Chapter 7
Autonomous Surface Vessels

7.1 Introduction

The control of surface vessels has been investigated by many researchers in the past decade. In most classical literature, the controllers have been designed to maintain the motion of a surface vessel on a linear course with a constant speed. These controllers are known as autopilots. They are meant to assist the vessel’s crew in controlling the vessel on long trips, and work similar to an automobile’s cruise control. The controllers have been used on large- and medium-size ships. However, they cannot be used for faster smaller surface vessels that must work autonomously, for which controllers capable of trajectory tracking are needed.

Designing controllers for fast surface vessels is challenging. Uncertainty in dynamic models, significant sea disturbances, underactuated dynamics, and lack of nonholonomic kinematic constraints are the issues that a designer must deal with while designing a robust controller for a surface vessel. The more accurate model of a surface vessel has six DOFs. It is common to simplify this model to a 3-DOF model that only reflects surge, sway, and yaw DOFs, the ones that have to be controlled by a trajectory-tracking controller. With this simplification, the model of a surface vessel seems similar to that of a mobile robot. However, there are strong reasons why these two are very different and have to be treated differently.

- The dynamic rather than the kinematic model of the surface vessel must be used for designing the controllers. Because, first, forces and moments are the available physical control inputs. Second, a kinematic model alone cannot determine the lateral motion response of a surface vehicle due to the lack of a nonholonomic lateral motion constraint.
- A surface vessel has a nonlinear dynamic model. The controller development for a surface vessel may be simplified by using linearized models and the classical PID control methods. However, with linearized dynamic model and classical control methods, one can only prove the quality of performance of the controller for the maneuvers in which the state of the system is in the vicinity of the linearization state. Using nonlinear control theories, on the other hand, one can conclude about the quality of the system response for the full range of vessel’s motion.
• Since there is no constraint for the lateral motion of surface vessels, they can be categorized as holonomic systems. Also, a surface vessel has more DOFs than actuators. Therefore, surface vessels are considered as underactuated systems. This makes the controller design for such a system even a more challenging task. For a surface vessel as an underactuated holonomic system, due to the absence of the lateral motion constraint, the vessel’s orientation during its motion is not necessarily tangent to the motion path. Therefore, the stability of the zero dynamics of the vessel’s unactuated DOF needs rigorous proof based on the vessel’s dynamic model.

These three problems, which are specific to the control of surface vessels, are addressed in this chapter. First, the 6-DOF dynamic model of a surface vessel is presented. This dynamic model is reduced to a 3-DOF model. Then, a control strategy based on the “control point” is presented, in which the unactuated dynamics of the vessel can be analyzed separately than the actuated DOFs. The inherent stability of the unactuated DOF is investigated. Next, two methods for trajectory-tracking controller design for a surface vehicle are introduced. These methods are the feedback linearization method and the robust sliding mode control. Finally, the problem of controlling multiple surface vessels simultaneously in group formation maneuvers is solved using a decentralized leader-follower approach.

7.2 Dynamics of a Surface Vessel

In this section, first, the 6-DOF dynamic model of a surface vessel is presented. The 6-DOF dynamic model is useful for simulating the motion of a surface vessel. However, for control development, a simpler 3-DOF model is more appropriate. Therefore, later in this section, the 6-DOF dynamic model is reduced to derive a 3-DOF model.

The six DOFs for a surface vessel consist of the three global position components of the center of mass of the vessel and three angles that define the orientation of the vessel’s body frame with respect to the inertial global frame. These six DOFs, which can uniquely define the configuration of the vessel at any instant in time, are accompanied by six generalized speed components, which define the dynamic state of vessel. These generalized speeds are defined in terms of the vessel’s body frame. They are the surge \(u\), sway \(v\), and heave \(w\) linear speeds, and the angular speeds about the longitudinal \(p\), transversal \(q\), and normal \(r\) axes.

For a surface vessel, normally there are two control inputs. The types of inputs depend on the drive train of the vessel. For example, two independent propellers can provide the driving force \(F\) and steering torque \(T\) for the system. If the inertia of the vessel can be assumed to be constant, the vessel has an elliptical body, and the higher-order damping forces can be neglected, the following equations describe the dynamics of the vessel in the local coordinate system [32]: