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Recent Developments in Ship Control Systems Design

The application of the latest results in guidance, navigation and control (GNC) provides the ship owners with highly sophisticated ship control systems with increased functionality, reliability and a large number of automatic modes.

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Thanks to the development of low-cost satellite navigation systems, new and improved sensor, communication and computer technology, digital charts and electronically available weather forecasts it is now possible to design and implement a new generation of multipurpose GNC system on a micro PC onboard a ship. A multipurpose GNC system could include automatic modes for:

- Course-keeping and course-changing manoeuvres (conventional auto-pilot)
- Way-point tracking control using digital charts and weather data
- On-line way-point generation (re-planning) and collision avoidance
- Automatic docking systems
- Dynamic positioning (station-keeping)
- Weather vaning or weather optimal control
- Fin and rudder roll stabilisation
- Supervisory control and mission planning

Functionality like dynamic positioning requires that the ship is equipped with thrusters or propellers such that the ship can be controlled in 3 degrees of freedom (DOF) simultaneously, that is surge, sway and yaw. Similarly, fins and/or rudders aft of the ship are needed for effective roll damping. Notice that a conventional ship with main propellers, rudders or water jets can only obtain auto-pilot and way-point tracking functionality.

A brief history of automatic steering of ships

The first recorded construction of the gyroscope is usually credited to C. A. Bohnenberger in 1810 while the first electrically driven gyroscope was demonstrated in 1890 by G. M. Hopkins, see Allensworth [1]. The development of the electrically driven gyroscope was motivated by the need of more reliable navigation systems for steel ships and underwater warfare. A magnetic compass as opposed to a gyro compass is highly sensitive for magnetic disturbances, which are easily generated within steel ships and submarines, equipped with electrical devices. In parallel works, Dr. H. Anschutz of Germany and Elmer Sperry of the USA both worked on a practical application of the gyroscope. In 1908 Dr. H. Anschutz patented the first North seeking gyrocompass while Elmer Sperry was granted a patent for his ballistic compass including vertical damping three years later.

The work on the gyrocompass was further extended to ship steering and closed-loop control by Elmer Sperry (1860-1930) who constructed the first automatic ship steering mechanism in 1911, see Allensworth [1] and Bennet [2]. This device is refereed to as the ”*Metal Mike*” and it was capturing much of the behaviour of a skilled pilot or a helmsman. ”*Metal Mike*” did compensate for varying sea states using feedback control and automatic gain adjustments. Later in 1922, Nicholas Minorsky (1885-1970) presented a detailed analysis of a position feedback control system where he formulated a *three-term* control law which today is refereed to as *Proportional-Integral-Derivative* (PID) control, see Minorsky [5]. Observing the way in which a helmsman steered a ship motivated these three different behaviours. In Bennet [2] there is an

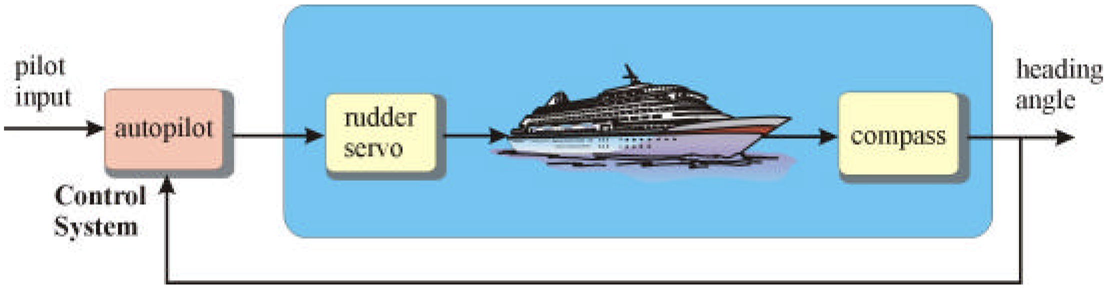

Figure 1. The conventional auto-pilot viewed as a feedback control system.

interesting discussion on the work of Sperry and Minorsky and their contributions to auto-pilot design.

Modern auto-pilot systems

The auto-pilot systems of Sperry and Minorsky were both single-input single-output (SISO) control systems where the heading (yaw angle) of the ship is measured by a gyro compass. Today this signal is fed back to a computer in which a PID control system (autopilot) is implemented in software. The auto-pilot compares the pilot set-point (desired heading) with the measured heading and computes the rudder command which is transmitted to the rudder servo for corrective action. This is illustrated in Figure 1.

The main difference between the auto-pilot systems of Sperry and Minorsky and the modern auto-pilot is that increased functionality has been added and sophisticated features like:

- Wave filtering; avoid that 1st-order wave disturbances are fed back to the actuators.
- Adaptation to varying environmental conditions, shallow water effects and time-varying model parameters e.g. changes in mass and centre of gravity.
- Wind feedforward for accurate and rapid course-changing manoeuvres.
- Reference feedforward using a dynamic model for course changing. The motivation for this is to avoid overshoots for large set-point changes for instance by defining a three phase manoeuvre: (1) acceleration, (2) turning at constant yaw rate and (3) de-acceleration to zero yaw rate.

It is beneficial to test new control algorithms by using hardware in the loop simulations, rapid prototyping and experiments with model ships. A GNC-laboratory for rapid prototyping of ship control systems has recently been established at the Norwegian University of Science and Technology, see Fossen [4]. In this laboratory Matlab/Simulink is used to construct and test new control algorithms. The control law is automatically downloaded as c-code on a PC controlling the model ship. The experimental set-up and results from this work is described more closely in [4].

Way-point tracking control systems

The conventional auto-pilot system can be modified to follow a pre-defined path by using position feedback in addition to feedback from the yaw angle.

The path or trajectory is constructed by using a set of way-points, which can be generated automatically from weather data (minimum resistance or energy approach), or given manually as pilot inputs. An advanced way-point tracking control system can be viewed as a *three-level hierarchical system*, see Fossen [4, 5]:

1. Weather routing system using electronically wind, wave, current and collision data.
2. Guidance system constructing way-points and reference trajectories.
3. Way-point tracking control and navigation systems.

Most commercial products have the functionality of the 2nd and 3rd levels while the success of implementing the weather routing system (level 1) depends on the accuracy of

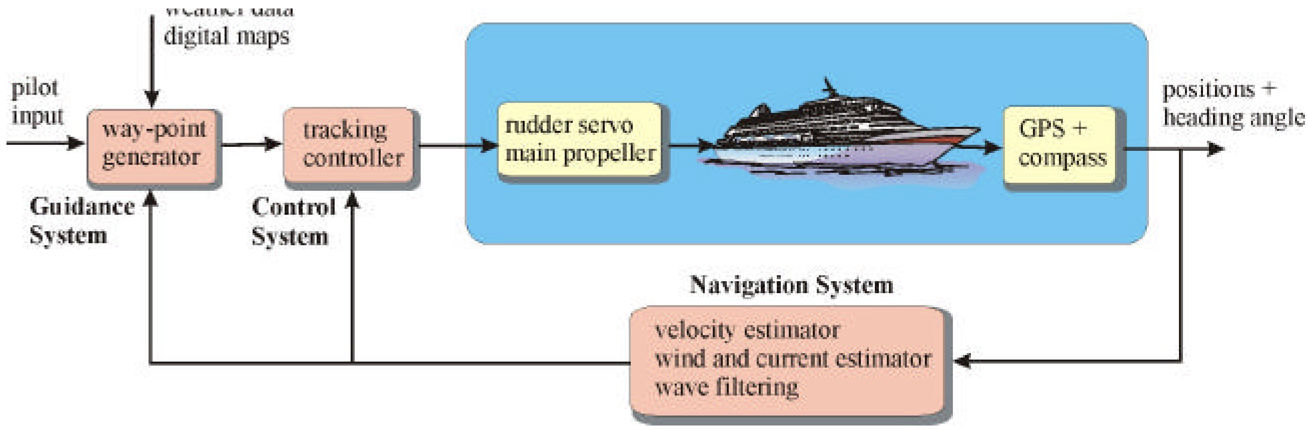

Figure 2. Guidance, navigation and control system for way-point tracking.

weather forecasts/measurements and ship/hull resistance computations. This is currently an active field of research.

Dynamic positioning (DP) systems

The conventional auto-pilot is a SISO (single-input single-output) control system in the sense that the heading (yaw angle) of the ship is measured by a gyro compass and fed back to a PID control system (auto-pilot). The auto-pilot compares the pilot set-point (desired heading) with the measured heading and transmits a command to the rudder servo. Hence, only one actuator (rudder) is needed to control the yaw mode.

Station-keeping or DP implies that the surge, sway and yaw modes of the ship must be controlled simultaneously by means of three of more actuators. Hence, we have a MIMO (multiple-inputs multiple-outputs) control system. In order to maintain the position of the ship at low speed the ship must be equipped with main propellers in combination with azimuthing thrusters and/or tunnel thrusters. This is necessary since fins and rudders have limited effect at low speed.

For navigation it is common to use differential GPS in combination with roll and pitch angles measurement so that the GPS positions can be computed at the location of the GPS antenna and the ship centre of gravity. DP systems have been widely used for supply vessels and offshore rigs since the 1970s, see Fossen [4, 5].

Today low cost DP systems can be designed for smaller vessels like yachts by using the latest products in computer and communication technology.

Weather optimal positioning control systems

An exotic extension of the classical DP system is weather optimal positioning control (WOPC) systems.

In 1998 a new concept for WOPC was patented by ABB. This system keeps the ship on a constant position while the heading of the ship is automatically rotated until there are no environmental loads on the ship in the transverse (sway) direction and the yaw moment is zero. Moreover, the ship is orientated such that the resulting mean forces due to wind, waves and currents attacks the ship in the bow (surge direction). This is done by copying the dynamics of a pendulum in the gravity field where gravity is considered to be an unknown force moving the pendulum to its equilibrium position.

Similarly, a ship can be constrained to move on a *virtual circle* until it balances the environmental forces, see Figure 3. Notice that the ship moves on *virtual circle* and that there is no cable connecting the ship to the circle origin. At the same time as the ship rotates the circle centre is translated such that the ship maintains a constant position during the operation. Hence, the pilot only observes a slowly-varying change in heading as the weather conditions change and no change in position.

The main motivation for WOPC is the fuel saving potential during station-keeping.

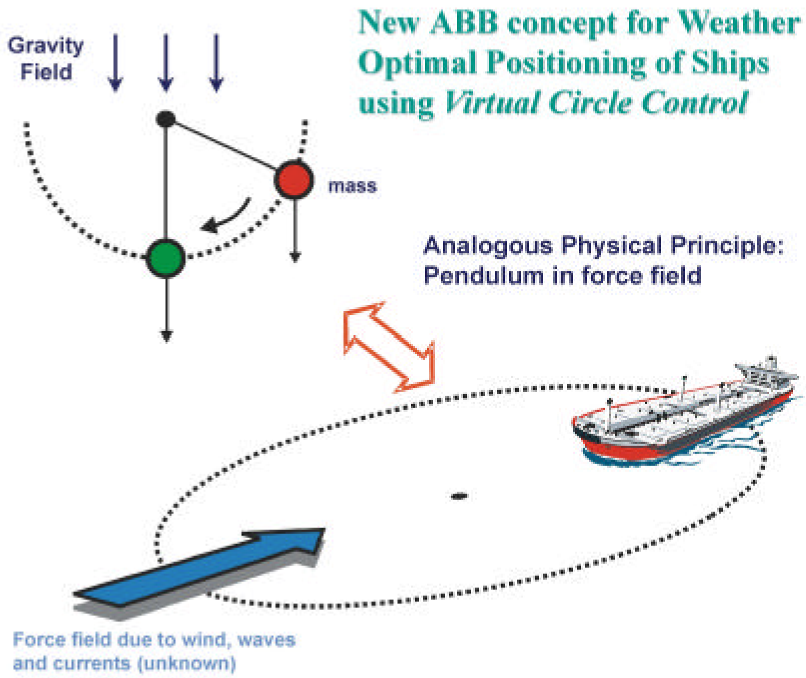

Figure 3. Analogy between a pendulum in the gravity field and weather optimal positioning.

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Biography

Thor I. Fossen is a Professor of Guidance, Navigation and Control at the Norwegian University of Science and Technology and Scientific Advisors for ABB Industri and Marintek.

Fossen has participated in several industrial projects with ABB including dynamic positioning systems, identification of ship dynamics and DGPS/INS navigation systems. This also includes a patent on weather optimal positioning control for marine vessels.

Fossen is the author of the book "Guidance and Control of Ocean Vehicles" (Wiley, 1994).