Ship Motion Control and Models

(Module 9)

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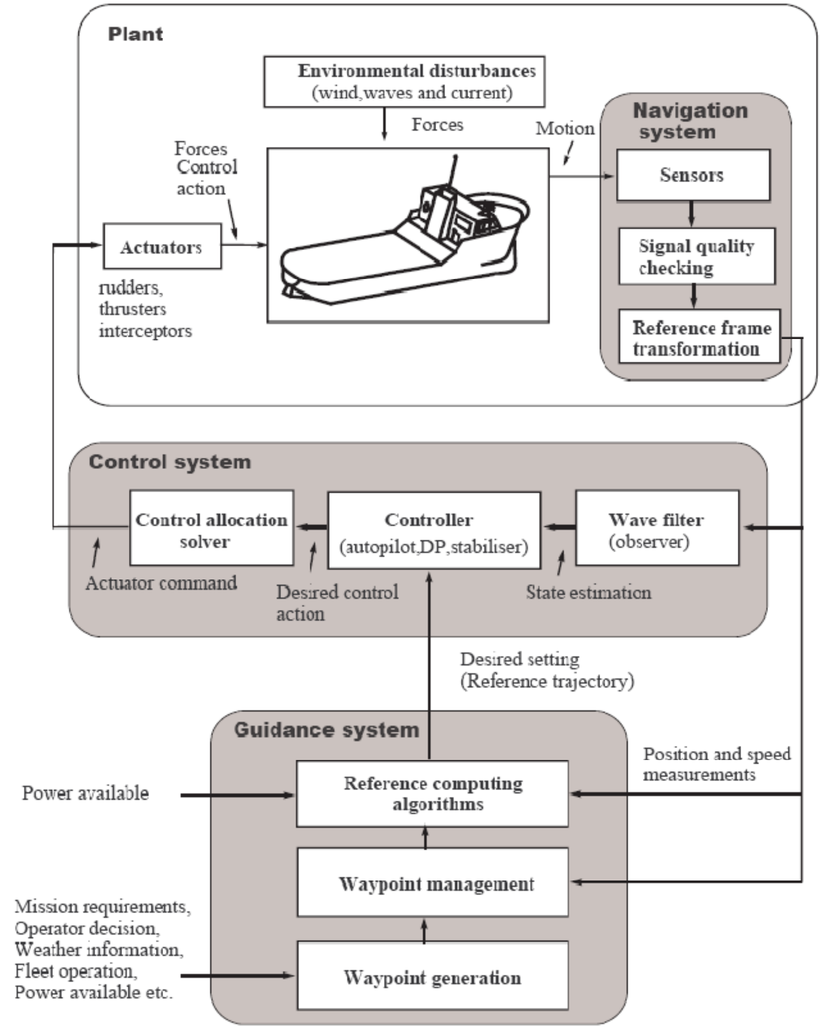
Guidance, Navigation and Control

(GNC)

Guidance, Navigation and Motion Control



Guidance: *is the action or the system that continuously computes the reference (desired) position, velocity and acceleration of a vessel to be used by the control system. These data are usually provided to the human operator and the navigation system.*

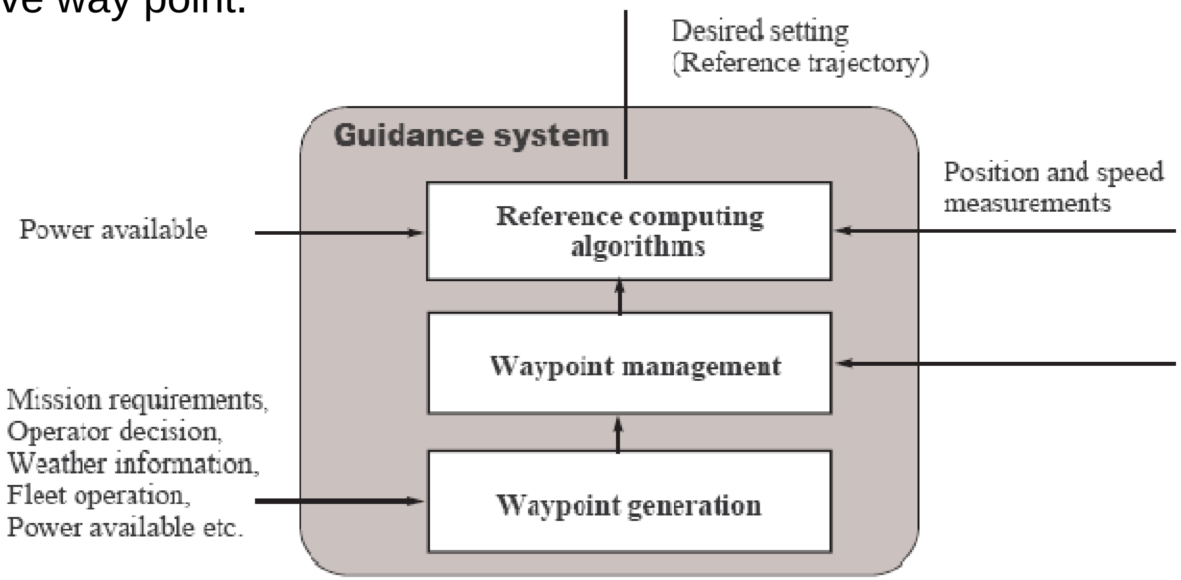
Navigation is derived from the Latin navis, "*ship*," and agere, "*to drive*." It originally denoted the art of ship driving, including steering and setting the sails. This includes planning and execution of safe, timely, and economical operation of ships, underwater vehicles, aircraft, and spacecraft.

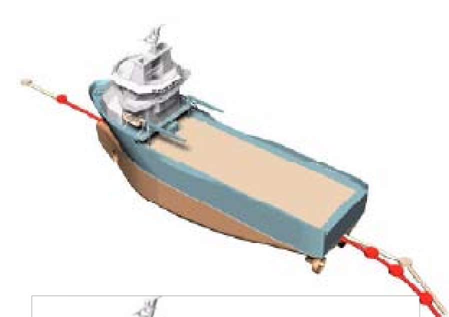
Control: *is the action of determining the necessary control forces and moments to be provided by the vessel in order to satisfy a certain control objective.*

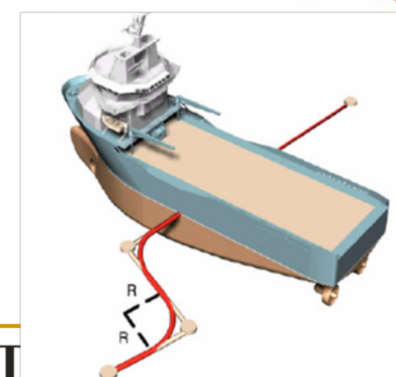
Guidance system

Generates the desired trajectories (position, velocity and acceleration).

- ***The waypoint generator*** establishes the desired wayponits according to mission, operator decision, weather, fleet operations, amount of power available *etc.*
- ***The waypoint management system*** updates the active waypoint based on the current position of the ship.
- ***The reference computing algorithms*** generate a smooth feasible trajectory based on a reference model, the ship actual position, amount of power available, and the active way point.



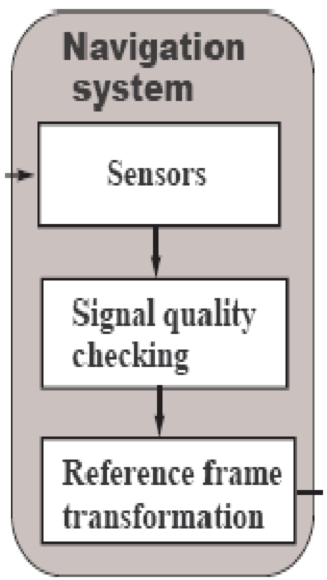


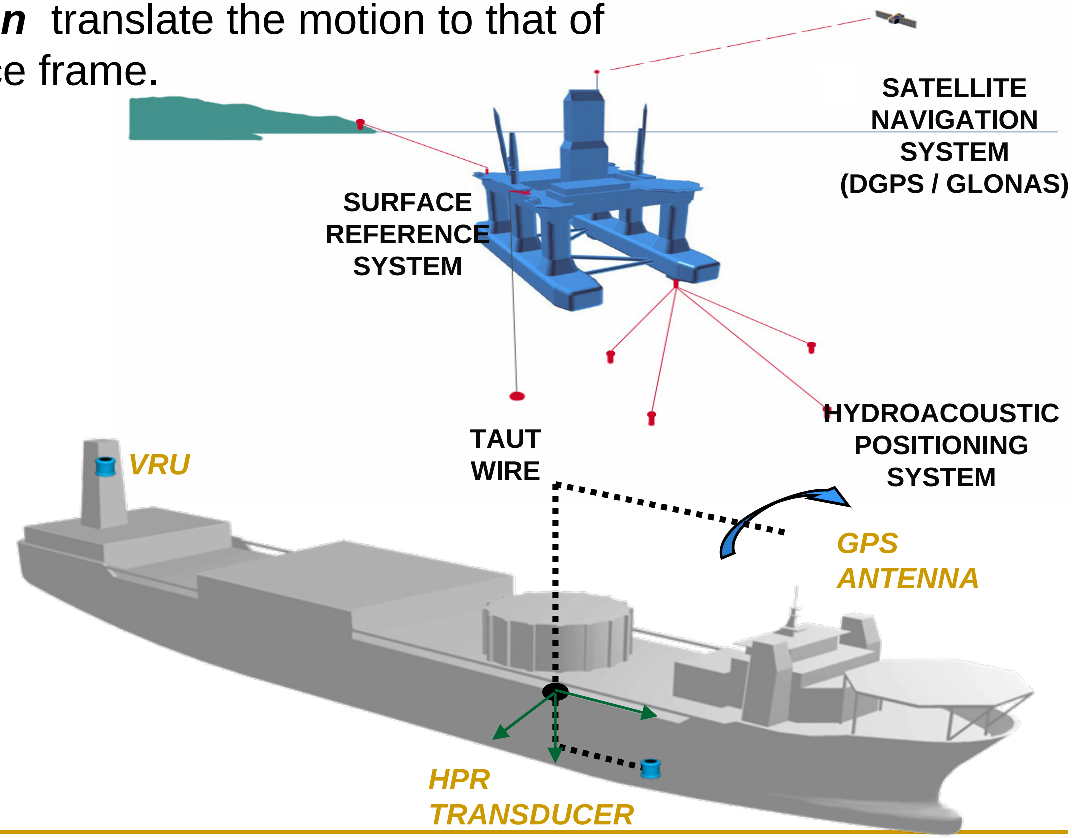


Navigation System

Generates appropriate feedback signals

- ***Sensors*** Satellite navigation systems, GPS, radar, gyros, accelerometers, compass, HPR, *etc.*
- ***Signal quality checking*** Statistic analysis, fault detection, voting, data fusion.
- ***Reference frame transformation*** translate the motion to that of the origin of the adopted reference frame.





Set-point Regulation, Trajectory Tracking Control or Path Following Control?

- **Set-Point Regulation:** The most basic guidance system is a constant input (set-point) provided by a human operator. The corresponding controller will then be a regulator. Examples of set-point regulation are constant depth, trim, heel and speed control, etc.

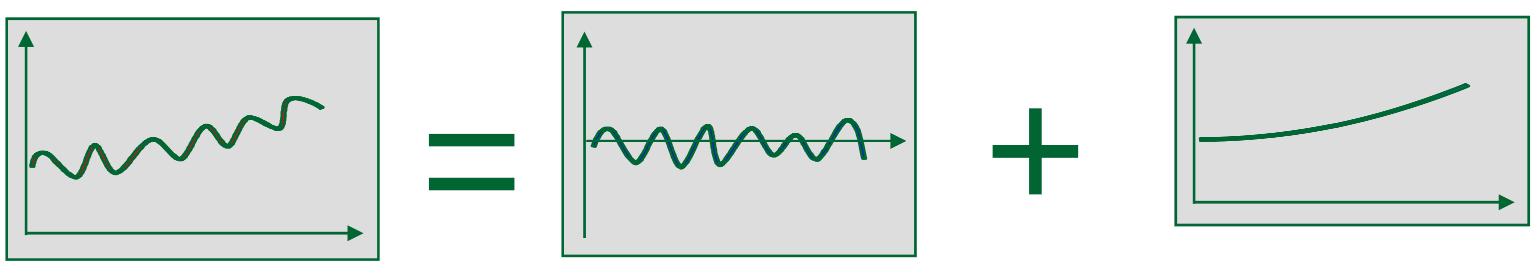
- **Trajectory Tracking Control:** The objective is for the position and velocity of the vessel to track given desired time-varying position and velocity reference signals. The corresponding feedback controller must then be a trajectory tracking controller. Tracking control can be used for course-changing maneuvers, speed changing, attitude control, etc. An advanced guidance system computes optimal time-varying trajectories from a dynamic model and a predefined control objective. If a constant set-point is used as input to a low-pass filter (reference model) the outputs of the filter will be smooth time-varying reference trajectories for position, velocity and acceleration (PVA).

- **Path Following Control:** Follow a path in 3D independent of time (geometric assignment). In addition, a dynamic assignment (speed/acceleration) along the path can be assigned. The corresponding controller is a path following/maneuvering controller.

Ship Motion Control

The task of a ship motion control system consists of making the ship to track/follow a *desired trajectory* or *path.* Sometimes this also includes motion damping.

In most ship operational conditions, the desired trajectory is slowly varying motion (LF motion) compared to the oscillatory motion induced by the waves (WF motion).



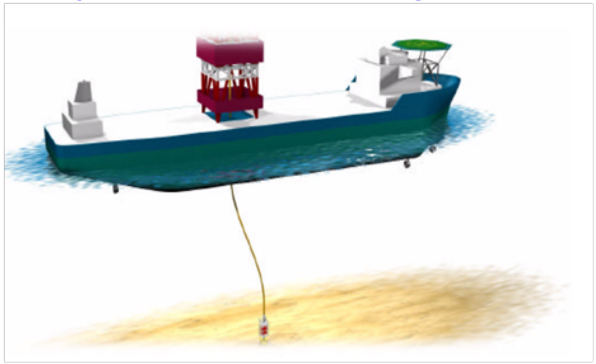
Total motion = Oscillatory motion (due to 1st order Wave induced loads) + Slowly varying motion (due to 2nd Wave loads, current, wind)

Ship Motion Control Objectives

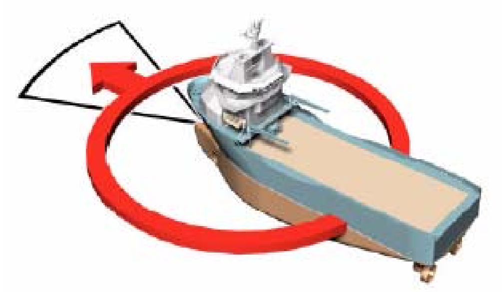
Due to the motion of ships, motion control problems can have different objectives:

- ***Control only the LF motions*** (Autopilots, Dynamic Positioning (DP), Position mooring systems)
- ***Control only the WF motions*** (Heave, roll and pitch stabilisation, ride control)
- ***Control both*** (DP with roll and pitch stabilisation in high seas, course keeping and roll stabilisation)

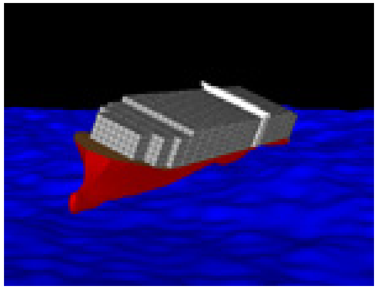
Dynamic Positioning



Autopilot



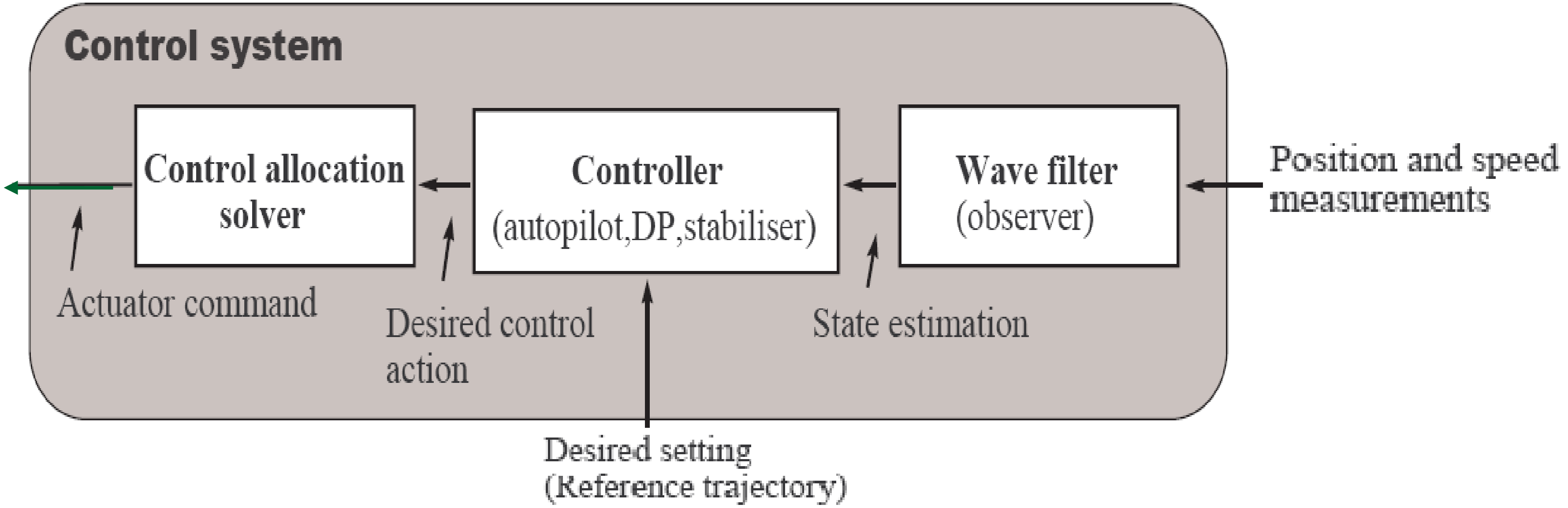
Roll stabilisation



Plant Control System

Generates appropriate actuator commands.

- ***Wave filter (observer):*** Recover slowly varying motion signals from the total measurements
- ***Controller:*** Generates force commands (desired control action)
- ***Control allocation:*** Translate force commands into actuator commands (RPM, PWR, Torque).



Wave Filtering

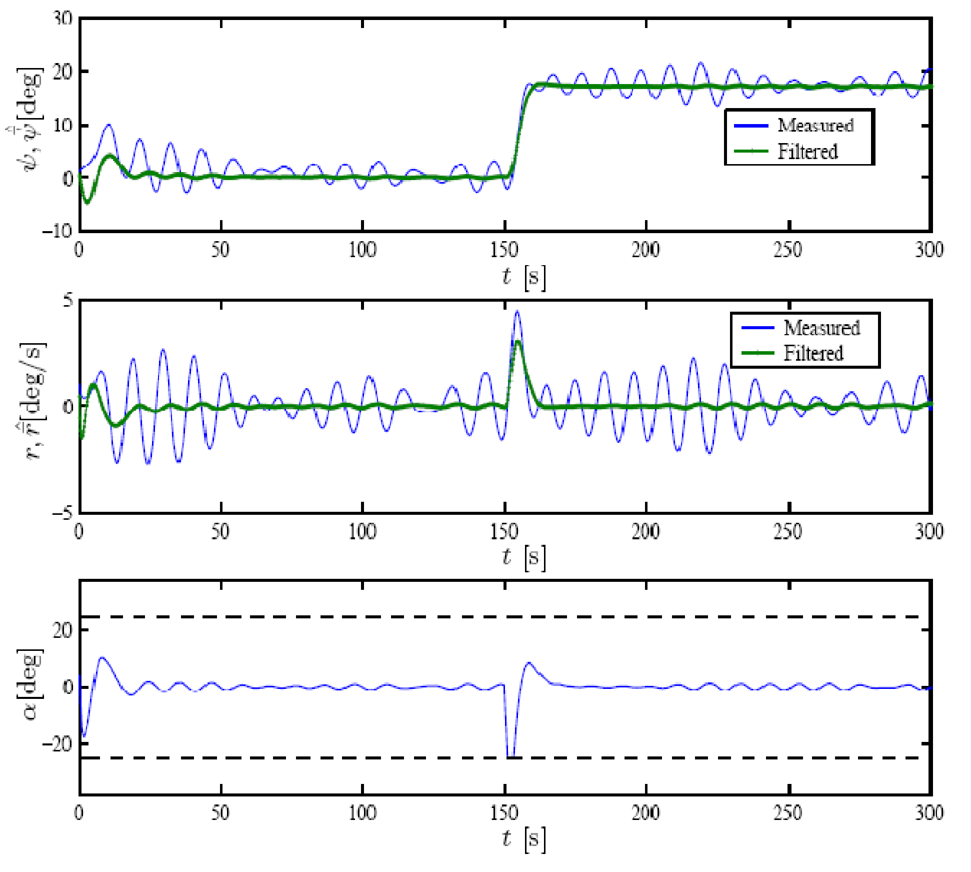
Removes first order (oscillatory) wave-induced motion

Example course autopilot wave filtering
Perez (2005):

Heading angle

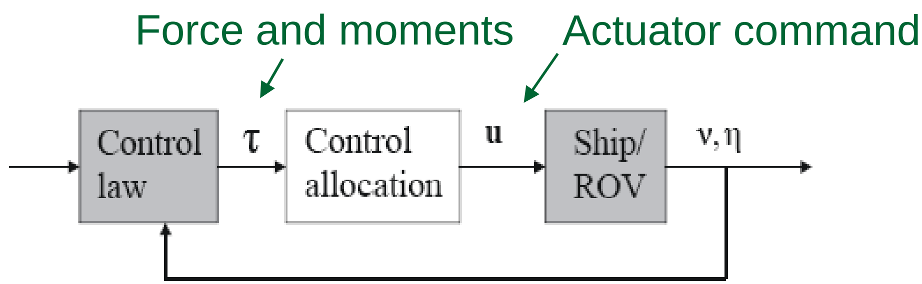
Heading rate

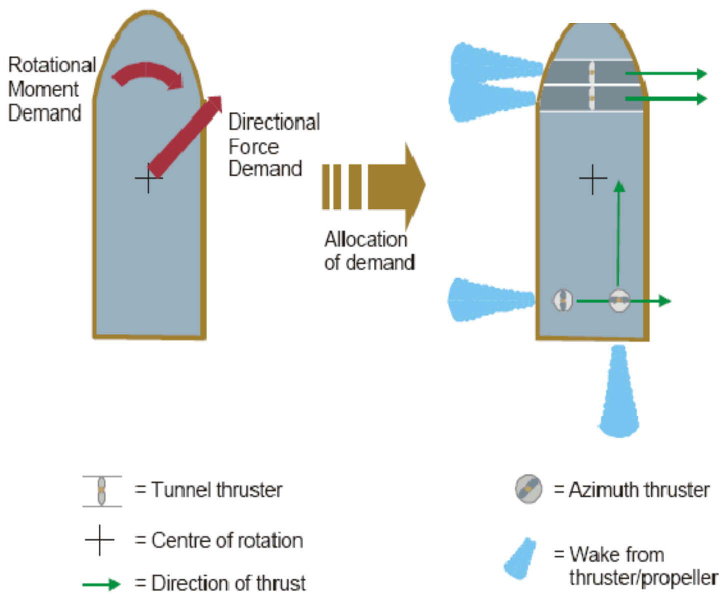
Rudder angle

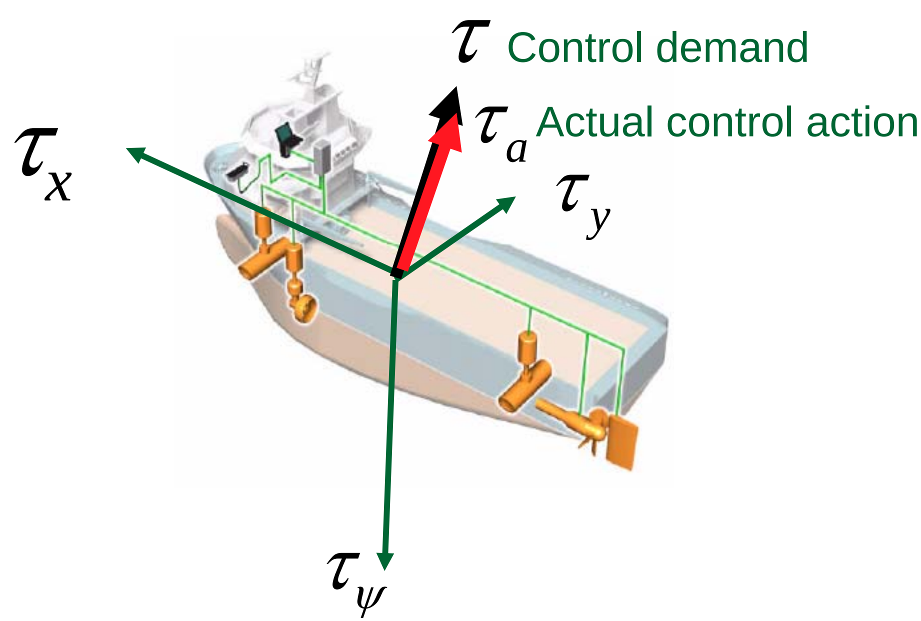


Control Allocation

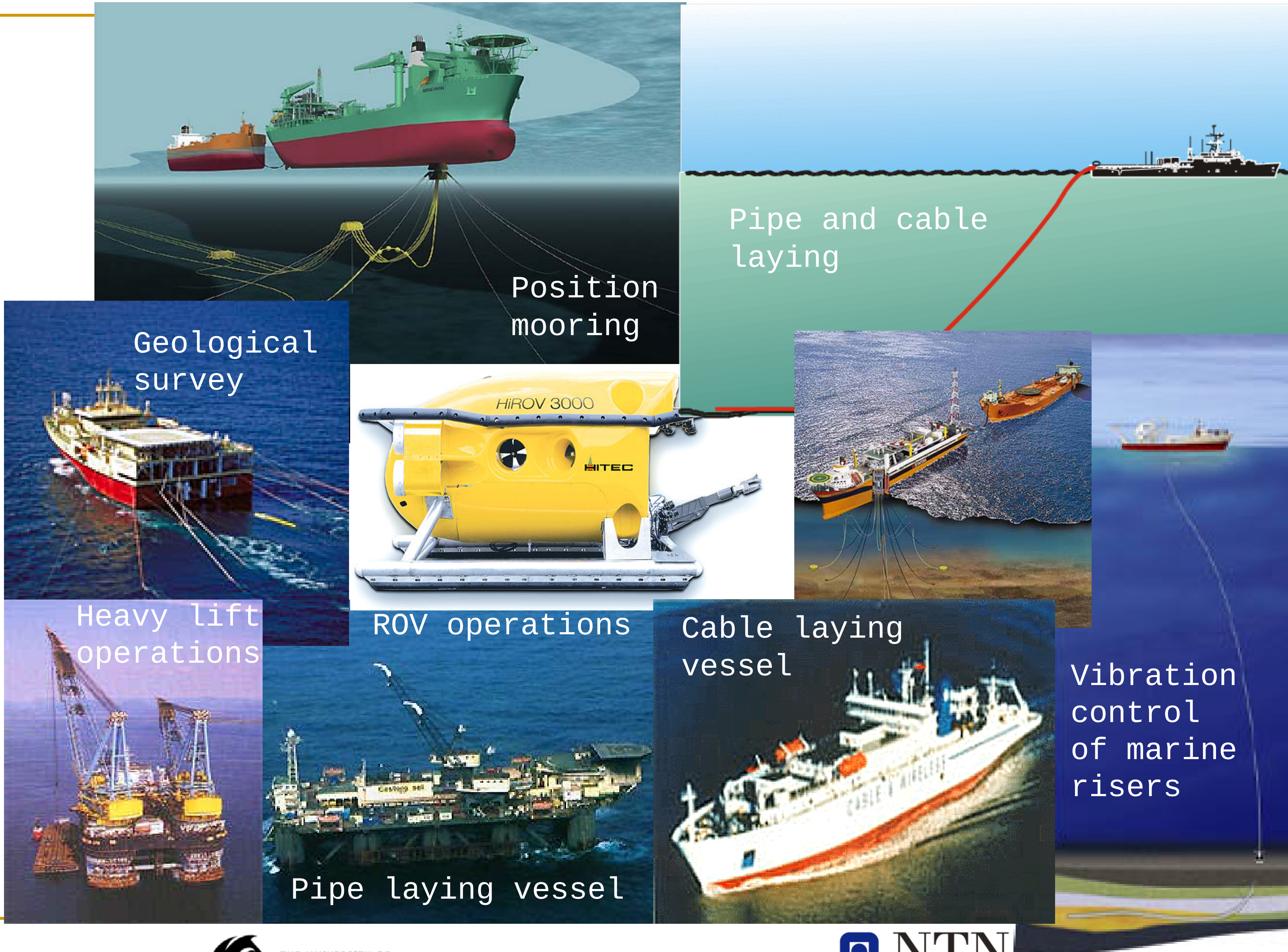
Some marine control systems are over-actuated to guarantee reliability and high performance – optimization problem







Marine Control Problems and Models


Position mooring
Pipe and cable laying
Geological survey
HiROV 3000
HITEC
Heavy lift operations
ROV operations
Cable laying vessel
Vibration control of marine risers
Pipe laying vessel

Trajectory Tracking & Maneuvering Control

Fully actuated supply ship cruising at low speed.

Underactuated container ship in transit.

Italian supply ship **Vesuvio** refueling two ships at sea.

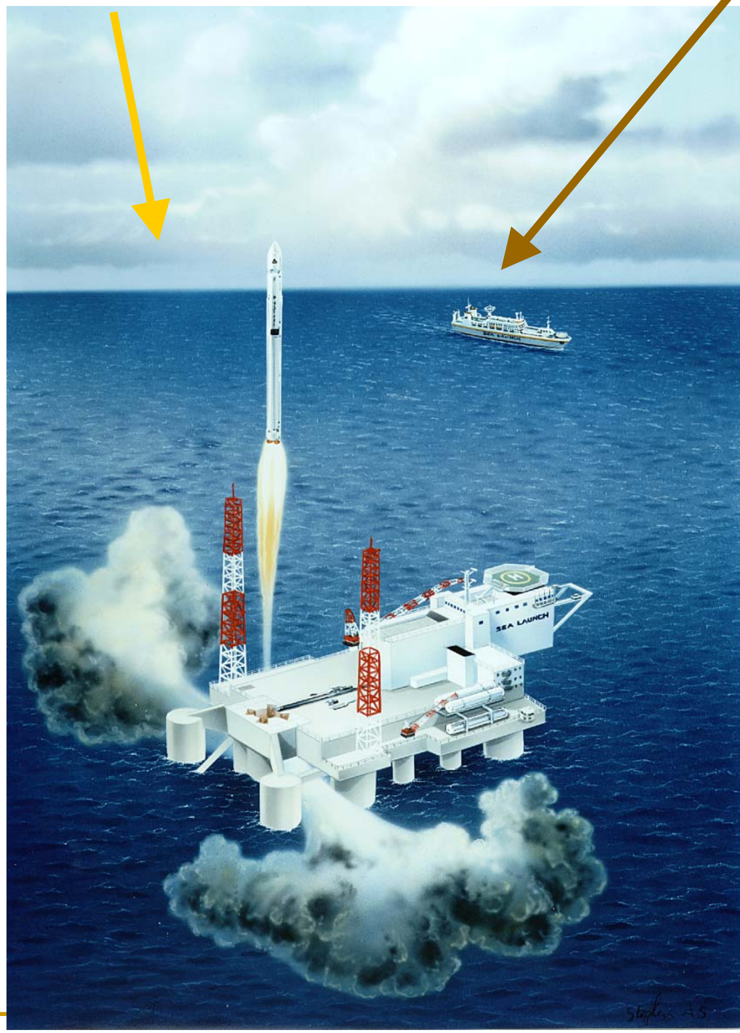
Courtesy: Hepburn Eng. Inc.

Formation Control/Underway Replenishment

Interdisciplinary: Rocket Launch / DP system / THCS

Launch Platform

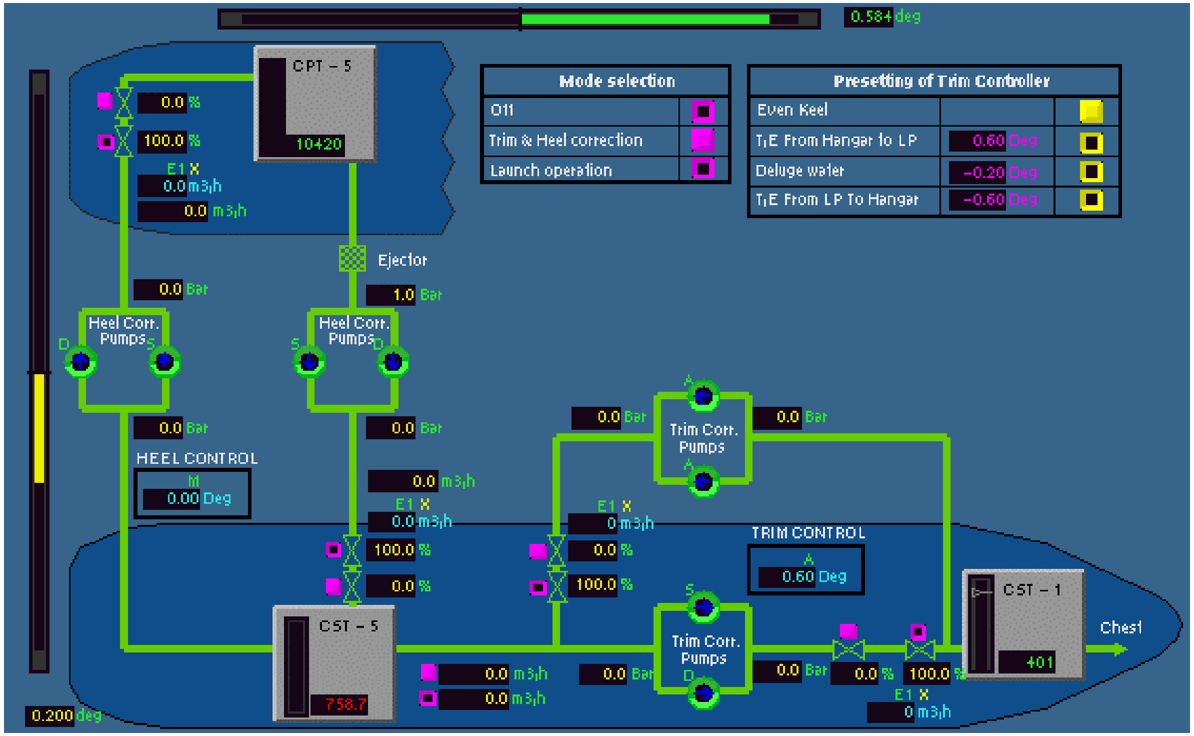
Assembly Command Ship

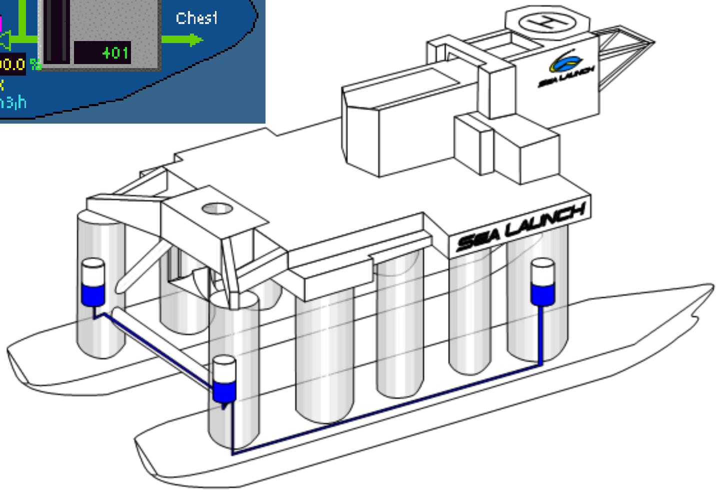


SEA LAUNCH

Marine Segment SM

Trim & Heel Correction System (THCS)

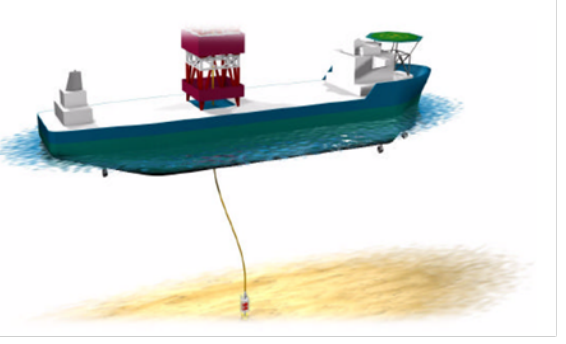




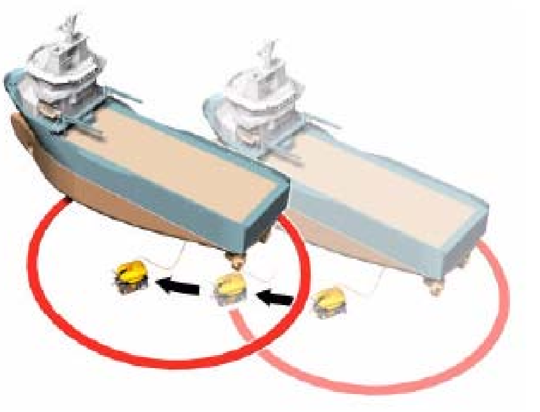
Process Control
or
Marine Control?

Dynamic Positioning

Drilling vessel (Regulation)



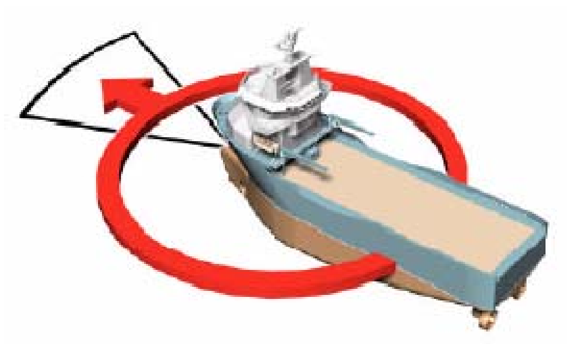
ROV operations (tracking)



- Control objective: Keep position; follow slow changes in set point.
- DOF: 1,2,6 (surge, sway and yaw) [pitch and roll can be incorporated in high sea states in offshore rigs]
- Model: time-domain model which includes cross-flow drag effects. The Munk moment, which is in the added mass Coriollis-centripetal terms should be added. Alternatively, use current coefficients (experimental data).
- Disturbances: Wind, current, mean wave drift and slowly varying wave forces.

Course and Heading Autopilots

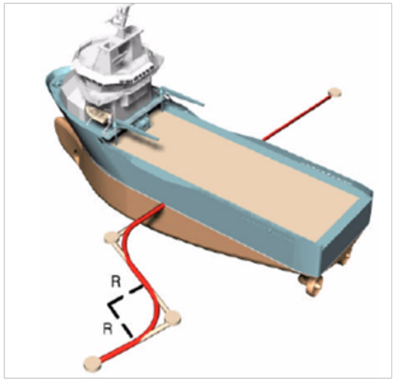
Heading



Course keeping

- Control Objective: Keep heading or course. For course keeping autopilots, positioning control and guidance systems must also be designed (outer loop).
- DOF: 2,[4], 6 (sway, roll, yaw) There is strong coupling between sway and yaw which is not convenient to ignore, and roll also affect these modes.
- Model: Manoeuvring model; at high speed lift-drag effects are significant. The model can be linearised for control design because the must operate close to equilibrium conditions.
- Disturbances: Wind, waves (there must be a wave filter); for a course keeping autopilot, current is also a disturbance.

Manoeuvring Control

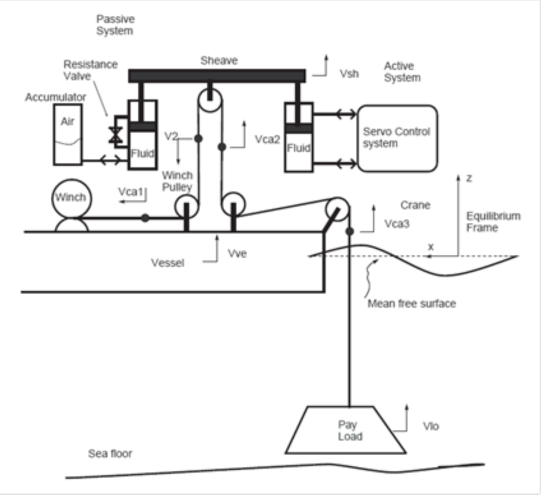


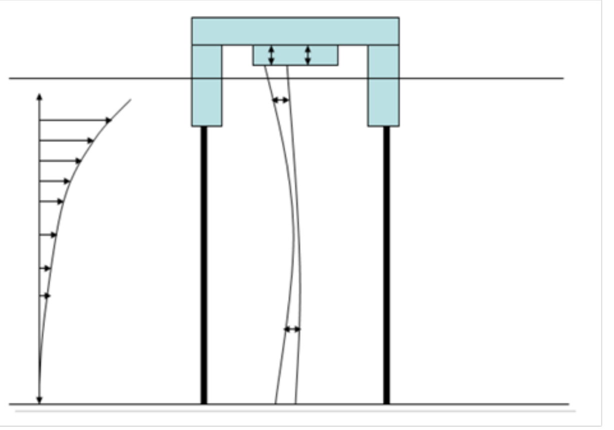
- Control objective: geometric and dynamic conditions for path following, way-point or trajectory tracking.
- DOF: 1,2,[4],6.
- Model: nonlinear manoeuvring model.
- Disturbances: wind, waves, current.

Ride Control

- Control objectives: reduce roll and pitch.
- DOF: 4,5.
- Model: linear time-domain model, with viscous corrections for roll.
- Disturbances: 1st order wave induced motion; wind, trim variations with speed.

Heave Compensation





- Control objective: reduce the effect of heave motion in different components of the system.
- DOF: 3,[5].
- Model: linear time-domain model + nonlinear viscous effects and structural stiffness.
- Disturbances: 1st order wave-induced motion, and rapidly-varying 2nd order wave-induced motions

Ship-to-Ship Operations

- Control objective: keep formation.
- DOF: 1,2,6.
- Model: time-domain model with ship-to-ship hydrodynamic interaction if vessels are too close.
- Disturbances: waves, wind, current

Modelling Disturbances for Control Design

If a model-based control design requires disturbance modelling,

Waves:

- 1st-order wave loads (due to wave spectrum) can be modelled using multi-sinces with random phases or filtered white noise (wave spectrum).
- Mean wave drift loads can be modelled as a 1st-order Wiener process (1st-order system driven by white noise.)

Currents:

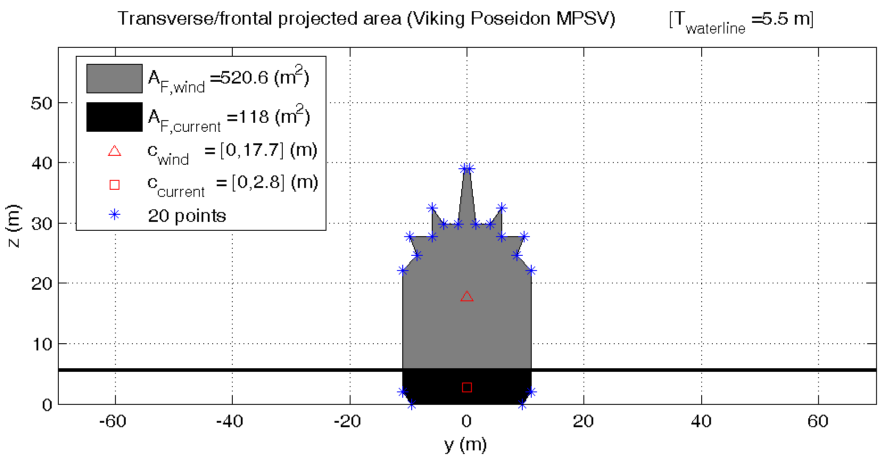
- Current loads can be included using the concept of relative velocity in surge, sway and yaw (in DP current coefficients can also be used)

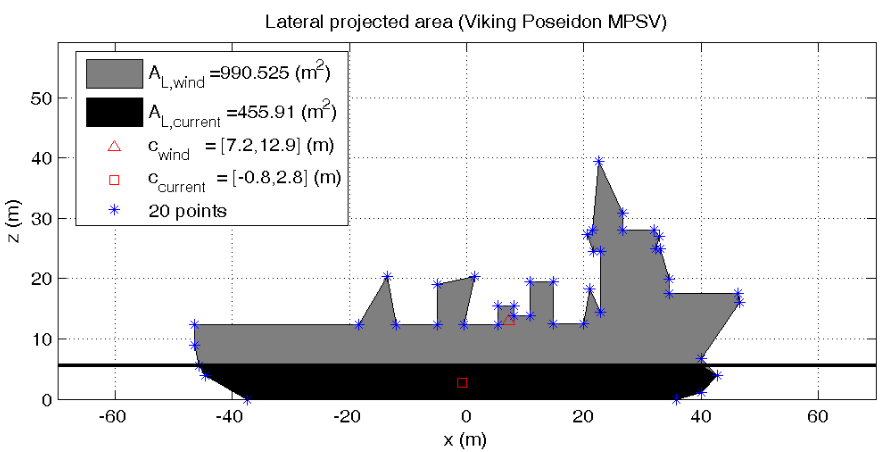
Wind:

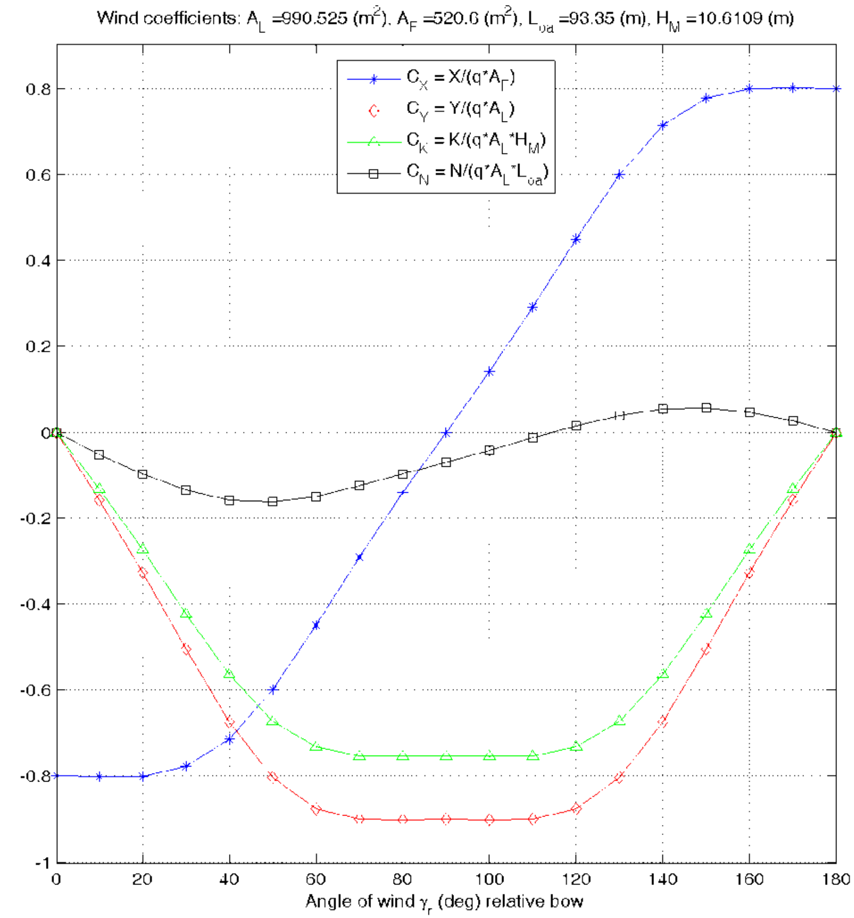
- Wind loads are included using wind coefficient tables.

Wind Loads

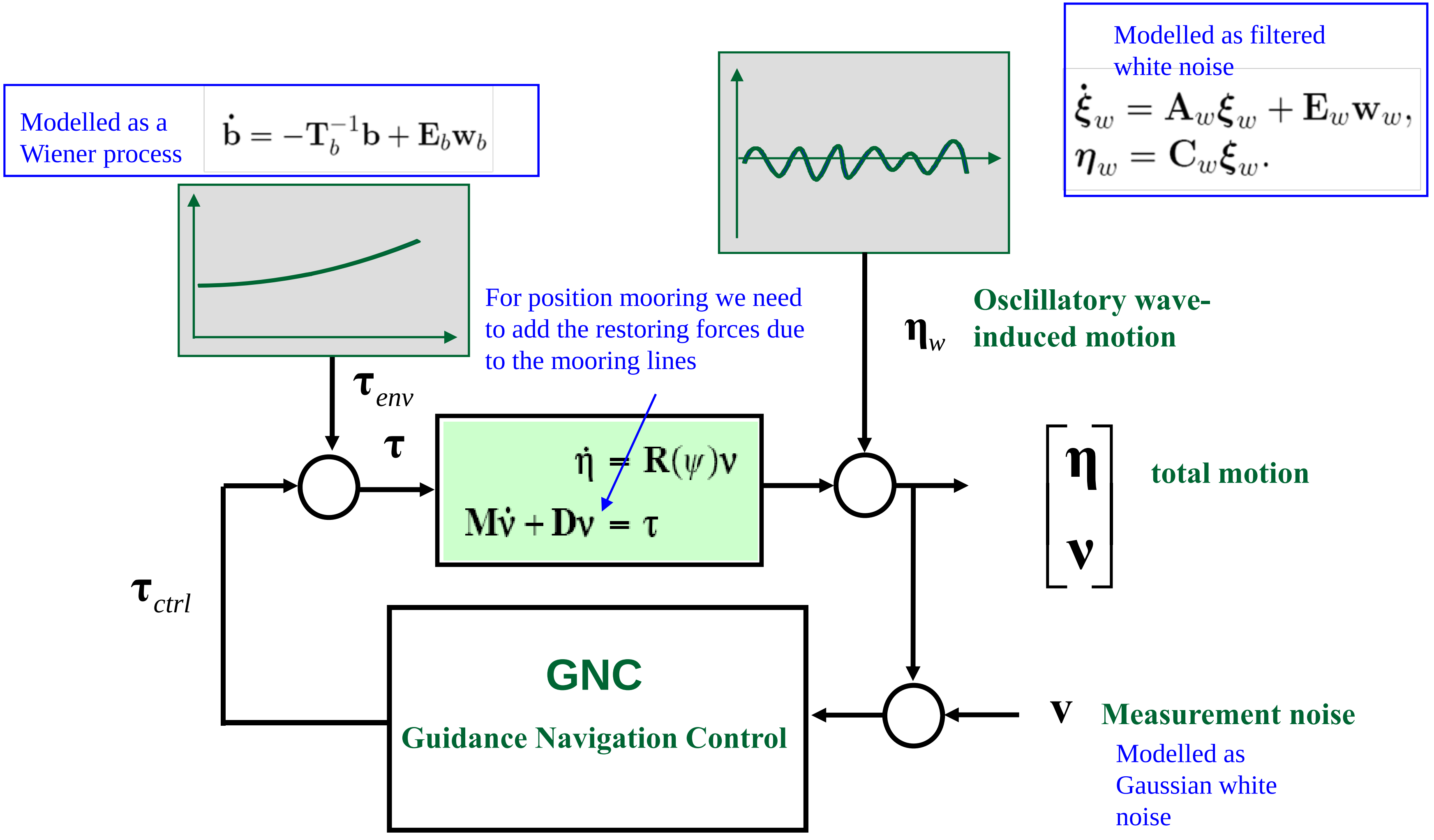
- Wind areas and centroids from digitized GA
- For best results experimental data from wind tunnels should be used.







Example: Simulation of Wave Loads in DP



This model is typically used to design control and observers.

Useful References

- **Fossen, T. I. (1994).** *Guidance and Control of Ocean Vehicles*, John Wiley
- **Fossen, T.I. (2002)**. *Marine Control Systems*. Marine Cybernetics.
- **Perez, T. (2005).** *Ship Motion Control*. Springer Verlag.
- **Sørensen, A.J. (2005).** *"Marine Cybernetics".* Lecture Notes Dept. of Marine Technology, NTNU, Norway