Dynamic Ship Positioning Robust Control based on Kalman Filtering

Vidya S. Rao, Dr. V. I. George.

Abstract—This paper considers both low and high frequency dynamics of the ship. The estimator used is the Kalman filter for the estimation of the position. The approach was developed for the application to the dynamic ship positioning control problem.

Index Terms—Dynamic Ship Positioning Control, Kalman Filter, Low frequency dynamics of the ship, High frequency dynamics of the ship.

1. INTRODUCTION

Dynamic positioning (DP) is a system to automatically maintain a ship's position and heading by using its own propellers and thrusters at its specified value. This allows operations at sea where mooring or anchoring is not feasible due to deep water congestion on the sea bottom (pipelines). Modern controllers use a mathematical model of the ship that is based on a hydrodynamic description concerning some of the ship's characteristics such as mass and drag. The ship's position and heading are fed into the system and compared with the prediction made by the model. This difference is used to update the model by using Kalman Filtering technique. The model also has input from the wind sensors and feedback from the thrusters.

The Kalman filter is an efficient recursive filter which estimates the state of a dynamic system from a series of incomplete and noisy measurements. The Kalman filter has two distinct phases: Predict and Update. The predict phase uses the estimate from the previous time step to produce an estimate of the current state. In the update phase, measurement information from the current time step is used to refine this prediction to arrive at a new, more accurate estimate.

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2. THE SYSTEM DESCRIPTION

Fig 1. Basic components in a Dynamic Positioning System

The environmental forces acting on the ship induce movements in six degrees of freedom (surge, sway, yaw, heave, roll, and pitch). In the dynamic positioning mode of operation, only vessel motions in the horizontal plane, surge, sway and yaw are controlled. The other motions and their interactions with surge, sway and yaw are considered negligible. It is usual to design the sway and yaw control equations together and then include the surge system as a separate design. This is possible because the linearised vessel dynamics in the surge low frequency motion are decoupled from the sway and yaw motions.[2]. In this paper only sway and yaw motions have been considered. The assumption is made that the low and high frequency motions are determined separately and that the total motion is the sum of each of them.[3].

2.1 LOW FREQUENCY DYNAMICS

In order to formulate an efficient control scheme using Kalman filtering, a good mathematical model of the system is necessary.
dynamics is required. The reason for this is that the Kalman filter uses the model dynamics, together with some knowledge of the noise statistics, to generate estimates of the state variable. The low frequency motions are determined by solving the equations of motion of the vessel in sway and yaw. The model equations can be developed from a set of tank and wind tunnel tests on models.[2].

The low frequency motions are controllable via thruster action Fig1. The ship positioning problem is to control the low frequency motions given that the measured position of the ship. The object in the following is to design a state estimator to provide estimates of the low frequency motions and using this estimate to design the controller.

A full low frequency model for sway and yaw motions should include the sway position and heading angle states together with a simplified form of thruster dynamics. The thruster dynamics can be expressed as

$$\dot{x} = A_i x_i + B_i u_i + D_i W_i$$

$$x_i(t) \in \mathbb{R}^2, u_i(t) \in \mathbb{R}^2, W_i(t) \in \mathbb{R}^2$$

$$y_i = C_i x_i + V_i$$

Where $W_i$ is the process noise and $V_i$ is the measurement noise. The matrices $A_i, B_i, C_i$ may be expressed as

$$A_i = \begin{bmatrix} -0.056 & 0 & 0.0016 & 0 & 0.5435 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0.573 & -0.0695 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1.55 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1.55 \end{bmatrix}$$

$$B_i = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0.5435 \\ 0 \end{bmatrix}, D_i = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 9.785 \end{bmatrix}, C_i = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},$$

The low frequency component of the position of the vessel in sway and heading is thus:

$$y_i = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

Where the two low frequency components of $y_i$ are $y_1$ and $y_2$ in the sway and yaw positions, respectively. [2,3].

3. DYNAMIC POSITIONING CONTROL SYSTEMS AND ESTIMATOR

Dynamic Positioning systems may contain the following subsystems in it.

3.1. Power System: This comprises all units necessary to supply the system with power.

3.2. Control System: This comprises

3.2.1. Computer systems


3.2.3. Display System and operator panels.

3.2.4. Associated cabling and cable routing.

3.3. Thruster System: This involves all components and systems necessary to supply the system with thrust force and direction. The thruster system includes thrusters with drive units and necessary auxiliary systems, including piping and main propellers and rudders that are under the control of Dynamic Positioning System. [7].

4. KALMAN GAIN

The state equations of the vessel can be written in the form which is normally used for specifying the Kalman filtering problem. That is, Predict

$$\dot{\hat{x}} = A_i \hat{x} + B_i u_i + D_i W_i \quad \text{(predicted state)} \quad \ldots \quad (5)$$

$$P = C_i P C_i^T + Q \quad \text{(predicted estimate covariance)} \quad \ldots \quad (6)$$

Update $$\eta = y_i - C_i \hat{x} \quad \text{(innovation or measurement residual)} \quad \ldots \quad (7)$$

$$K = P C_i^T [C_i P C_i^T + R]^{-1} \quad \text{(Kalman gain)} \quad \ldots \quad (8)$$

$$\hat{x} = \hat{x} + K \eta \quad \text{(updated state estimate)} \quad \ldots \quad (9)$$
\[ P = (I - KC_t)P \text{ (updated estimate covariance)} \] \[ \text{[7]} \quad \text{[10]} \]

Where \( \hat{x} \) is the estimated state. \( K \) is the Kalman Gain. Both controller gain and Kalman gain are used in the feedback control system so as to minimize the error as shown in the Fig.2.

5. HIGH FREQUENCY DYNAMICS

High frequency motions are due to the wave motions and are oscillatory in nature. The Control loops for dynamically positioned ship include filters to remove the wave motion signals. This is necessary because the thrust devices are not intended and are not rated to suppress the wave induced motions. While modeling the high frequency motions of the ship, the assumption made in this project is that the sea state is known and can be described by a spectral density function (2,9). It is further assumed that the wind action has a stationary characteristic of white noise with unit power spectral density that is \( S_I(\omega) = 1.0 \). An internationally accepted wave energy standard, Pierson – Moskowitz power spectral density function given by the following expression\([10]\) has been used to describe the high frequency wave spectrum.

\[ S_I(\omega) = 1.0 \]

Where \( \omega \) is the angular frequency in rad/s

\[ A = 4.894 \quad B = \frac{3.1094}{h} \frac{3}{h} \]

The term \( h/3 \text{ (m)} \) is defined as the significant wave height. The sea spectrum described by the Pierson – Moskowitz expression has been approximated by a rational proper transfer function representation using the following identity:

\[ S_I(\omega) = |G(j\omega)|^2S_I(\omega) \]

The transfer function \( G(j\omega) \) consists of at least two cascaded second order sections. The single section of the transfer function may be expressed as:

\[ G_I(s) = \frac{2s\zeta_i \omega_i}{s^2 + 2s \zeta_i \omega_i + \omega_i^2} \]

Where \( \zeta_i \) is the \( i \)th section damping coefficients \( b_i \) are the d.c gains, \( \omega_{ni} \) are the \( i \)th section resonant frequencies. Thus the high frequency oscillations are suppressed by the filter which is designed assuming that high frequency wave spectrum as Pierson – Moskowitz power spectral density function.

6. CONTROLLER DESIGN BY ROBUST CONTROL TECHNIQUE

The main objective of the robust controller is to compensate the low frequency disturbances, such as wind and current, and to reduce the thruster modulation to the lowest possible level. These can be achieved by selecting appropriate weighting functions \( W_1, W_2, W_3 \). Where \( W_1 \) is sensitivity weighting function \( W_2 \) is control weighting function and \( W_3 \) is complementary sensitivity weighting function. The complementary sensitivity weighting function \( W_3 \) should be chosen to be a high pass filter. The controller is required to compensate the low frequency motion, using the thruster to reject the high frequency motion to avoid thruster modulation.

The robust optimal controller can be calculated using the Matlab robust control toolbox. The controller has sufficient gain at low frequencies to compensate the disturbance loads and moments, a notch type response about the wave control frequencies to reduce the thruster modulation saturation and a high cutoff rate at high frequencies to filter measurement noise. In this project the weights \( W_1, W_2, W_3 \) are chosen as follows,

\[ W_1 = 0.5 \left( s + 10 \right) \left( s + 10 \right) \]

\[ W_2 = 0 \]

\[ W_3 = 20 \left( s + 10 \right) \left( s + 400 \right) \]

A popular approach for loop shaping is \( H_\infty \) sensitivity loop shaping which is implemented by the 

Control Toolbox command. The Syntax is, \( K= \text{sys} \)

\( W_1 [], W_3 \).

Model reduction technique used in this project is \( \text{Rissanen} \).

Singular Value Model reduction.

![Fig 2. Kalman Filter State Estimate Feedback Scheme](image-url)
7. SIMULATION RESULTS

The linearised low frequency model of the vessel can be represented by (1) and (2) where the state vector is defined as,

\[
x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \\ x_6(t) \end{bmatrix}\]

\(x_1(t)\) sway velocity
\(x_2(t)\) sway position
\(x_3(t)\) yaw angular velocity
\(x_4(t)\) yaw angle
\(x_5(t)\) thruster one
\(x_6(t)\) thruster two.

The system matrices [1] corresponding to the zero current condition and the continuous time state equations become as in (3). The covariance of the process noise is dependent upon the wind force level and can be defined as \(Q = \text{diag}(4 \times 10^{-6}, 9 \times 10^{-5})\) and sway and yaw covariances \(R = \text{diag}(10^{-5}, 1.22 \times 10^{-5})\) [3]. Using high frequency model of the ship \((11)\) to \((14)\) and assuming \(h=30 \text{ m}, w=100 \text{ rad/s}, b_i = 1 \times 10^{-5}, \zeta_i = 0.8\ \omega_n = 10 \text{ rad/s},\) the transfer function becomes \(G(s) = \frac{0.000032}{s^2 + 0.16s + 100},\) and comparable with that of 8 state controller. The simulation of Kalman filtering is done using MATLAB [6]. Using above data the sway position (estimated as well as measured) is shown (Fig 3).

Conclusion

Closed Loop Control: For Robust controller, step response of the system with the controller with 8 states is shown whose performance is satisfactory (Fig 4). The high frequency wave spectrum is also considered along with low frequency model of the ship. The control loops for dynamically positioned ship include filters to remove the wave motion signals.

Fig. 3. Kalman filter performance

Fig. 4. Sway and Yaw responses

ACKNOWLEDGMENT

The authors are grateful to Instrumentation and Control engineering Dept. MIT Manipal University, Manipal for having provided an opportunity to complete this work.

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