Chapter 4

An Overview about Dynamic Positioning of Ships

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A ship is continuously exposed to environmental disturbances. The objective of a Dynamic Positioning System is to maintain the desired position and heading applying adequate propeller thrust and without using device as anchor. Dynamic Positioning can be described as an integration of a number of shipboard systems to obtain the ability of accurate maneuverability.

1. INTRODUCTION

Dynamic Positioning System (DPS) is the system to automatically keep ship or offshore structure at the fixed position with the thrust of propeller or thruster and without using such fixing device as anchor.

Dynamic positioning may either be absolute in that the position is locked to a fixed point over the bottom, or relative to a moving object like another ship. One may also position the ship at a determined angle towards wind and waves.

DPS have been commercially available since the 1960s, and today a DP system is a natural component in the delivery of many new vessels. The first ship to fulfil the accepted definition of dynamic positioning was the “Eureka” (1961), of about 450 tons displacement and length 130 feet. This ship was fitted with an analogue control system, interfaced with a taut wire reference. Equipped with steerable thrusters fore and aft in addition to her main propulsion.

In 1980 the number of Dynamic positioning capable ships was about 65, in 1985 the number had increased to about 150. Currently it stands at over 1.000 and is still expanding.

It is interesting to note the diversity of ships types and functions using Dynamic Positioning. A list of activities include: coring, platform supply, shuttle tanker offtake, floating production, heavy lift cargo transport, exploration drilling, production drilling, diver support, pipeline, rocket launch platform positioning, repair/maintenance support to military vessels, ship-to ship transfer, manoeuvring conventional ships cable lay and repair, pre and post operational survey, multi-role, accommodation services, hydrographic survey, wreck survey, savage and removal, dredging, rockdumping, subsea installation, lifting, well simulation and workover, passenger cruises, mine countermeasures, oceanographical research, and seabed mining.

The Dynamic Positioning Systems have become more sophisticated and complicated, as well as more reliable.

The DPS development came in the mid 1970's with the application of Kalman filters and linear quadratic optimal controllers. These systems were computationally demanding compared to the computer resources then available [1-7]. In the 1990's a renewed interest for the subject was shown by the application of alternative control strategies; designs based on H∞-control was introduced [8,9], controller minimising self-induced rolling and pitching were proposed [10], and control strategies based on non-linear methods were suggested [11-13]. The non-linear techniques developed for dynamic positioning in [14] were successfully applied to a full scale turret-anchored FPSO. In [15] was showed a two-layered controller for moored ships dedicated to minimise a general cost function punishing important operational parameters such as rolling, riser traction and fuel consumption.

In general, depending on the supported functionality we may crudely divide dynamic positioning market into two segments: an high-end market demanding tailor-made solutions and high operational safety; and in the other end, there are lightweight systems offering a selection of the functionality available in the high-end brand. These systems typically offer simple station keeping functionality, course-keeping auto-pilots, and manual control.

The advantages of fully DP operated ships are the ability to operate in deep-water, the flexibility to quickly establish position and leave location, and to start up in higher sea states than if a mooring system should be connected.

2. BASIC PRINCIPLES OF DYNAMIC POSITIONING

A Dynamic Positioning Systems can be described as an integration of a number of shipboard systems to obtain the ability of accurate manoeuvrability. The main functions performed by a DPS are showed in Figure 1. The position and heading of ship are estimated based on the ship model, the position and heading measurements, and the forces acting on the ship. The control commands to the thrusters are calculates based on the difference between the desired position and heading and the estimated position and heading. The thrusters provide the necessary forces to counter the external forces and moment acting on the ship

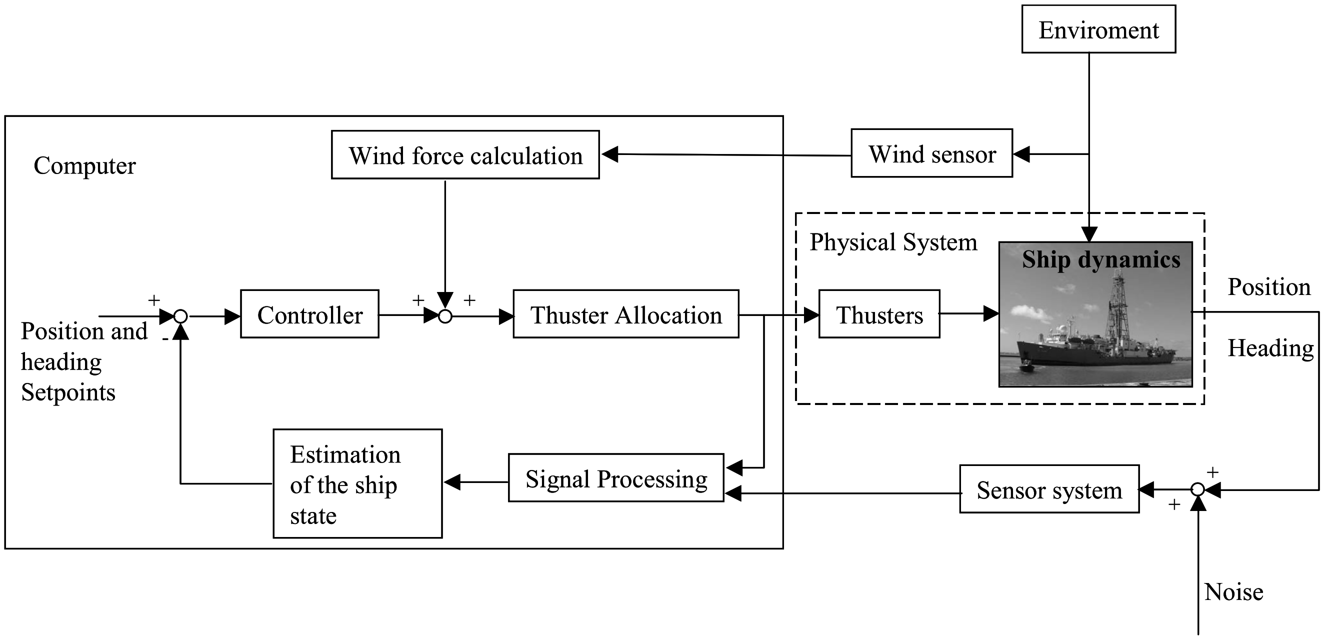

Figure 1. Schematic diagram of a Dynamic Positioning Systems

The measured signals are processed by the signal processing module, this block performs tests identifying high variance, wild point, frozen signals, and signal drift. Erroneous signals are rejected. Roll and pitch compensation of position measurements is also performed in this block.

The main objective of the Estimation module is to provide estimates of ship's positions, heading and velocities. The rapid, purely oscillatory motion induced by wave has to be filtered out. In order to estimate ship position, The DPS uses information about the sensor system, that is a Position Measurement Equipment or Position Reference System, and its own internal model of the ship. The measurements are noisy. The source of noise depends on the sensors and on the method used for measuring position.

A conventional feedback controller is of PD-type using the position and heading estimates. Some kind of integral action is required to compensate for static environmental disturbance. The controller feedforward normally consists reference and feed-forward.

The trhuster allocation block maps the controller the controller outputs (such as force and moment demands) into thuster set points such as propeller speed, azimuth nad rudder angles, pitch ratio.

3 MODELING OF MARINE VEHICLES

The number of published investigations about ship modelling is immense. For example, a nonlinear model in 6 degree of freedom is shown in[16], a survey of ship models and experimental techniques for identification of ship dynamics are described in several publications [17-19].

The hydrodynamic and derivatives coefficients occurring in the equations of motion cannot be calculated analytically and hence tests with the physical model are carried out in towing tanks, rotating arms tanks and Planar Motion Mechanism (PMM). Experimental techniques (as described in [20]) can be used to determine these coefficients.

The use of system identification techniques to determine ship-dynamics has been increasing, and different input signals are defined (see for example the early work of Aström and Kälström [21], or [22], where classical least squares algorithms are used). However, the extra complexity associated with non-linear systems, with constrains and no initial information of model structure, means that exhaustive search is not always feasible. In these cases genetic identification strategy can be used to obtain initial values.

Experiments in towing tanks are concerned with the determination of the motion transfer functions. Usually, tests in regular waves are made to experimental determination of the motion transfer functions. In this case, it is necessary to record the sinusoidal motions of the model and to determine the motion amplitudes experienced for a variety of different waves frequencies. The incident waves can be measured using a wave probe mounted on the towing carriage. This introduces a phase shift in the recorded motions and it is necessary to correct for this effect in the analysis.

In general, the ship model is a set of equations of motion that is used to predict the motion of the ship when know forces and moment are applied. In order to achieve good performance of the DPS the model has to be as detailed as practically possible. The model parameters are verified by sea trials. However the model only represents some behaviour of the ship, so the model is an approximation and is not perfect.

Without loss of generality, the dynamics of a surface ship are described by a model based on the horizontal motion with the motion variables of surge, sway and yaw. The movement of the ship is determined by the hydrodynamic forces and moments, the input variables of which are shaft angular velocity, related to propeller thrust, and the rudder deflection angle. These physical input variables subject to constraints. The ship motion can be defined over two coordinate frames using a body-fixed frame of surge-sway (X_0Y_0) and a global reference frame of North-East (XY)

The three degrees of freedom non-linear ship motion equations can be written as [17]:

$$
\begin{aligned}
m\left(\frac{du}{dt} - vr - x_G r^2\right) &= X\left(u, v, r, \frac{du}{dt}, \delta, n\right) \\
m\left(\frac{dv}{dt} + ur + x_G \frac{dr}{dt}\right) &= Y\left(v, r, \frac{dv}{dt}, \frac{dr}{dt}, \delta\right) \\
I_z \frac{dr}{dt} + m x_G \left(\frac{dv}{dt} + ur\right) &= N\left(v, r, \frac{dv}{dt} \frac{dr}{dt}, \delta\right)
\end{aligned}
$$

where t is time index, u, v denote surge and sway velocity, r is yaw angular velocity, m and Iz are mass of ship and the moments of inertia about the normal axis of X_0Y_0 plane, x_G is the

Cartesian coordinate of the centre of gravity along X_0 axis, δ denotes the rudder deflection angle and n is the shaft velocity, $X(.)$, $Y(.)$ and **N(.)** are external forces (along the surge X_0, sway Y_0 axis) and moment (for yaw rotation X_0-Y_0).

For underwater vehicle moving in six degree of freedom at high speed, the motion is highly nonlinear and coupled. However, in many applications the vehicle will only be allowed to move at low speed. If the vehicle has three planes of symmetry, then some coupled elements can be neglected (see [17]).

4 POSITION REFERENCE SYSTEM

Accurate, reliable and continuos position information is essential for dynamic positioning. A DPS requires data at a rate of once per second to achieve high precision. The dynamic position ships have some position reference system independent of the normal navigation system.

The most commonly used position reference for DPS is DGPS (Differential Global Position System) [23]. In order to improve GPS accuracy to levels useful for dynamic positioning, differential corrections are applied to GPS data. This is done by establishing reference stations at know points.

The basic concept of DGPS is the use of 2 receivers, one at a known location and one at an unknown position, that see GPS satellites in common. By fixing the location of one of the receivers, the other location may be found either by computing corrections to the position of the unknown receiver or by computing corrections to the pseudoranges. By using DGPS, effects of selective availability can be removed. For short baseline distances between receivers, some of the biases from the atmosphere can be removed as well. This cancellation effect is the result of both receivers seeing the same things. If one receiver location is known, then the bias in the pseudorange to the known receiver can be calculated and used to correct the solution of the unknown receiver location. Using double differenced observables can eliminate selective availability effects as well as other biases. Double differences are primarily used for surveying and geodetic research using phases; however, they are not limited to those applications. First, single differences are formed by subtracting observation equations from two separate receivers to a single satellite. Taking the difference between two single differences for a specific receiver pair gives the carrier phase double difference.

Some DGPS services accept multiple differential inputs obtained from an array of reference stations widely separated. Network DGPS systems provide greater stability and accuracy, and remove more of the ionospheric error than obtainable from a single reference station. The accuracy obtained by a DGPS is of 1 to 3 meters dependent upon the distances to the reference stations, ionospheric conditions, and the constellation of satellites available.

Others position reference systems used in dynamic positioning are: Hydroacoustic Position Reference, Taut Wire, Laser-based systems and Artemis.

In general, DPS combine position reference data from two or more position reference systems.

The ship heading is provided by one or more gyro compasses, which transmit data to the DPS.

5 ESTIMATION

The measurement from Position Reference System are noisy. This noise depends on the sensors and method used for measuring position. Then, the problem is how do you estimate the position and attitude state of the ship whit an approximate knowledge of the ship dynamics and with noisy measurements. The answer to this problem is the use of Kalman filtering techniques. In a Dynamic Positioning application a Kalman filter is used to estimate the state of the vessel (for which a dynamics model has been developed) based on noisy measurements from reference systems and sensors.

In 1960, R.E. Kalman published his famous paper describing a recursive solution to the discrete data linear filtering problem [24]. Since that time, due in large part to advances in digital computing, the Kalman filter has been the subject of extensive research and application, particularly in the area of autonomous or assisted navigation. A very “friendly” introduction to the general idea of the Kalman filter can be found in Chapter 1 of [25], while a more complete introductory discussion can be found in [26], which also contains some interesting historical narrative. You can see also [27].

The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of (noisy) measurements. As such, the equations for the Kalman filter fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for the feedback—i.e. for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate.

The time update equations can also be thought of as predictor equations, while the measurement equations can be thought of as corrector equations. Indeed the final estimation algorithm resembles that of a predictor-corrector algorithm for solving numerical problems.

The specific equations for the time and measurement updates are:

Time update:

$$\begin{aligned} \dot{\hat{x}}_k &= A\hat{x}_{k-1} + Bu_{k-1} \\ P_k^- &= AP_{k-1}A^T + Q \end{aligned}$$

Measurement update:

$$\begin{aligned} K_k &= P_k^- H^T (HP_k^- H^T + R)^{-1} \\ \hat{x}_k &= \hat{x}_k^- + K_k (z_k - H\hat{x}_k^-) \\ P_k &= (I - K_k H) P_k^- \end{aligned}$$

After each time and measurement update pair, the process is repeated with the previous a posteriori estimates used to project or predict the new a priori estimates. This recursive nature is one of the very appealing features of the Kalman filter—it makes practical implementations much more feasible than (for example) an implementation of a Wiener filter which is designed to operate on all of the data directly for each estimate. The Kalman filter instead recursively conditions the current estimate on all of the past measurements.

The measurement noise covariance R is usually measured prior to operation of the filter. Measuring the measurement error covariance R is generally practical (possible) because we need to be able to measure the process anyway (while operating the filter) so we should generally be able to take some off-line sample measurements in order to determine the variance of the measurement noise.

The determination of the process noise covariance Q is generally more difficult as we typically do not have the ability to directly observe the process we are estimating. Sometimes a relatively simple (poor) process model can produce acceptable results if one "injects" enough uncertainty into the process via the selection of Q. Certainly in this case one would hope that the process measurements are reliable.

In either case, whether or not we have a rational basis for choosing the parameters, often times superior filter performance (statistically speaking) can be obtained by tuning the filter parameters Q and R. The tuning is usually performed off-line, frequently with the help of another (distinct) Kalman filter in a process generally referred to as system identification.

6 CONTROLLER DESIGN

The main purpose of a positioning control system is that a ship maintains a specified position and compass heading unaffected by the disturbances action upon it. The positioning control problem is one of attenuating these disturbances by applying proper counteracting forces.

Increased computational power has provided the opportunity to implement more sophisticated control algorithms. More demanding control strategies such as model predictive control and online numerical optimization techniques have been commercialized.

Different controllers are proposed in the literature. See for example [28-32]. Some of these controllers have been successfully installed on several commercial DP systems.

Many DPS rely on multivariable PID algorithms in conjunction with an observer providing state estimates [30]. The basic principle of a PID control law is to generate a thrust for which the different terms are respectively proportional to the 3-dimensional position and heading deviation vector as referred to the ship position relative to the desired setpoint (the proportional term), to the velocity deviation vector (the differential term), and to the accumulated deviation vector (the integral term). All these vectors are referred to a specific time instant t. Based on this principle, the required thruster force vector in the body-fixed frame can be formulated as sum of the three terms corresponding to proportional, derivative and integral actions.

The H_∞ design approach provides a step forward in the technology of dynamic ship positioning systems that are equally important as the introduction of the Kalman filtering optimal control schemes. The advantages of the latter were so obvious that ship operators demanded this capability and the consequence was that the Kalman filtering system was widely applied and used in practice [32].

The H_∞ robust design technique was developed for uncertain systems and its main objective was to provide a design that is more robust than that can be obtained with LQG/Kalman filtering methods or other techniques. The fundamental problem with Kalman filtering methods is that there is no formal method in the problem description in which modeling errors in the plant can be taken into account. In many cases as will be explained below, information is available in the frequency ranges where ship models are poor. However, there is no method for incorporating this information in Kalman filtering/optimal control schemes. The consequence is that many hours can be spent on commissioning. Moreover, it is likely that unpredictable performance will occur in unusual sea-state conditions.

Intelligent techniques as fuzzy control can be used also. FLC provides a nonanalytic alternative to the classical control theory [33].

Fuzzy control is based on an I/O function that maps each very low-resolution quantization interval of the input domain into a very low-low resolution quantization interval of the output domain. As there are only 7 or 9 fuzzy quantization intervals covering the input and output domains the mapping relationship can be very easily expressed using the “if-then” formalism. (In many applications, this leads to a simpler solution in less design time.) The overlapping of these fuzzy domains and their linear membership functions will eventually allow to achieve a rather high-resolution I/O function between crisp input and output variables

ACKNOWLEDGMENTS

Authors gratefully appreciate the support given by the Science and Technology Ministry of Spain under grant DPI2003-09745-C04-01.

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