Chapter 9 – Introduction

9.1 Historical Remarks
9.2 The Principles of Guidance, Navigation and Control
9.3 Setpoint Regulation, Trajectory-Tracking and Path-Following
9.4 Control of Underactuated and Fully Actuated Craft

Part II of the book deals with the design of model-based GNC systems.

The theory and cases studies are organized as four independent chapters:

• **Chapter 10: Guidance Systems:**
  Systems for automatically guiding the path of a marine craft, usually without direct or continuous human control.

• **Chapter 11: Sensor and Navigation Systems:**
  Systems for determination of the craft's position/attitude, velocity and acceleration.

• **Chapter 12: Motion Control Systems:**
  PID design methods for automatic control of position/attitude, velocity and acceleration. This involves control systems for stabilization, trajectory-tracking and path-following control of marine craft.

• **Chapter 13: Advanced Motion Control Systems:**
  Design of advanced motion control systems using optimal and nonlinear control theory.
9.2 The Principles of Guidance, Navigation and Control

A motion control system is usually constructed as three independent blocks denoted as the guidance, navigation and control (GNC) systems. These systems interact with each other through data and signal transmission.

In the figure, the guidance system makes use of the estimated alternatively measured positions and velocities. This is referred to as a closed-loop guidance system while a guidance system that only use reference feedforward (no feedback) is an open-loop guidance system.
9.2 The Principles of Guidance, Navigation and Control

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

The basic components of a guidance system are:

- Motion sensors
- External data such as weather data (wind speed/direction, wave height/slope, current speed/direction)
- Computer

The computer collects and processes the information, and then feeds the results to the motion control system. In many cases, advanced optimization techniques are used to compute the optimal trajectory or path for the marine craft to follow. This might include sophisticated features such as fuel optimization, minimum time navigation, weather routing, collision avoidance, formation control and synchronization.
Navigation is the science of directing a craft by determining its position/attitude, course and distance traveled.

In some cases velocity and acceleration are determined as well. This is usually done by using a global navigation satellite system (GNSS) combined with motion sensors such as accelerometers and gyros.

The most advanced navigation system for marine applications is the inertial navigation system (INS).

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. The skill is even more ancient than the word itself, and it has evolved over the course of many centuries into a technological science that encompasses the planning and execution of safe, timely, and economical operation of ships, underwater vehicles, aircraft and spacecraft.
9.2 The Principles of Guidance, Navigation and Control

Control, or more specifically motion control, is the action of determining the necessary control forces and moments to be provided by the craft in order to satisfy a certain control objective. The desired control objective is usually seen in conjunction with the guidance system.

Examples of control objectives are:

- Minimum energy
- Setpoint regulation
- Trajectory-tracking control
- Path-following control
- Maneuvering control

Constructing the control algorithm involves the design of feedback and feedforward control laws. The outputs from the navigation system, position, velocity and acceleration, are used for feedback control while feedforward control is implemented using signals available in the guidance system and other external sensors.
9.3 Setpoint Regulation, Trajectory-Tracking and Path-Following Control

When designing motion control systems, the control objective must be well defined in order to satisfy the requirement specifications for safe operation of the craft.

It is important to distinguish between the following three important control objectives:

- **Setpoint Regulation**: The most basic guidance system is a constant input or setpoint provided by a human operator. The corresponding controller will then be a regulator. Examples of setpoint regulation are constant depth, trim, heel and speed control. It could also be regulation to zero (stationkeeping).
- **Trajectory-Tracking Control**: The position and velocity of the marine craft should track desired time-varying position and velocity reference signals. The corresponding feedback controller is a trajectory-tracking controller. Tracking control can be used for course-changing maneuvers, speed-changing and attitude control.
- **Path-Following Control**: This is to follow a predefined path independent of time (no temporal constraints). Moreover no restrictions are placed on the temporal propagation along the path. This is typical for ships in transit between continents or underwater vehicles used to map the seabed.
9.4 Control of Underactuated and Fully Actuated Craft

When designing motion control systems for marine craft, it is important to distinguish between:

- Underactuated Marine Craft
- Fully Actuated Marine Craft

It is trivial to control a fully actuated marine craft while underactuation puts limitations on what control objectives that can be satisfied.

Definition 9.1 (Degrees of Freedom (DOF))

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. When simulating the motion of such a craft, a total of 12 ODEs are needed since the order of the system is:

\[
\text{order} = 2 \times \text{DOF}
\]
9.4.1 Configuration Space

Control systems for underactuated and fully actuated marine craft are designed by defining a workspace in which the control objective is specified.

**Definition 9.2 (Configuration Space)**

The $n$-dimensional configuration space is the space of possible positions and orientations that a craft may attain, possibly subject to external constraints.

The configuration of a marine craft can be uniquely described by an $n$-dimensional vector of generalized coordinate—that is, the least number of coordinates needed to specify the state of the system.

If there exists $k$ geometric constraints:

$$h_i(\eta) = 0 \quad i = 1, \ldots, k$$

the possible motions of the craft is restricted to an $(n-k)$-dimensional submanifold.
9.4.1 Configuration Space

Example 9.1 (6 DOF Motions) For a marine craft operating in 6 DOF, the displacements and rotations are described by \( n = 6 \) generalized positions and velocities:

\[
\eta = [x, y, z, \phi, \theta, \psi]^T \in \mathbb{R}^3 \times S^3 \\
\nu = [u, v, w, p, q, r]^T \in \mathbb{R}^6
\]

where the Euler angles \( \phi, \theta \) and \( \psi \) are defined on the interval \( S = [0, 2\pi] \). Thus the order of the system is 12. This is typically the case for underwater vehicles.

Example 9.2 (3 DOF Motions) For a marine craft restricted to operate in the horizontal plane (surge, sway and yaw), \( n = 3 \) generalized positions and velocities:

\[
\eta = [x, y, \psi]^T \in \mathbb{R}^2 \times S \\
\nu = [u, v, r]^T \in \mathbb{R}^3
\]

are needed to describe the motions. Thus the order of the system is 6. This is typically the case for ships and offshore rigs.
9.4.1 Configuration Space

**Definition 9.3 (Underactuated Marine Craft)**
A marine craft is underactuated if it has less control inputs than generalized coordinates \( r < n \)

**Definition 9.4 (Fully Actuated Marine Craft)**
A marine craft is fully actuated if it has equal or more control inputs than generalized coordinates \( r \geq n \)

From this follows that a marine craft which operates in \( n \) DOF has a configuration space of dimension: \( \text{dim}(\eta) = n \)

– If the craft only has actuators in surge, sway and yaw, the craft is underactuated in sense of operation in 6 DOF while the design of a motion control system for the horizontal plane motion (DP system) can be achieved using only three control inputs.

– Underwater vehicles that have actuators that produces independent forces and moments in 6 DOF are fully actuated.

**Formulate the control objective in a workspace of dimension** \( m < n \) **instead of the** \( n \) **dimensional space. Hence, only** \( m \) **actuators are needed.**
9.4.2 Workspace and Control Objectives

Definition 9.5 (Workspace)

The workspace is a reduced space of dimension \( m < n \) in which the control objective is defined.

- The workspace of a conventional heading autopilot system is \( m = 1 \) since only the yaw motion is controlled.
- The workspace of a horizontal plane controller, for instance a DP system controlling the motions in surge, sway and yaw, is \( m = 3 \)

If \( r \) is the number of independently controlled actuators spanning different directions in the \( n \)-dimensional configuration space, then:

- **Full actuation** means that independent control forces and moments are simultaneously available in all directions. Moreover, all positions in the configuration space have actuation such that \( r = n \)
- An **underactuated marine craft** has independent control forces and moments in only some DOF. Moreover, \( r < n \). Stabilizing and tracking controllers for underactuated craft are usually designed by considering a workspace of dimension \( r < n \) satisfying \( m = r \) (fully actuated in the workspace but not in the configuration space)
- **Underactuated control** is a technical term used in control theory to describe a motion control system for a craft that is underactuated in the workspace \( (r < m) \). To design a control system that achieves stabilization, trajectory-tracking and path-following control for this case is nontrivial and NOT used in practical systems. Hence, this is not discussed in this book.
9.4.2 Workspace and Control Objectives

Example 9.3 (Path-Following Control) Consider an underactuated craft in the horizontal plane with actuation in surge and yaw (no actuation in sway). A path-following control system is usually designed by using feedback from the heading angle $\psi$ and surge velocity $u$. Then it is possible to control the speed of the craft along the path using a speed controller and at the same time force the craft onto the path using a heading controller producing rudder commands. The workspace of this system is $m = 2$ while the motions in surge, sway and yaw corresponds to a configuration space of dimension three ($n = 3$). Consequently,$$
m < n$$and only two controls ($r = 2$) are needed to satisfy the path-following control objective. However, the uncontrolled sway equation introduces a constraint representing the sway dynamics of the craft. This equation must be stable in order for the overall system to be stable (Fossen et al., 2003b).

Example 9.4 (Dynamic Positioning) Consider a fully actuated craft operating in the horizontal plane with actuation in surge, sway and yaw ($r = 3$). A dynamic positioning system can be designed by using feedback from the position $(x, y)$ and the heading angle $\psi$. The dimension of the workspace is $m = 3$ and the dimension of the configuration space is $n = 3$. Hence, $m = n = r$ and it is straightforward to control $(x, y, \psi)$.
9.4.3 Weathervaning of Underactuated Craft in a Uniform Force Field

Marine craft are usually controlled in surge, sway and yaw by using three controls. However, unlike wheeled cars and other craft operating on the surface of the Earth, it is possible to stabilize the positions of a marine craft by means of two controls.

The main reason for this is that marine craft are exposed to drift forces generated by waves, wind and ocean currents. This means that the equations of motion are forced.

For stationkeeping, it is common to assume that the drift forces are slowly varying such that the resulting component due to wind, waves and ocean currents can be treated as a constant uniform force. Hence, a marine craft can be modeled as a rigid-body operating in a unified force field similar to a pendulum in the gravity field (Fossen and Strand 2001).
9.4.3 Weathervaning of Underactuated Craft in a Uniform Force Field

It is possible to stabilize a marine craft in a uniformed force field using only two controls \((r = 2)\) even though the configuration space of the craft is surge, sway and yaw \((m = 3)\).

The Beauty of Weathervaning

- Use one controller to compensate for the drift force that acts along the longitudinal axis of the body.
- Use one controller to align the craft to the force field. This is similar to a weathervane which is aligned to the force field created by the wind.

Motion control systems can be designed to behave such as a weathervane and they are used offshore for stationkeeping of supply vessels and tankers near floating structures in order to save energy.

The drawback is that stationkeeping using only two controls implies that the desired heading cannot be specified arbitrarily. Simultaneously control of the motions in surge, sway and yaw to arbitrarily values requires three controls.