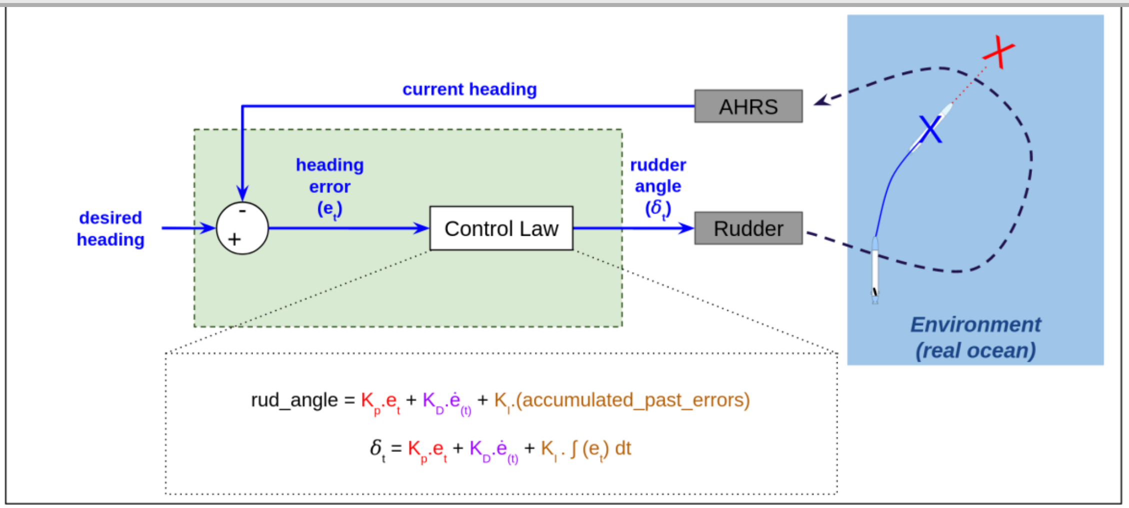

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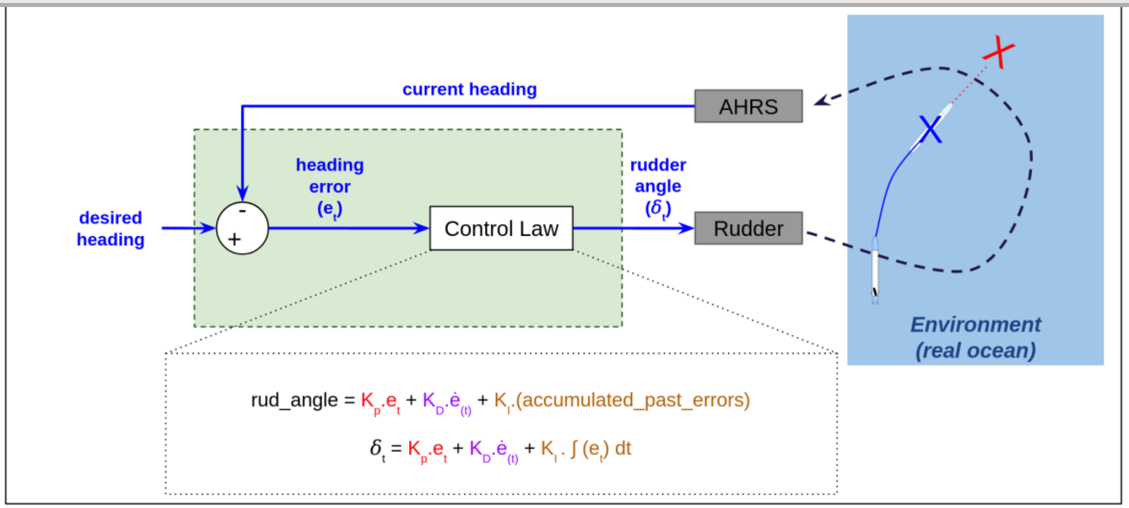
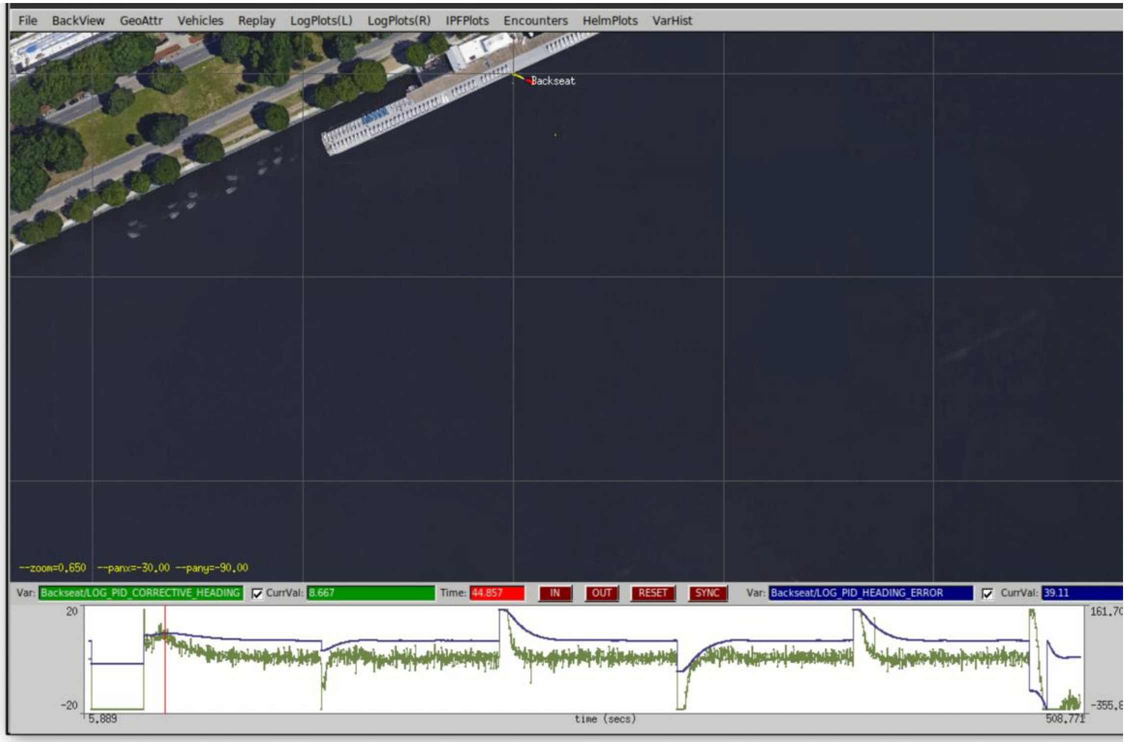
- Example E: Kp = 0.2, Ki = 0.1 & Kd = 1.5
    - The steady-state error is reduced.

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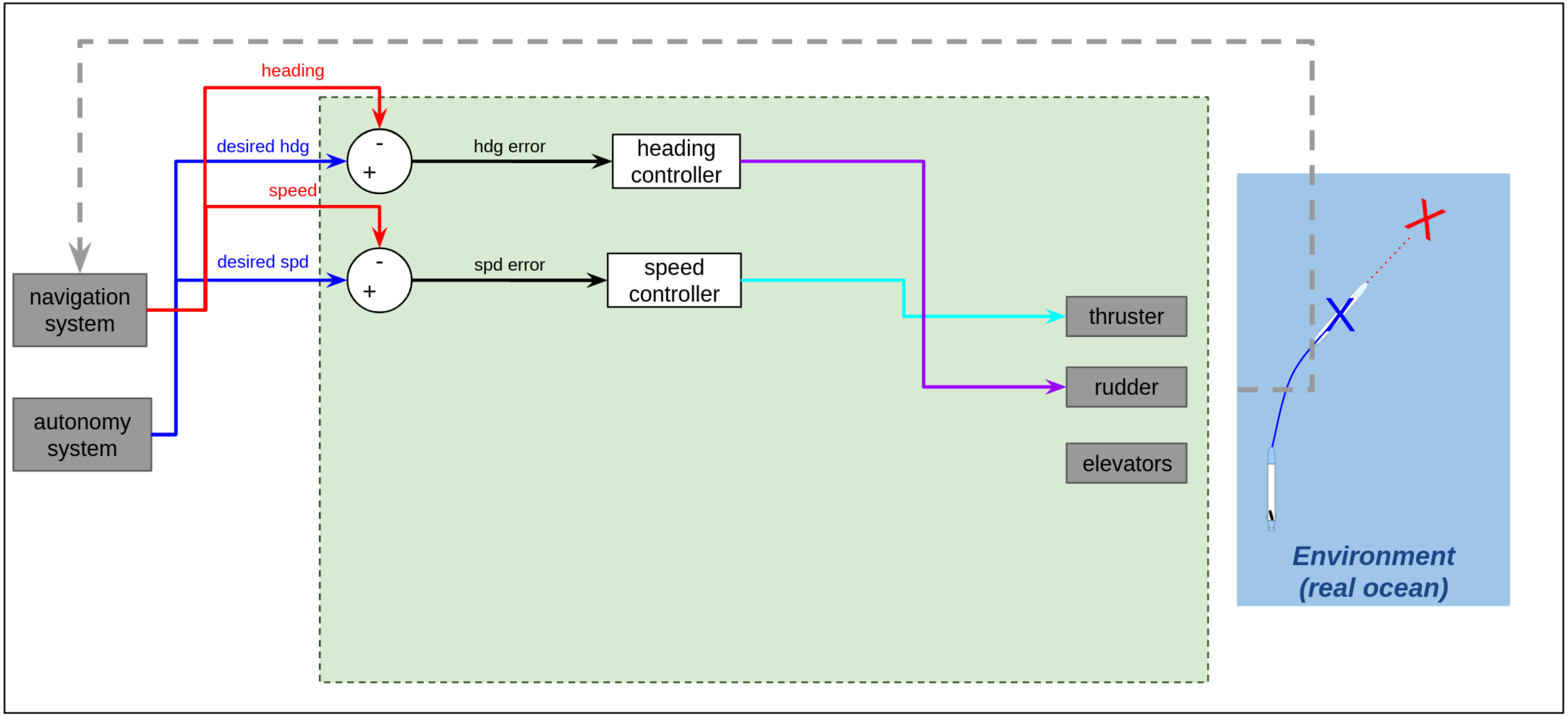
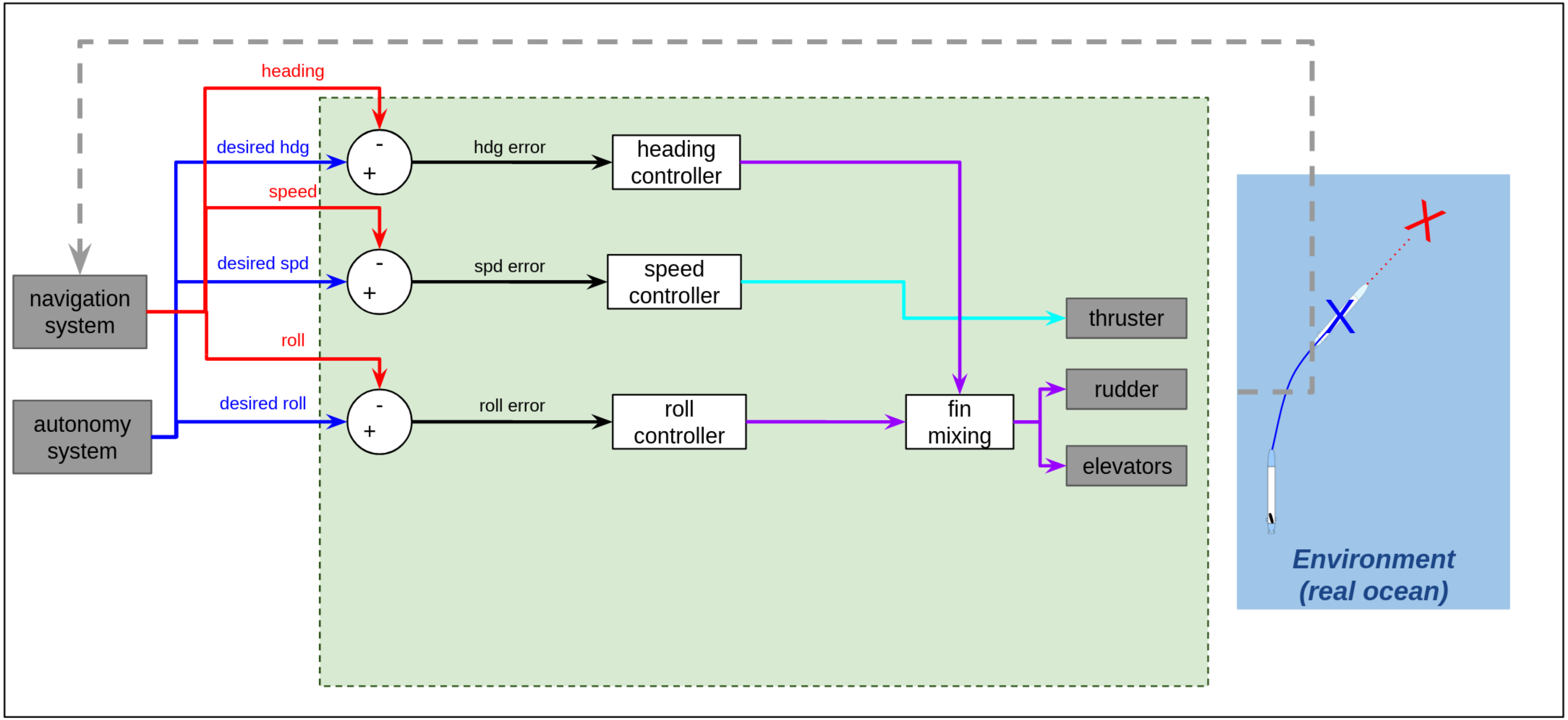
# Heading and speed control sub-systems

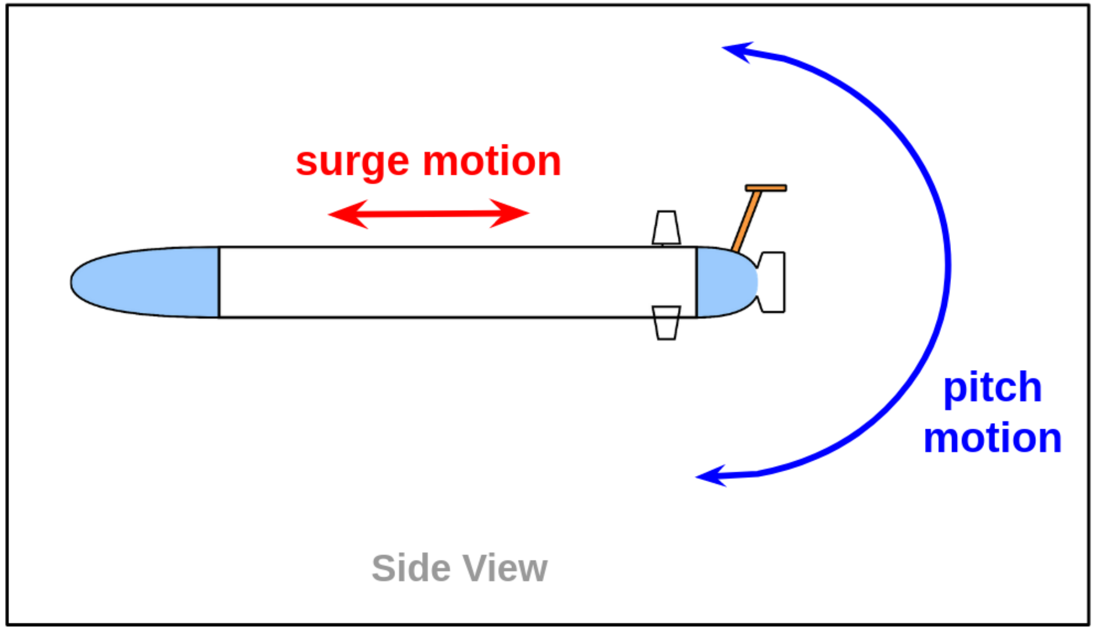


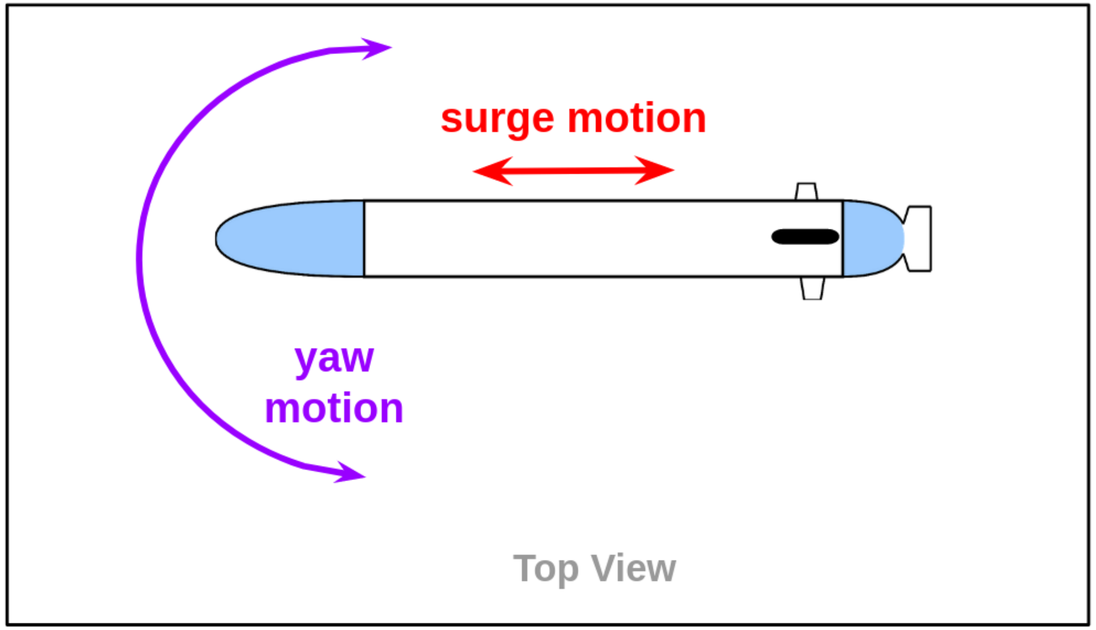
# Heading, speed and roll control sub-systems



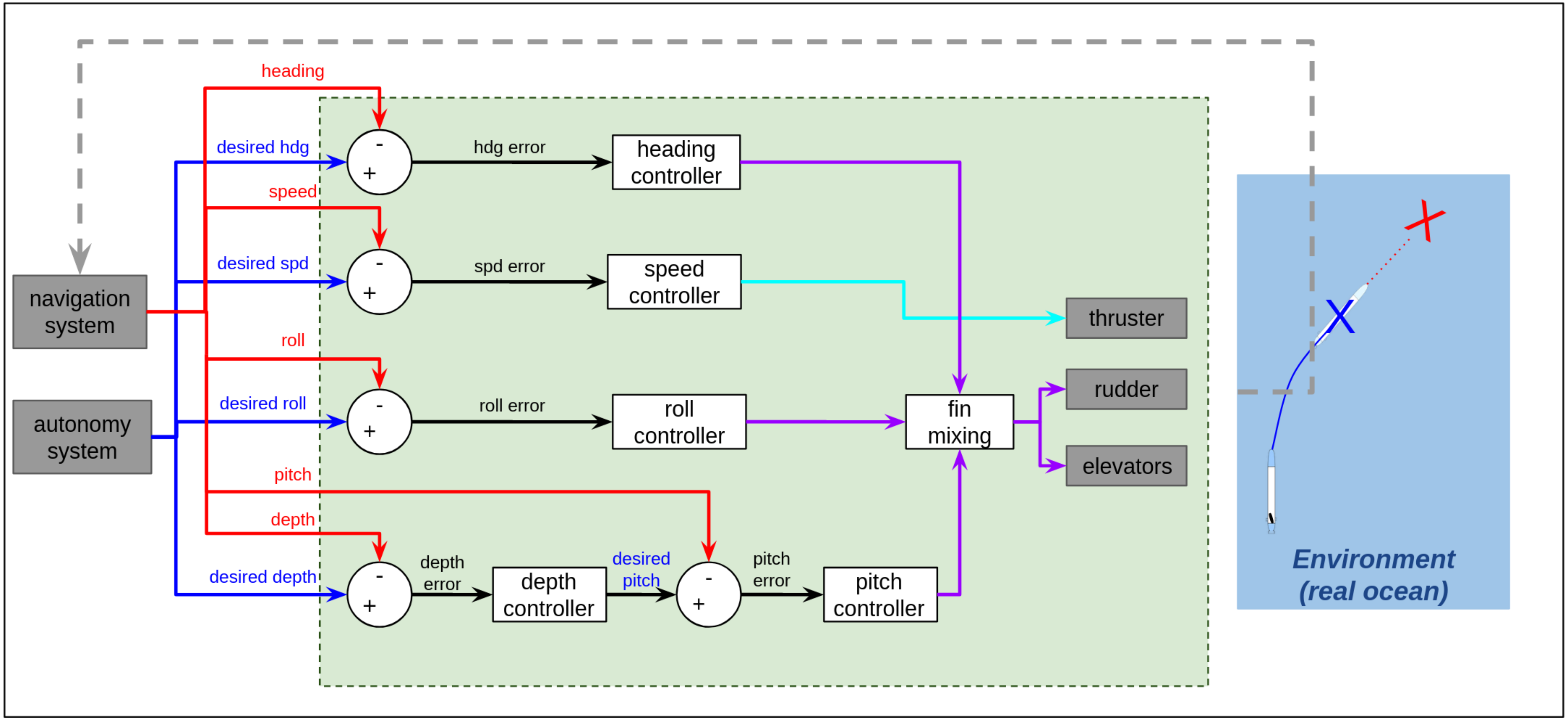
# Under-actuation

- Most torpedo-shaped AUVs, including the SeaBeaver, are under-actuated vehicles. I.e. they don't have direct control over all six degrees-of-freedom (6-DOF)
- The vehicle needs to pitch the nose up/down, while moving forward to change depth
- The vehicle needs to yaw, while moving forward to change lateral position



# Heading, speed, roll and depth control sub-systems

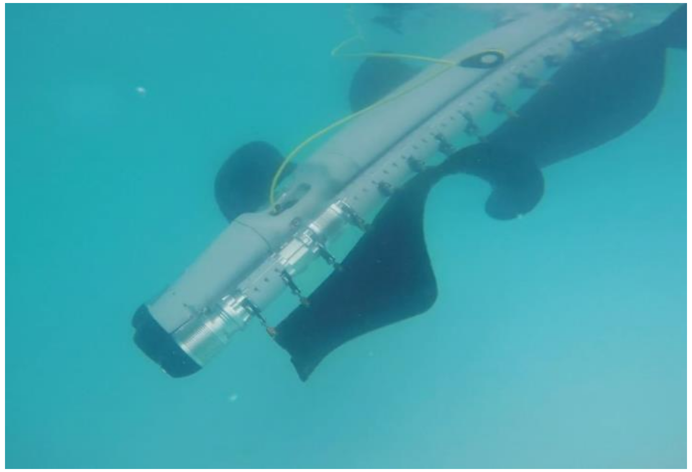


# Vehicles with multiple control modes

- There are vehicles that has multiple operational modes; e.g. multi-domain vehicles, hybrid vehicles.

- C-Ray autonomous amphibious vehicle is an example multi-domain vehicle. It has many modes:
  - Underwater operation mode
  - Surface operation mode
  - Ground operation mode
  - Seabed operation mode

- The control strategy should switch as the mode switches.



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# End