Lecture Notes:
TTK 4190 Guidance and Control of Vehicles
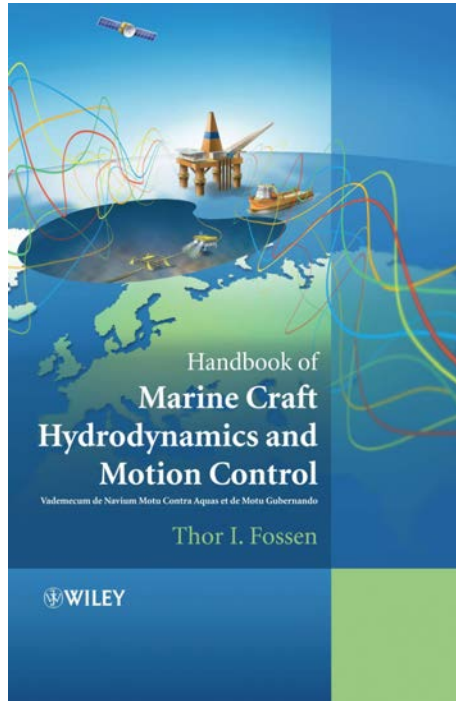
Professor Thor I. Fossen

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Home page: http://www.fossen.biz/

Textbook and Notation

Fossen, T. I. (2020)
Handbook of Marine Craft Hydrodynamics and Motion Control (2nd edition). Wiley.
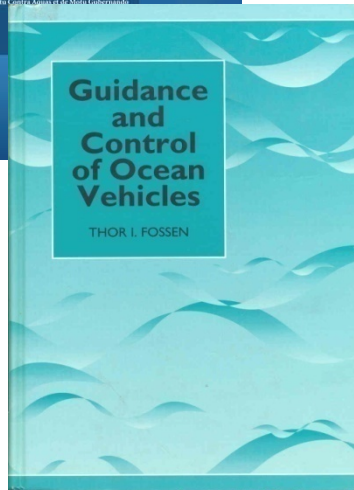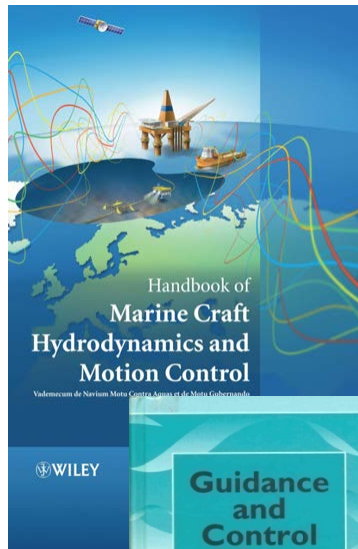
MSS Toolbox:
http://github.com/cybergalactic/MSS

✓ **SNAME (1950).** Nomenclature for Treating the Motion of a Submerged Body Through a Fluid. *The Society of Naval Architects and Marine Engineers, Technical and Research Bulletin No. 1-5, April 1950, pp. 1-15.*

v (*sway*) q (*pitch*)

y_b

p (*roll*) r (*yaw*)

u (*surge*)

x_b w (*heave*)

z_b
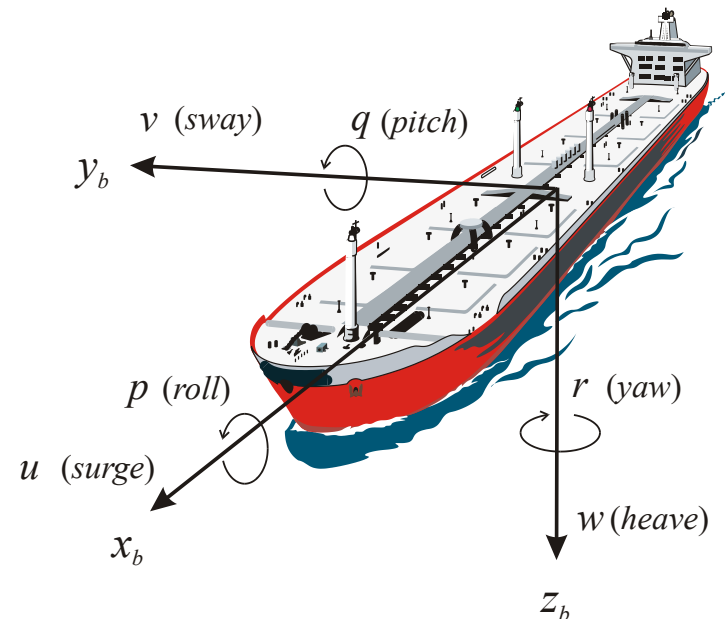
Previous Books

✓ **Fossen, T. I. (2011)**
Handbook of Marine Craft Hydrodynamics and Motion Control (1st edition). Wiley.
ISBN-13: 978-1119991496

✓ **Fossen, T. I. (1994).**
"Guidance and Control of Ocean Vehicles",
Wiley.
ISBN-13: 978-0471941132

Goals for the Course

1. Mathematical modeling of vehicles. This includes:

   - Kinematics
   - Kinetics
   - Equations of motion for marine craft and aircraft
   - Wind, wave and ocean current models
   - Hydrodynamics: maneuvering and seakeeping theory

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2. Design of guidance, navigation and motion control systems for a large number of applications

3. Simulate the motions of marine craft and aircraft in the time-domain using hydrodynamic/aerodynamic models

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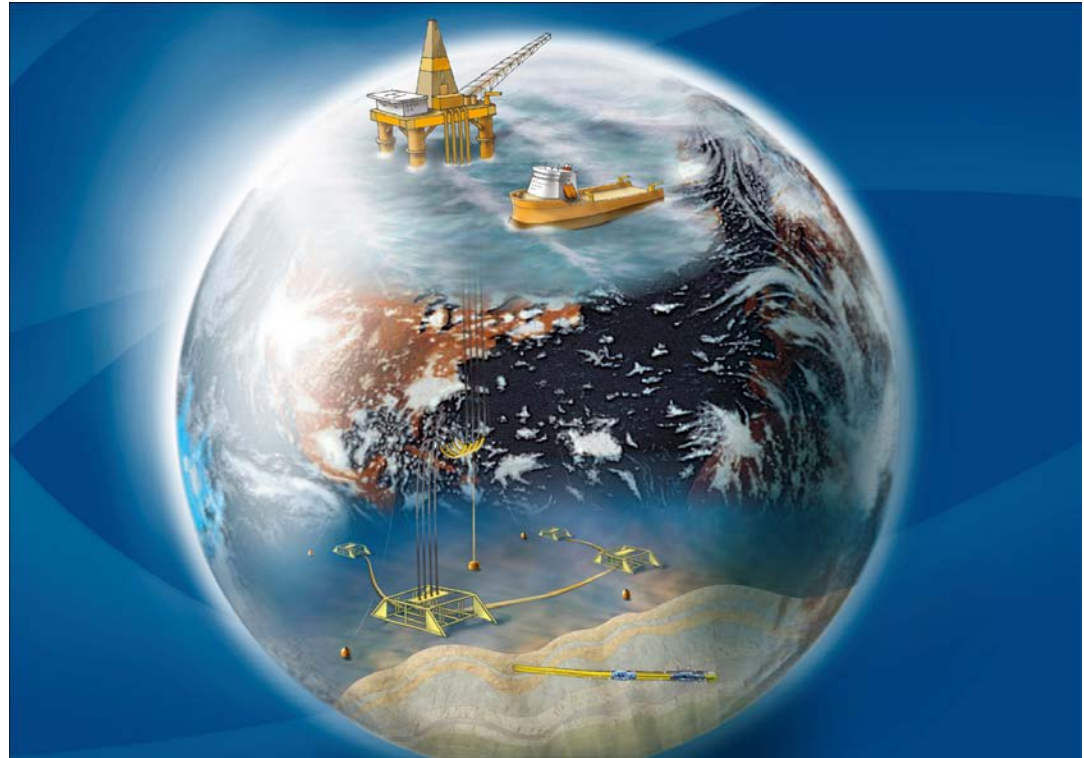
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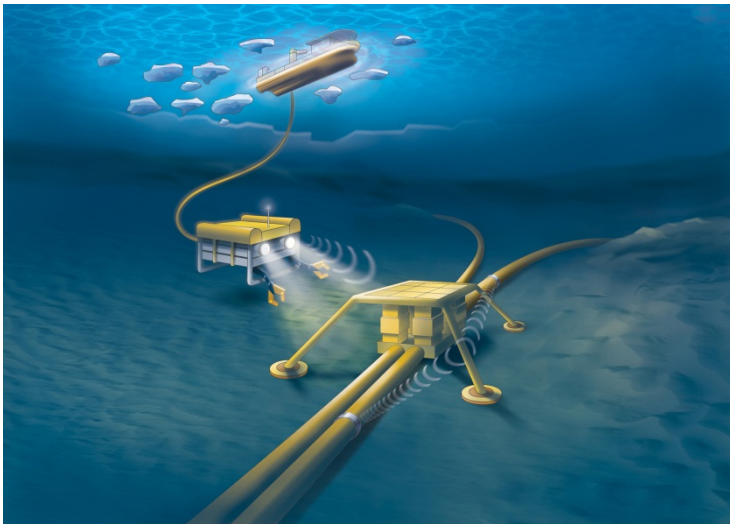
Applied Underwater Robotics Laboratory

The fleet of the AUR-Lab at NTNU Trondheim
https://www.ntnu.no/aur-lab

Remus 100 AUV

Light AUV (LAUV)

Hugin AUV

ROV Minerva

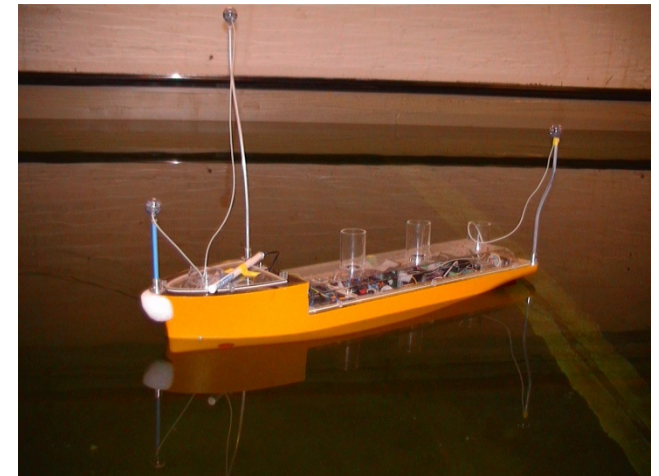Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

Marine Cybernetics Laboratory (MCLab)

MCLab Dimensions:

$$L \times B \times D = 40 \text{ m} \times 6.5 \text{ m} \times 1.5 \text{ m}$$

✓The software is developed by using rapid prototyping techniques and automatic code generation under Matlab/Simulink™ and RT-Lab™.

✓The target PC onboard the model scale vessels runs the QNX™ real-time operating system, while experimental results are presented in real-time on a host PC using Labview™.

Cybership II

Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

NTNU Research Vessel Gunnerus

31 meters long
Top speed 13 knots

http://www.ntnu.edu/marine/gunnerus

Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

UAV Factory Penguin B w/ Piccolo SL

- 28 m/s cruise speed
- Gasoline, 8 hr endurance
- MTOW 21 kg
- 2-5 kg payload capacity
- Large payload bay
- 80W generator
- Avionics system integration made with Maritime Robotics based on Cloudcap technology
- Telemetry on 2.4 GHz radio, GPRS (and VHF)
- Catapult launch
- Custom payload system integration with avionics interface

Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

Skywalker X8 w/Ardupilot

- 18 m/s cruise speed
- Catapult launch
- Belly or net landing
- Electric, 1hr endurance
- Large payload bay
- >1 kg payload capacity
- Inexpensive
- Flexible avionics and payload system integration with ArduPilot open source autopilot and mission planning SW
- Currently telemetry on 433 MHz or 5.8 GHz radio for VLOS
- Can be set up for BLOS with GPRS and VHF radio links

Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

Microdrone Quad-copter

- Turn-key solution
- Various camera, video and radio systems
- Electric, 45 min endurance
- 2-3 kg payload capacity

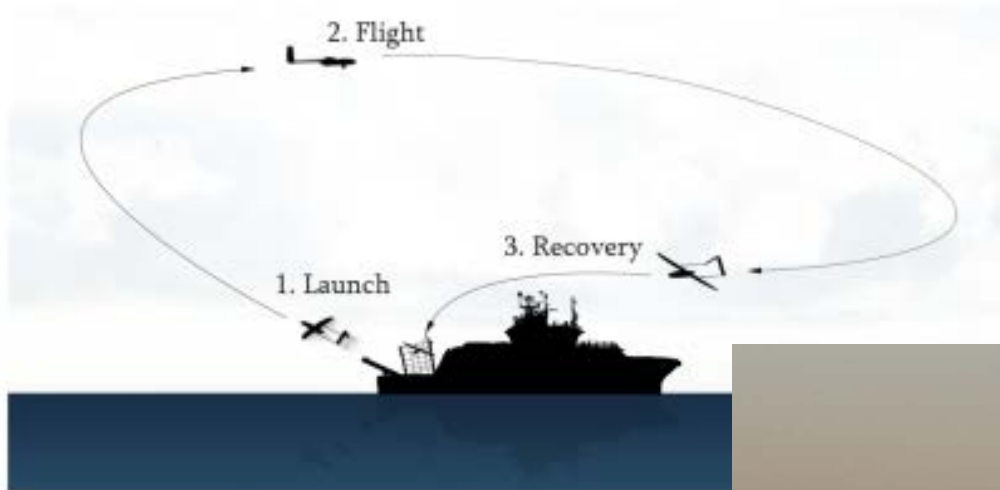Lecture Notes TTK 4190 Guidance and Control of Vehicles (T. I. Fossen)

NTNU Airfield at Agdenes

Located 94 km North-West of Trondheim

We also use the airports at Eggemoen and Ørland

Offshore UAV Launch and Recovery Systems

Launching – The Easy Part "Human-Inspired Approach"

Automatic Launch of the Penguin UAV

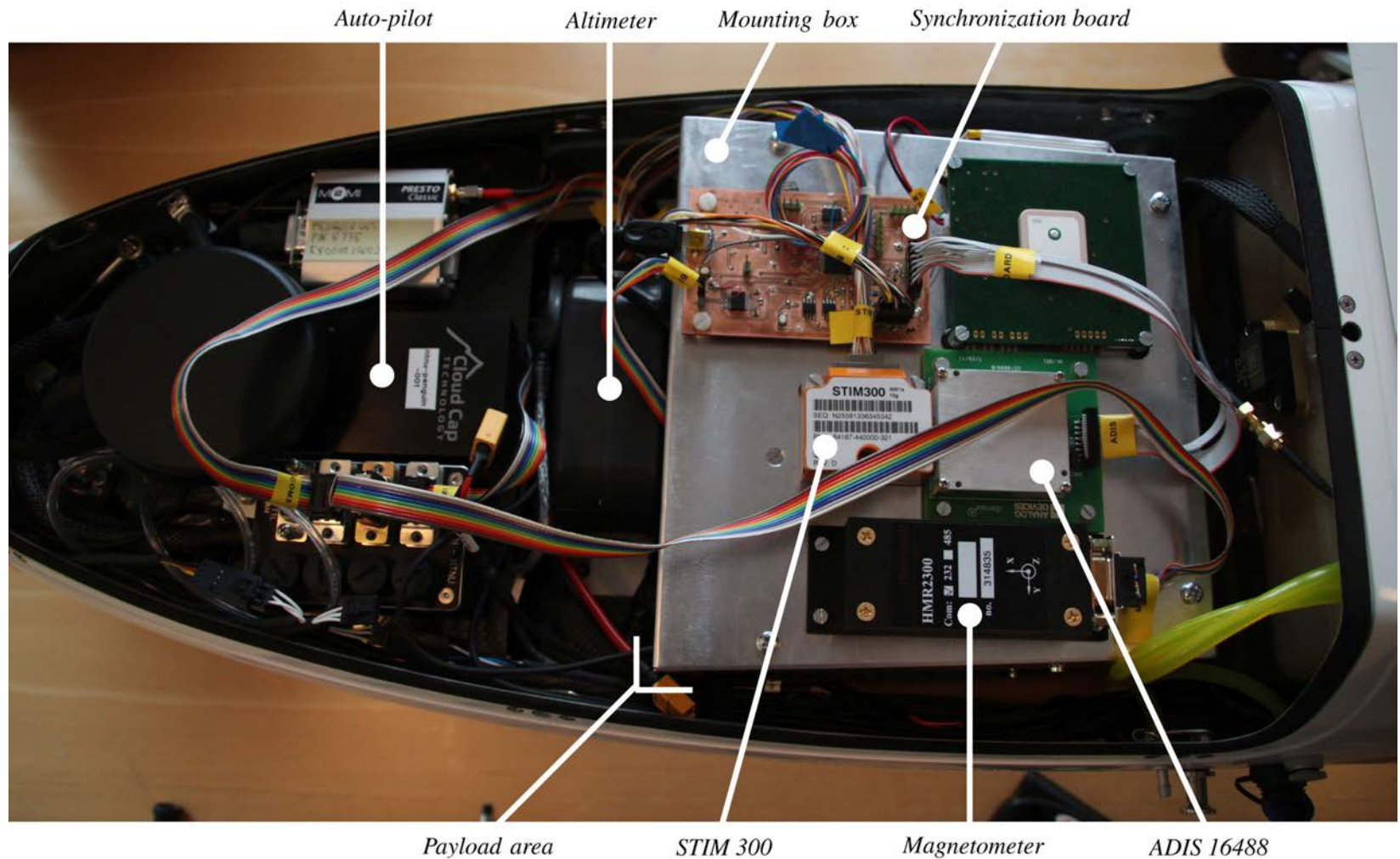# Net Landing onboard a Research Vessel outside the Azores in 2016

UAV as a Remote Sensing Platform

Penguin equipped with Camera, INS and GPS Sensor Suite for Data Logging

Auto-pilot   Altimeter   Mounting box   Synchronization board

Payload area   STIM 300   Magnetometer   ADIS 16488

Penguin navigation payload: Two IMUs, optical camera, infrared camera, RTK GPS and embedded controller for data logging

Marine Craft

Marine craft: ships, high-speed craft, semi-submersibles, floating rigs, submarines, remotely operated and autonomous underwater vehicles, torpedoes and other propelled/powered structures for instance a floating air field.

Vehicles that do not travel on land (ocean and flight vehicles) are usually called craft.

Vessel: "hollow structure made to float upon the water for purposes of transportation and navigation; especially, one that is larger than a rowboat ".

The words vessel, ship and boat are often used interchangeably. In Encyclopedia Britannica, a ship and a boat are distinguished by their size through the following definition:

Ship: "any large floating vessel capable of crossing open waters, as opposed to a boat, which is generally a smaller craft. The term formerly was applied to sailing vessels having three or more masts; in modern times it usually denotes a vessel of more than 500 tons of displacement.

Submarine: "any naval vessel that is capable of propelling itself beneath the water as well as on the water's surface.

Underwater Vehicle: "small vehicle that is capable of propelling itself beneath the water surface as well as on the water's surface. This includes unmanned underwater vehicles (UUV), remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV).

Marine Craft

Marine vessels are also classified according to their maximum operating speed. For this purpose it is common to use the Froude number

$$F_n := \frac{U}{\sqrt{gL}}$$

U: ship speed
L: overall (submerged length of the ship)
G: acceleration of gravity

The pressure carrying the vessel can be divided into hydrostatic and hydrodynamic pressure. The corresponding forces are:

- Buoyancy force due to the hydrostatic pressures (proportional to the displacement of the ship)

- Hydrodynamic force due to the hydrodynamic pressure (approximately proportional to the square of the speed)
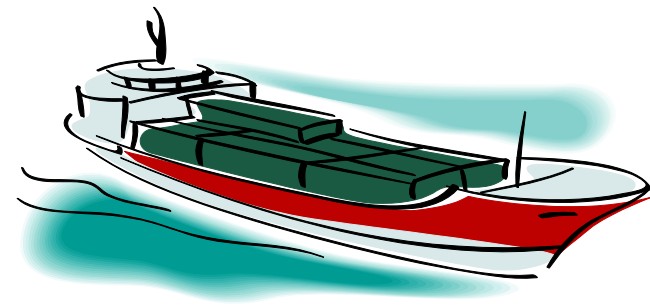
In this course, only displacement vessels are covered

Then we can classify the vessels according to (Faltinsen 2005):

- Displacement vessels (Fn<0.4): The buoyancy force dominates .
- Semi-displacement vessel (0.4-0.5<Fn>1.0-1.2):
  The buoyancy force is not dominant at the maximum operating speed.
- Planning vessels (Fn>1.0-1.2): The hydrodynamic force mainly carries the weight.

Classification of Models
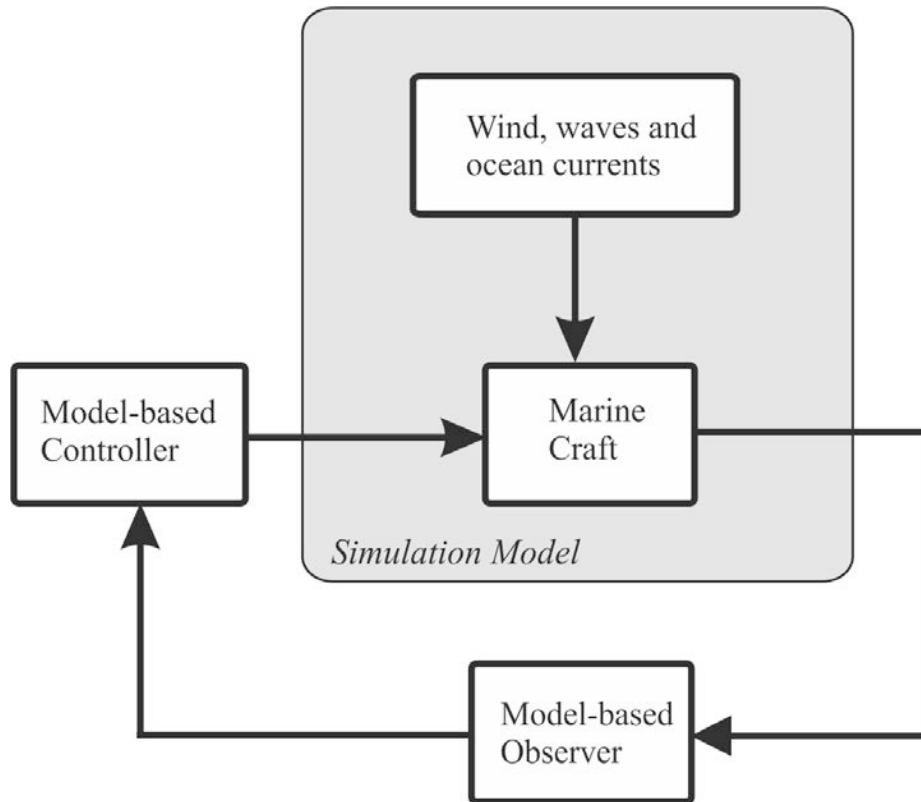
Simulation Model: This model is the most accurate description of a system, for instance a 6-DOF high-fidelity model for simulation of coupled motions in the time domain.

Control Design Model: The controller model is a reduced-order or simplified simulation model that is used to design the motion control system. In its simplest form, this model is used to compute a set of constant gains for a PID controller.

Observer Design Model: The observer model will in general be different from the model used in the controller since the purpose is to capture the additional dynamics associated with the sensors and navigation systems as well as disturbances.

The Classical Models in Naval Architecture

The motions of a marine craft exposed to wind, waves and ocean currents are usually modeled in 6 DOF by applying Newton's 2nd law:

$$m[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})] = X$$

$$m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) + x_g(qp + \dot{r})] = Y$$

$$m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(rp - \dot{q}) + y_g(rq + \dot{p})] = Z$$

$$I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy}$$
$$+ m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = K$$

$$I_y\dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz}$$
$$+ m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] = M$$

$$I_z\dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx}$$
$$+ m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] = N$$

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The Classical Models in Naval Architecture

The external forces and moments X,Y,Z,K,M and N acting on a marine craft are usually modeled by using:

Maneuvering Theory: The study of a ship moving at <u>constant positive speed U</u> in <u>calm water</u> within the framework of maneuvering theory is based on the assumption that the hydrodynamic coefficients are frequency independent (no wave excitation).

The zero-frequency assumption is only valid for surge, sway and yaw since the natural period of a PD controlled ship will be in the range of 100-150 s.
For 150 s this gives

$$\omega_n = \frac{2\pi}{T}$$
$$\approx 0.04 \ rad/s$$

Seakeeping Theory: The motions of ships at <u>zero or constant speed</u> in <u>waves</u> can be analyzed using seakeeping theory where the hydrodynamic coefficients and wave forces are computed as a function of the wave excitation frequency using the hull geometry.

Fossen's Robot-Inspired Model for Marine Craft

In Fossen (1991) the robot model:

$$\mathbf{M(q)\ddot{q}} + \mathbf{C(q,\dot{q})q} = \boldsymbol{\tau}$$

- **q** is a vector of joint angels
- $\boldsymbol{\tau}$ is a vector of torque
- **M** and **C** are the system inertia and Coriolis matrices

was used as foundation to write the 6-DOF marine craft equations of motion in a compact vectorial setting.

Matrix-Vector Representation

The robot model was modified to describe marine craft according to:

$$\mathbf{M\dot{v}} + \mathbf{C(v)v} + \mathbf{D(v)v} + \mathbf{g(\eta)} + \mathbf{g}_0 = \boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave}$$

- body-fixed velocities: $\boldsymbol{\nu} = [u, v, w, p, q, r]^\top$
- position and Euler angles $\boldsymbol{\eta} = [x^n, y^n, z^n, \phi, \theta, \psi]^\top$
- **M, C** and **D** denote the system inertia, Coriolis and damping matrices
- **g** is a vector of gravitational and buoyancy forces and moments

Degrees of Freedom (DOF)

DOF		Forces and moments	Linear and angular velocities	Positions and Euler angles
1	motions in the x-direction (surge)	X	u	x^n
2	motions in the y-direction (sway)	Y	v	y^n
3	motions in the z-direction (heave)	Z	w	z^n
4	rotation about the x-axis (roll)	K	p	ϕ
5	rotation about the y-axis (pitch)	M	q	θ
6	rotation about the z-axis (yaw)	N	r	ψ

For a marine craft, DOF is the set of independent displacements and rotations that completely specify the displaced position and orientation of the craft. A craft that can move freely in the 3-D space has maximum 6 DOFs—three translational and three rotational components.

Consequently, a fully actuated marine craft operating in 6 DOF must be equipped with actuators that can produce independent forces and moments in all directions.
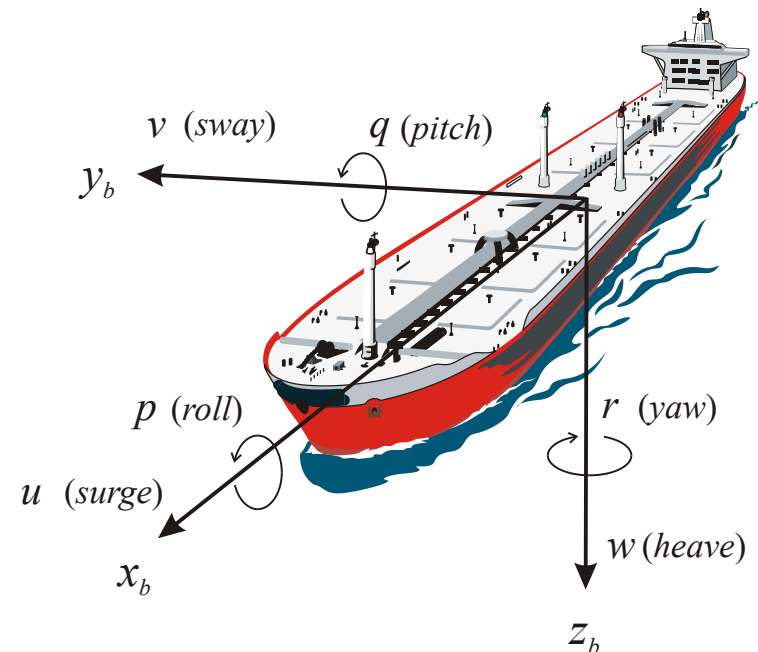
Degrees of Freedom (DOF)

When designing feedback control systems for marine craft, reduced-order models are often used since most vehicles do not have actuation in all DOF. This is usually done by decoupling the motions of the vessel according to:

1-DOF models can be used to design forward speed controllers (surge), heading autopilots (yaw) and roll damping systems (roll).

3-DOF models are usually horizontal-plane models (surge, sway and yaw) for ships, semi-submersibles and underwater vehicles that are used in DP systems, trajectory-tracking control systems and path-following systems. For slender bodies such as torpedo-shaped AUVs and submarines, it is also common to assume that the motions can be decoupled into longitudinal and lateral motions.

- Longitudinal models (surge, heave and pitch) for forward speed, diving and pitch control.
- Lateral model (sway, roll and yaw) for turning and heading control.

4-DOF models (surge, sway, roll and yaw) are usually formed by adding the roll equation to the 3-DOF horizontal-plane model. These models are used in maneuvering situations where the purpose is to reduce roll by active control of fins, rudders or stabilizing liquid tanks.

6-DOF models (surge, sway, heave, roll, pitch and yaw) are fully coupled equations of motion used for simulation and prediction of coupled vessel motions. These models can also be used in advanced control systems for underwater vehicles, which are actuated in all DOF.