Ship Motion Control and Models
(Module 9)

Dr Tristan Perez
Centre for Complex Dynamic Systems and Control (CDSC)

Prof. Thor I Fossen
Department of Engineering Cybernetics
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 waypoins 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).

\[ \text{Total motion} = \text{Oscillatory motion} + \text{Slowly varying motion} \]

- 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)
**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
Pipe laying vessel
Geological survey
Position mooring
Heavy lift operations
ROV operations
Pipe laying vessel
Pipe and cable laying
Cable laying vessel
Vibration control of marine risers
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
Trim & Heel Correction System (THCS)

Process Control or Marine Control?
Dynamic Positioning

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 Coriolis-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

- **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: 1\textsuperscript{st} order wave-induced motion, and rapidly-varying 2\textsuperscript{nd} 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:
- 1\textsuperscript{st}-order wave loads (due to wave spectrum) can be modelled using multi-sin-ses with random phases or \textit{filtered white noise (wave spectrum)}.  
- Mean wave drift loads can be modelled as a 1\textsuperscript{st}-order Wiener process (1\textsuperscript{st}-order system driven by white noise.)

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

Wind:
- Wind loads are included using \textit{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

\[
\dot{\mathbf{b}} = - T_b^{-1} \mathbf{b} + \mathbf{E}_b \mathbf{w}_b
\]

Modelled as a Wiener process

Oscillatory wave-induced motion

\[
\dot{\xi}_w = A_w \xi_w + E_w \mathbf{w}_w,
\]
\[
\eta_w = C_w \xi_w.
\]

Measurement noise

Modelled as Gaussian white noise

For position mooring we need to add the restoring forces due to the mooring lines

This model is typically used to design control and observers.
Useful References


- **Perez, T. (2005).** *Ship Motion Control*. Springer Verlag.

- **Sørensen, A.J. (2005).** “*Marine Cybernetics*”. Lecture Notes Dept. of Marine Technology, NTNU, Norway