Ship Maneuvering: The past, the present and the future

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Ship Maneuvering: Past, Present, and Future

In the past, ship steering systems were based on controlling the ship heading to a desired heading by the measurement of a gyrocompass. As new measurements are available as well as the knowledge of advanced nonlinear control techniques, it is today possible to perform much more complicated maneuvers by automatic control. This has and will continue to increase the functionality and reliability of commercially available automatic ship navigation systems. Maneuvering a ship along a desired path is the present challenge.

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Ship steering systems

Maneuvering a craft, vehicle, or vessel means that there are two coupled tasks to be performed to achieve the desired motion. The first is a *geometric task* stated in terms of a desired curve or path to be followed, and the second is a *dynamic task* given as a desired speed or, perhaps, acceleration along the path. For a ship in transit, the desired path will be some feasible curve connecting the departure point and the destination. This must be coupled to a dynamic objective which perhaps is to keep a constant desired cruise speed, or more advanced; a speed profile along the path constructed by optimizing fuel economy versus time constraints.

A flashback on the history of automatic ship steering

Automatic steering of ships started with the invention of the gyrocompass. Based on the earlier developed gyroscope, Dr. Anschütz-Kaempfe (1872-1931) patented the first north seeking gyrocompass in 1908. This work had attracted considerable attention from engineers around the world, and already the same year Elmer Sperry (1860-1930) introduced the first ballistic gyrocompass which subsequently was patented in 1911; see [1], [2], and [3]. Soon thereafter, Sperry designed an automatic pilot, the gyropilot, for automatic steering of ships. This was first commercially available in 1922, and it "had been christened 'Metal-Mike' by the officers of the ship *Moffett*, …, and the performance of 'Metal-Mike' seemed uncanny to many because it apparently had built into the 'intuition' of an experienced helmsman" [2].

The gyropilot, today known as a conventional autopilot, is a single-input single-output (SISO) control system where the heading, measured by the gyrocompass, is regulated to a desired heading by corrective action of the rudder. In spite of the relatively simple ship model the autopilot controller is based on, it has had great success for many years. However, with the introduction of new measurement systems, in particular the global positioning system (GPS), and the need to perform more advanced maneuvers with a ship motivated creative thinking which opened new possibilities and directions of research. Preeminently, this resulted in *dynamical positioning* (DP) systems which were first designed in the 1960s by three decoupled *proportional-integral-derivative* (PID) controllers.

A DP system is a multiple-input multiple-output (MIMO) control system where 3 degrees-of-freedom (3DOF), that is, surge, sway, and yaw, are controlled by a number of azimuth and tunnel thrusters. The model-based DP controller uses an advanced nonlinear hydrodynamic ship model, derived from first principles, which is simplified to a linear model for almost zero speed applications. Building on the extensive theory generated by the DP research community, the research on ship steering is now going in the direction of high-speed tracking of desired moving position references; see e.g. [4]. This leads to the theory of *maneuvering* which, as briefly explained above, incorporates a *desired feasible path* to be followed and a *desired speed* along it; see [5-9].

Maneuvering a ship

In a conventional way-point tracking system, only the heading is controlled to take the ship from one way-point to the next, perhaps using a *line-of-sight* (LOS) algorithm. The easiest way to make this problem into a path following problem is to connect the straight line segments between the way-points by inscribed circles; see Figure 1. Indeed, as pointed out by numerous authors, the shortest distance path connecting two points consists of only straight lines and circular arc segments; see e.g. [10]. However, such a path is not feasible for a ship since at the point where the path switches from a straight line to a circular segment, the desired yaw rate would jump from zero to a nonzero constant. A feasible (and perhaps optimal in some sense) path between two points must be a curve which is at least two times differentiable.

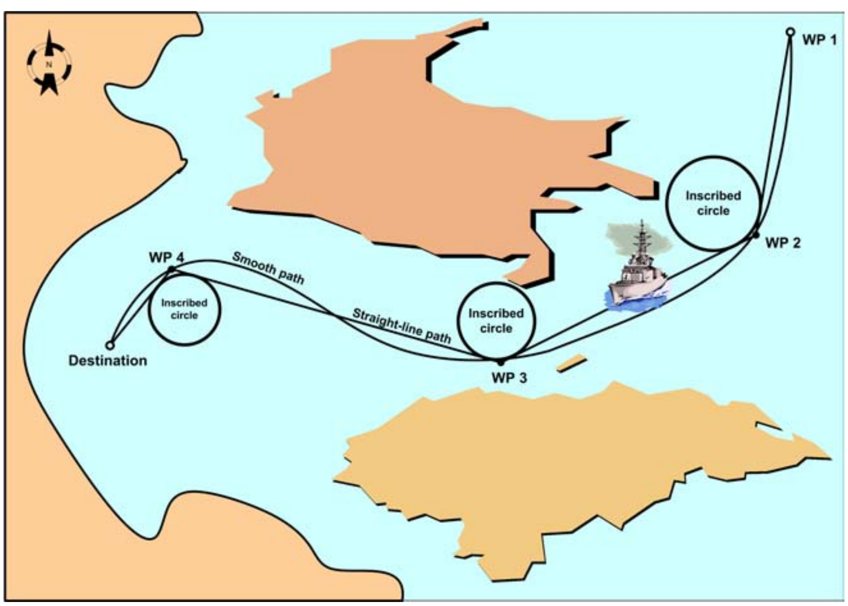

Figure 1: An example of a digital map where a path is constructed by straight-line segments and inscribed circles at the way-points. An alternative smooth path is also shown.

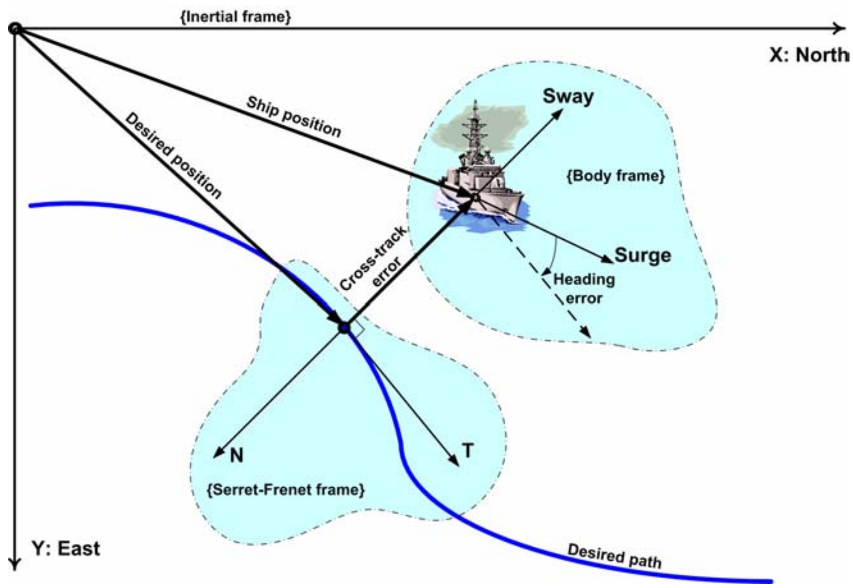

Figure 2: Shows a ship in the inertial frame, the desired path (blue line), and the corresponding Serret-Frenet frame in which the cross-track and heading deviations are found.

Feasibility of the path is a property of each ship, its minimum turning radius and its dynamic response. Not concerning us with the shape of the path in the process of control design, the objective in **The Maneuvering Problem** is; see [7]:

- ✓ **Geometric Task:** -force the ship to converge to and follow the desired path.
- ✓ **Dynamic Task:** -make the ship move at a desired velocity, either given as a speed profile along the path, or by inputs from the pilot.

The desired heading will ideally be pointed along the tangent vector of the path, but it can also be adjusted by an offset to compensate for ocean currents or 'weather' forces in order to facilitate "weather optimal" maneuvering. Numerous applications arise in this setup; cruising, docking, or formation (fleet) maneuvering to name a few.

Model-based Control for Higher Speed Maneuvering

Since maneuvering means controlling 3DOF, that is, both position and heading, present control theory requires in general at least three actuators producing force/moment in all degrees of freedom. However, by decomposing the position vectors in the *Serret-Frenet frame*, see Figure 2 and [5], it is possible to use only the rudder to eliminate the cross-track deviation from the path as well as keeping the desired heading. The main propeller will independently ensure a desired surge velocity along the path.

The dynamic ship model

In autopilot designs, usually a linear 1st or 2nd order Nomoto model [1] relating the rudder command to the yaw mode is used with a PID controller to regulate the heading to a reference. In maneuvering applications also the position should be controlled, and this necessitates a more complex nonlinear model since, as opposed to DP, the simplification to a linear hydrodynamic model of the ship is not valid at higher speeds (except for the special case where the heading and cruise speed are kept constant). In fact, the maneuvering model will include both Coriolis and centripetal forces and nonlinear damping terms.

A general ship model [1,11] consists of a kinematic equation and a dynamic equation derived from rigid-body dynamics and hydrodynamic forces. The main complications of this model in high speed are:

- ✓ The system inertia matrix is nonsymmetric and depends, among others, on the wave dynamics and frequency of encounter.
- ✓ No unified representation of the damping forces has been agreed upon. It is also unclear how to represent shallow water and close boundary effects with respect to this model.
- ✓ The mapping between the actuators, that is, the propeller revolutions and pitch angle, the rudder angle, etc., and the forces/moment they produce is special to each ship. Hence, control allocation on a case by case basis is necessary.

In addition to these complications, the component form equations given by the kinematic and dynamic equations are very messy and therefore make component form analysis very hard.

If the mapping between the actuators, and the forces and moment they produce is onto, that is, for each desired force/moment vector in surge, sway, and yaw there exists an actuator-setting which will produce that vector value, then the ship is *fully actuated*. On the other hand, if there exist force/moment values (within a neighborhood of the operating point) which cannot be produced by the actuator system, then the ship is *underactuated*. For 3DOF maneuvering, we say, for simplicity, that the ship is fully actuated if it has 3 or more controls and underactuated if there is less.

Some proposed methods

A good method for solving the maneuvering problem for fully actuated ships and vessels has recently been proposed in [7]; see also [8,9] for a performance analysis and formation control application of this method. Research on using the same method for underactuated ships is currently in progress; see [12] for a case study. However, solving the maneuvering problem by applying the *Serret-Frenet equations* [13] is also a promising method and this was first demonstrated in [6] and later in [5].

A reasonable assumption on the dynamic model is that the ship is port-starboard symmetric which implies that the surge mode is decoupled from the sway and yaw modes. In this case, an independent control system can keep the ship at a constant desired surge velocity u_d by using the main propeller. This implies that the state u can be treated as a constant in the sway and yaw modes, which under some smallness assumptions, $v,r \approx 0$, then becomes a linear parametrically varying (LPV) model. This is the basis for the design in [5] where the LPV maneuvering model of Davidson and Schiff; see [1] for details, represents the sway/yaw dynamics.

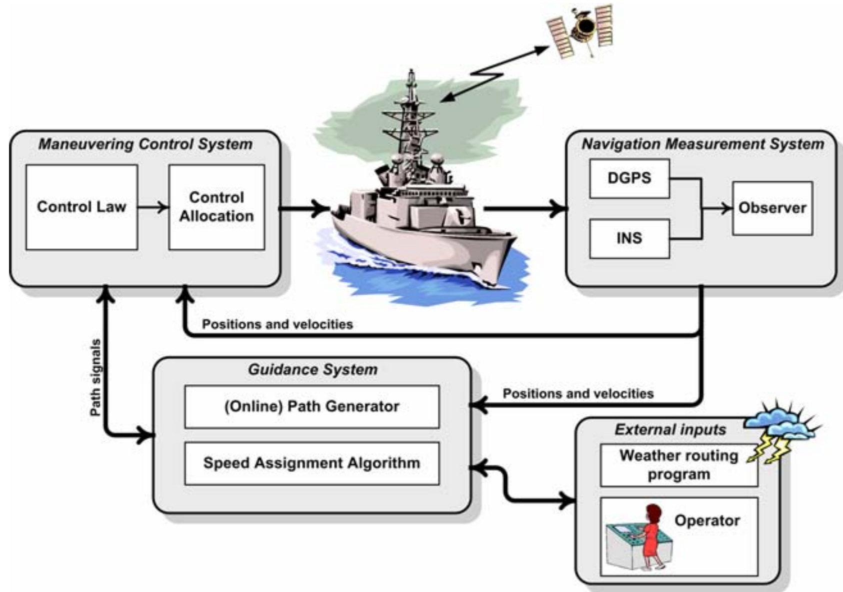

Figure 3: The closed-loop automatic navigation system which includes the measurement system, the guidance system with user interface, and the maneuvering controller.

The setup is this; given a desired feasible path, the cross-track and heading deviations are decomposed in the Serret-Frenet frame; see Figure 2. Then, the objectives are:

1. The surge velocity u is kept constant by some decoupled control system.
2. The rudder is used to regulate the cross-track deviation to zero while keeping the ship at the desired heading along the path.

The result is that the underactuated ship moves along the path with its preferred speed.

In [6] the authors presented a nonlinear control design for Objective 2 which included an estimator to deal with ocean currents. The model they used was not the Davidson and Schiff model which was the basis for the design in [5]. Here, the authors had to resort to both acceleration feedback and output redefinition to solve the same objective. In spite of the preliminary nature of these designs, they both indicate promising ideas towards the goal of a good, robust, and reliable maneuvering controller that can be implemented industrially.

A future challenge

Offshore operators have recently expressed a need for ship and vessel control systems which makes it possible to do offshore operations in extreme weather situations. Examples are station keeping in higher sea states, helicopter landing on ship decks in extreme weather, ROV operations in large waves, and robust maneuvering systems in extreme weather. This work must be rooted in both physical modeling, preferably based on first principles, control design, and an extensive experimental testing to validate the models and the closed-loop maneuvering performance; see [14].

At present, work is underway to identify and understand the hydrodynamic phenomena which occur in the ship model as the sea state increase. Once sufficient ship models has been established and agreed upon, the control engineers need to design robust maneuvering systems which can handle such extreme conditions. At our present knowledge, we are maneuvering ourselves on the path toward this goal.

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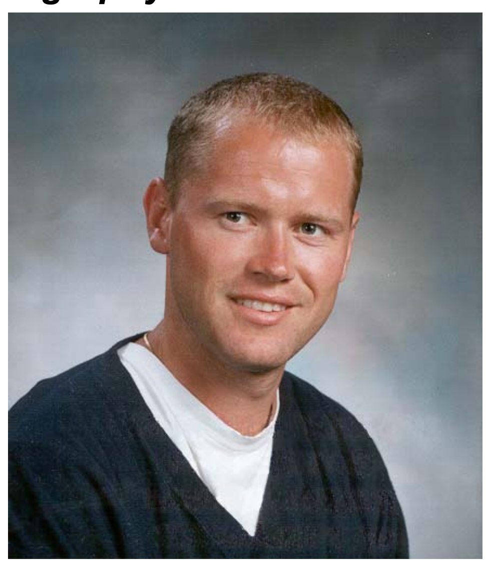
Biography



Roger Skjetne received in 2000 his B.S. and M.S. degrees in electrical and computer engineering from the University of California at Santa Barbara with emphasis on control theory and minor in digital signal processing. He is currently working toward the Ph.D. degree at the Norwegian University of Science and Technology at the Department of Engineering Cybernetics. His research interests are within guidance, navigation, and control of ocean vehicles, with emphasis on maneuvering control theory.

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