Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2013, 36(108) z. 1 pp. 182–187
ISSN 1733-8670

2013, 36(108) z. 1 s. 182–187

Control system design for dynamic positioning using vectorial backstepping

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Key words: dynamic positioning, backstepping, nonlinear passive observer

Abstract

The problem of synthesis a dynamic positioning system for low frequency model of surface vessel was considered in this paper. The recursive vectorial backstepping control design was used to keep a fixed position and heading in presence of wave disturbances. The passive observer was introduced to smooth the measurements and to estimate the velocities needed for the control algorithm. The computer simulation results were given to demonstrate the effectiveness of that combination of controller-observer system to compensate environmental disturbances.

Introduction

In view of the manoeuvre difficulties caused by the weight of ships, it is not an easy task to improve the quality of navigation, especially for ships moving at slow speed (called dynamic positioning). Dynamic positioning (DP) system for marine vehicles is a challenging practical problem. It includes station keeping, position mooring and slow speed references tracking. Of that three, the main purpose of DP is to maintain a certain accurate position and course, regardless of the interference such as wave and wind. This task should only be achieved under its own propulsion and using navigation systems. An application of the appropriate control method for DP is directly related to the adopted model, its purpose, structure and number of the installed actuators.

The station keeping for DP system can be achieved using only three control inputs when it is considered a fully actuated ship operating in the horizontal plane. Hence, the dynamic positioning system can be designed by using feedback from position and heading angle. These state variables are in some cases available through satellite navigation systems as GPS / DGPS, supported by the gyros and accelerometers. But in general more signals like for example velocities accelerations and stationary varying disturbances due to wind, ocean current and nonlinear wave effects, are necessary in the control law. In the process of ship steering, direct measurement of longitudinal and transverse velocity is not available when they attain low speed values. However, it is possible to calculate the estimated value of velocity on the basis of the position and direction measurements by the state observer. In most cases, an accurate state measurements are disturbed by the wind, waves and sea currents, as well as by the interference of the measuring sensors. Therefore, the estimates should be filtered by using so-called wave filtering (WF) techniques. Oscillatory disruptions of a WF motion components are filtered before feedback is applied. However, the remaining LF motion components which are associated with the deviation from the given position and direction are compensated by the control system.

The examples of several solutions mentioned above have been recently obtained. Most of them base on signal filtering, state estimation and appropriate selection of the control method. The first DP systems were designed using conventional PID controllers in cascade with low-pass and notch filters. Here, the wave disturbances were filtered before feedback was applied in order to avoid unnecessary control action. Model-based controls for dynamic positioning includes also LQG, sliding mode control [1], robust H∞ control [2, 3], nonlinear backstepping method [4] and another state – space techniques [5]. The artificial intelligence [6], fuzzy logic [7] and neural nets [8] were also used for DP. A number of researches were carried out within the scope of application.

In the DP systems, wave filtering and state estimation were resolved using Kalman filters [9, 10] or Luenberger observer. There is the most important drawback of that two observers-if the extended Kalman filter and Luenberger observer are combined with a state feedback controller, using state estimates, then a global expotential stability cannot be quaranteed. Alternative solution for the state feedback controllers is the backstepping observer [4] or passive observer and wave filtering [11]. These methods were designed by using Lyapunov stability theorem and Kalman Yakubovich – Popov theorem to ensure GES property. Passive observer in comparison to the backstepping observer has less tuning parameters, so it is easier to apply. In this study the vectorial backstepping controller in configuration with passive observer was considered to keep fixed position and heading at low forward speed. Both of these methods were designed based on Lyapunov stability theorem and assuming an a priori knowledge of mathematical vessel model.

Ship model

The mathematical vessel model of the ship used for DP in a horizontal plane is described in [5].

Kinematic model

Since we only consider the surge, sway and yaw the kinematic equations are given by:

$$\boldsymbol{\eta}' = \mathbf{R}(\psi)\,\mathbf{v} \tag{1}$$

where the state vector $\boldsymbol{\eta} = [x, y\ \psi]^{\mathrm{T}}$ denotes the position (x, y) and heading $0 < \psi < 2\pi$ of the ship in the earth-fixed frame. The vector $\mathbf{v} = [u, v, r]^{\mathrm{T}}$ denotes linear velocities in surge, sway and angular velocity in yaw coordinated in the body fixed frame. The rotation matrix $\mathbf{R}(\psi)$ with the property $\mathbf{R}^{\mathrm{T}} = \mathbf{R}^{-1}$ is given by:

$$\mathbf{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Low Frequency model

During dynamically positioning it is a common assumption to consider the low speed, low frequency model omitting the centrifugal / coriolis forces, moments and nonlinear damping effects:

$$\mathbf{M}v' + \mathbf{D}v = \boldsymbol{\tau} + \boldsymbol{\tau}_w \tag{3}$$

where the matrix of inertia $\mathbf{M} \in \mathbf{R}^{3\times3}$ and the damping matrix $\mathbf{D} \in \mathbf{R}^{3\times3}$ will defined in detail later. The control input vector $\boldsymbol{\tau} \in \mathbf{R}^3$, $\boldsymbol{\tau} = [\tau_x, \tau_y, \tau_n]^{\mathrm{T}}$ of forces and moments provided by the actuator system and the vector $\boldsymbol{\tau}_w$ of slowly varying forces and moments that act on the hull due to environmental disturbances such as wind, currents and waves or unmodelled dynamics can be written as:

$$\boldsymbol{\tau} = \mathbf{BK}(U)\,\mathbf{u} \tag{4}$$

$$\boldsymbol{\tau}_w = \mathbf{R}(\psi)^{\mathrm{T}}\,\mathbf{b} \tag{5}$$

where $\mathbf{B} \in \mathbf{R}^{3\times n}$ is a thruster configuration matrix, $\mathbf{K}(U) \in \mathbf{R}^{n\times n}$ is a diagonal matrix of speed – dependent force coefficients, $n \geq 3$ is the number of independent actuators and $\mathbf{u} \in \mathbf{R}^n$ is the control inputs vector.

Wave Frequency model

The following wave frequency model can be used for each degrees of freedom ($i = 1,2,3$), producing forces added to the position and heading measurements:

$$h_i(s) = \frac{2\zeta_i \varpi_{0i} \sigma_i}{s^2 + 2\zeta_i \varpi_{0i} s + \varpi_{0i}^2} \tag{6}$$

where: ζ_i – relative damping ratio, ϖ_{0i} – dominating wave frequency, σ_i – wave intensity parameter.

A state space realization of WF model can be expressed as:

$$\boldsymbol{\chi}' = \boldsymbol{\Omega}\boldsymbol{\chi} \tag{7}$$

$$\boldsymbol{\eta}_w = \boldsymbol{\Gamma}\boldsymbol{\chi} \tag{8}$$

Here, $\boldsymbol{\eta}_w = [x_w, y_w, \psi_w]^{\mathrm{T}}$ denotes position and heading measurement vector, $\boldsymbol{\chi} \in \mathbf{R}^6$ is a state vector, $\boldsymbol{\Omega} \in \mathbf{R}^{6\times6}$ is a constant matrix resulted directly from transformation of the transmittance (6) to the state space model:

$$\boldsymbol{\Omega} = \begin{bmatrix} 0_{3\times3} & I_{3\times3} \\ \Omega_{21} & \Omega_{22} \end{bmatrix} \tag{9}$$

$$\Omega_{21} = -\mathrm{diag}\left(\varpi_{01}^2, \varpi_{02}^2, \varpi_{03}^2\right) \tag{10}$$

$$\Omega_{22} = -\mathrm{diag}\left(2\xi_1\varpi_{01}^2, 2\xi_2\varpi_{02}^2, 2\xi_3\varpi_{03}^2\right) \tag{11}$$

The constant matrix $\mathbf{\Gamma} \in \mathbf{R}^{3\times6}$ converts the vector $\boldsymbol{\chi}$ to space $\mathbf{R}^3$:

$$\mathbf{\Gamma} = \begin{bmatrix} 0_{3\times3} & I_{3\times3} \end{bmatrix} \tag{12}$$

The bias state may be modelled by a first-order Markov process:

$$\mathbf{b}' = -\mathbf{T}^{-1}\mathbf{b} \tag{13}$$

where $\mathbf{T} \in \mathbf{R}^{3\times3}$ is a diagonal matrix representing positive bias time constants.

DP controller

In this section the control input vector $\mathbf{u}$ was designed to guarantee that $\boldsymbol{\eta}(t)$ and $\boldsymbol{\nu}(t)$ are bounded and to ensure asymptotic convergence of position and heading to their desired constant values, $\boldsymbol{\eta}(t) \rightarrow \boldsymbol{\eta}_d$, at $\boldsymbol{\nu}(t) \approx 0$ for all $t \geq 0$.

The classical vectorial backstepping method was used, discussed in detail [4]. The reference signals needed for control are the desired state vector $\boldsymbol{\eta}_d = [x_d, y_d, \psi_d]^{\mathrm{T}}$ and its first and second order derivatives. All reference signals, the heading angle ψ_d and position (x_d, y_d) are assumed to be bounded. The control design based on mathematical ship model (1)–(5) and consists of two steps.

At the first step of backstepping the virtual control variable $\boldsymbol{\nu}$ is designed for subsystem (1). The system is considered in a new error variables $\mathbf{z}_1 \in \mathbf{R}^3$ and $\mathbf{z}_2 \in \mathbf{R}^3$ given by:

$$\mathbf{z}_1 = [z_{11}, z_{12}, z_{13}]^{\mathrm{T}} = \boldsymbol{\eta} - \boldsymbol{\eta}_d \tag{14}$$

$$\mathbf{z}_2 = \boldsymbol{\nu} - \boldsymbol{\alpha} \tag{15}$$

where $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \alpha_3]^{\mathrm{T}}$ is a desired virtual control for $\boldsymbol{\nu}$, calculated with respect to the control Lyapunov function candidate. At the second step the actual control law $\mathbf{u}$ is designed for the subsystem (3) based on second Lyapunov theory. The following feedback control law is proposed:

$$\mathbf{u} = \mathbf{K}^{-1}\mathbf{W}^{-1}\mathbf{B}^{\mathrm{T}}\left(\mathbf{B}\mathbf{W}^{-1}\mathbf{B}^{\mathrm{T}}\right)^{-1} \cdot \\ \cdot \left[\mathbf{D}\boldsymbol{\nu} - \mathbf{M}\mathbf{R}^{\mathrm{T}}\left(\mathbf{C}_2\mathbf{z}_2 + \mathbf{z}_1 + \mathbf{R}'\boldsymbol{\nu} + \mathbf{C}_1\mathbf{z}_1' - \boldsymbol{\eta}_d''\right) - \mathbf{R}^{\mathrm{T}}\mathbf{b}\right] \tag{16}$$

where the first and second control Lyapunov function candidates and the desired virtual control are given by $V_1 = 0.5\mathbf{z}_1^{\mathrm{T}}\mathbf{z}_1$, $V_2 = V_1 + 0.5\mathbf{z}_2^{\mathrm{T}}\mathbf{z}_2$ and $\alpha = -\mathbf{C}_1\mathbf{z}_1 + \boldsymbol{\eta}'_d$. Now, the error dynamics can be written as:

$$\mathbf{z}_1' = -\mathbf{C}_1\mathbf{z}_1 + \mathbf{z}_2 \tag{17}$$

$$\mathbf{z}_2' = \mathbf{C}_2\mathbf{z}_2 - \mathbf{z}_1 \tag{18}$$

While all reference signals $\boldsymbol{\eta}_d$ are constant and the state variables $\boldsymbol{\eta}(t)$, $\boldsymbol{\nu}(t)$ are available measurably, then the equilibrium point $(\mathbf{z}_1, \mathbf{z}_2) = (0, 0)$ is GAS. It ensures convergence $\boldsymbol{\eta}(t) \rightarrow \boldsymbol{\eta}_d$ and $\boldsymbol{\nu}(t) \rightarrow \boldsymbol{\alpha}$. Stability is established by using LaSalle's theorem, since $V_2 > 0$ and $V_2' \leq 0$. Among the other things it is satisfied where designed parameter matrices $\mathbf{C}_1 = \mathbf{C}_1^{\mathrm{T}} > 0$ and $\mathbf{C}_2 = \mathbf{C}_2^{\mathrm{T}} > 0$ are chosen in a diagonal form.

DP model – based observer

The model-based observer described in detailed in [11] was used to reconstruct the system's non-measured states. The chosen observer was designed on the basis of the Lyapunov stability theory. The measured position and heading, $\mathbf{y}_m$ can be seen as a superposition of the LF motions and WF motions:

$$\mathbf{y}_m = \boldsymbol{\eta} + \boldsymbol{\eta}_w \tag{20}$$

The idea of passive observer is to reconstruct $\boldsymbol{\eta}$, $\boldsymbol{\eta}_w$ based on output $\mathbf{y}_m$ and vector forces $\boldsymbol{\tau}$. On the basis of a complete model which consists of a ship model (1)–(5), bias model (13) and WF model (7)–(12), the resulting observer is composed of the following equations including: state estimators (21–22), measurements estimator (23), bias estimator (24), wave estimator (25):

$$\dot{\hat{\boldsymbol{\eta}}} = \mathbf{R}(\mathbf{y}_m)\hat{\boldsymbol{\nu}} + \mathbf{K}_2\tilde{\mathbf{y}} \tag{21}$$

$$\dot{\hat{\boldsymbol{\nu}}} = -\mathbf{M}^{-1}\mathbf{D}\hat{\boldsymbol{\nu}} + \mathbf{M}^{-1}\mathbf{R}(\mathbf{y}_m)^{\mathrm{T}}\hat{\mathbf{b}} + \mathbf{M}^{-1}\boldsymbol{\tau} + \mathbf{R}(\mathbf{y}_m)^{\mathrm{T}}\mathbf{K}_4\tilde{\mathbf{y}} \tag{22}$$

$$\hat{\mathbf{y}} = \hat{\boldsymbol{\eta}} + \mathbf{\Gamma}\hat{\boldsymbol{\chi}} \tag{23}$$

$$\dot{\hat{\mathbf{b}}} = -\mathbf{T}^{-1}\hat{\mathbf{b}} + \mathbf{K}_3\hat{\mathbf{y}} \tag{24}$$

$$\dot{\hat{\boldsymbol{\chi}}} = \mathbf{\Omega}\hat{\boldsymbol{\chi}} + \mathbf{K}_1\tilde{\mathbf{y}} \tag{25}$$

Here, $\tilde{\mathbf{y}} = \mathbf{y}_m - \hat{\mathbf{y}}$ is the estimation error and $\mathbf{K}_1 \in \mathbf{R}^{6\times3}$, $\mathbf{K}_2$, $\mathbf{K}_3$ and $\mathbf{K}_4 \in \mathbf{R}^{3\times3}$ are diagonal observer gain matrices. The observer – gains $\mathbf{K}_1$, and $\mathbf{K}_2$ can calculated for the same order as shown in [11], based on the wave frequency model parameters (6). As can be seen the $\mathbf{K}_3$ and $\mathbf{K}_4$ are unknown diagonal matrices in the observer model besides sea state, which was assumed to be known.

Simulation Research

In this section the performance of the control system was verified. The scaled mathematical model of supply vessel was used as a case study [5, 12]. The vessel system matrices were given below:

$$\mathbf{M} = \begin{bmatrix} 1.1274 & 0 & 0 \\ 0 & 1.8902 & -0.0744 \\ 0 & -0.0744 & 0.1278 \end{bmatrix} \quad (26)$$

$$\mathbf{D} = \begin{bmatrix} 0.0358 & 0 & 0 \\ 0 & 0.1183 & -0.000124 \\ 0 & -0.000041 & 0.0308 \end{bmatrix} \quad (27)$$

Assuming that ship is equipped with two main aft propellers, one bow tunnel thruster and two rudders in the aft of the ship, matrixes **B**, **K** and the control allocation weights **W** are given by:

$$\mathbf{B} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 \\ 0.0656 & -0.0656 & 0.7874 & 0.4987 & 0.4987 \end{bmatrix} \quad (28)$$

$$\mathbf{W} = \mathrm{diag}([1\ 1\ 0.25\cdot(1+\exp(200\cdot U^2))\ \exp(1/(0.02+0.6\cdot U))\cdot 2.5\cdot 10^{-8}\ \exp(1/(0.02+0.6\cdot U))\cdot 2.5\cdot 10^{-8}]) \quad (29)$$

$$\mathbf{K} = 0.0025\cdot \mathrm{diag}([6.55\ 6.55\ 1.37\cdot\exp(-47\cdot U^2)\ 3.9+6.4\cdot 10^3\cdot U^2\ 3.9+6.4\cdot 10^3\cdot U^2]) \quad (30)$$

The tested controller-observer system were modeled in the computing environment called Matlab / Simulink. Simulations were carried out in time domain. Numerical integration was done using Runge-Kutta method in fourth-order integration with a period equal to 0.1 s. During a simulation tests all the simulation deploy the same parameters settings as follows. The initial conditions were chosen as: $\boldsymbol{\eta}(t_0) = (0, 0, 0)$, $\boldsymbol{\nu}(t_0) = (0.01, 0.01, 0.01)$ and the initial values of all estimates were set as zero. The desired position and orientation were changed after 30 s to the value $\boldsymbol{\eta}_d(t) = (10, 10, 45°)$.The simulation studies were carried out in the presence of wave disturbances (6). The parameters of the wave frequency model were set at $\zeta_i = 0.1$, $\omega_{0i} = 0.65$ rad/s, $\sigma_i = 0.5$ m. The amplitudes of the wave were set at 2.0 m, 2.0 m, 3° respectively for surge, sway and yaw directions. The observer – gains $\mathbf{K}_1$ and $\mathbf{K}_2$ were calculated on the basis of the appropriate wave frequency model parameters as shown in [11] and a bias time constants was assumed $\mathbf{T} = \mathrm{diag}(100, 100, 100)$. The tuned controller and observer parameters were $\mathbf{K}_3 = 0.01\cdot\mathrm{diag}(0.1, 0.1, 0.1)$, $\mathbf{K}_4 = 0.0208\cdot\mathrm{diag}(0.1, 0.1, 0.1)$, $\mathbf{C}_1 = \mathrm{diag}(0.05, 0.05, 5)$, $\mathbf{C}_2 = \mathrm{diag}(4, 4, 0.5)$.

The simulation tests aim at checking the operation correctness of the vectorial backstepping controller with passive observer. The following data (Figs 1–5) show the ability of the system to the convergence of the position and heading to their desired values, wave filtration and state estimation. The first 150 seconds of tests present the results with an observer and a wave filtering. During the next time state variables were not observed and filtered.

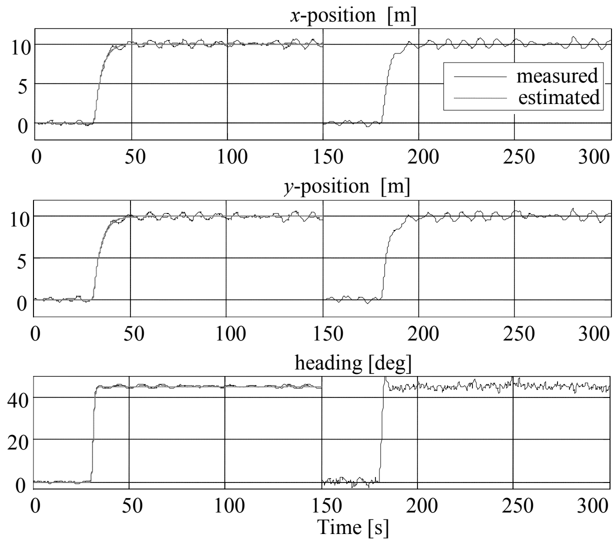

Fig. 1. Measured and filtered position and heading

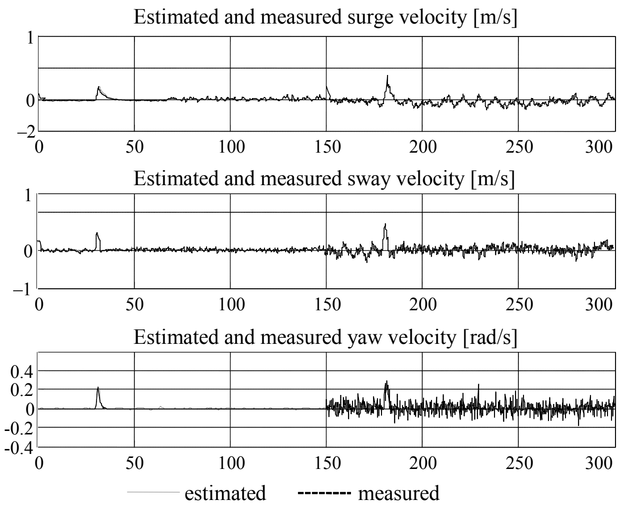

Fig. 2. Observer error of surge, sway velocities and yaw angle

The time-histories shown in figure 1 confirm a good ability of the backstepping controller to keep fixed position and heading in the presence of wave disturbances. The system confirms also good ability to state estimation and wave filtering. The gray line present measured position, black line estimated. The surge, sway velocity and yaw angle were also estimated from observer (Fig. 2). It is seen that all the observer errors tend to zero for velocities, position and heading. Velocity estimation error does not exceed 2% of the steady-state. The next figures present forces and moments in surge, sway and yaw direction during a simulation test without and in the presence of obsever and wave filtering. In a figure 4 we can see a actual ship position in the system with observer and without observer and wave filtering. The DP system with backsepping controller and passive observer gives an excellent positioning performance.

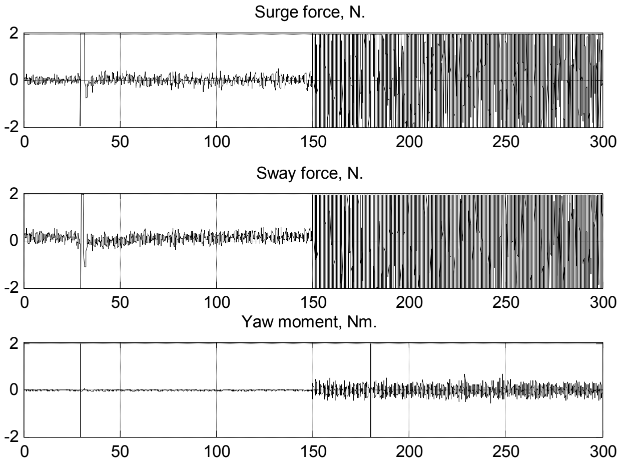

Fig. 3. Forces and moments in surge, sway and yaw direction

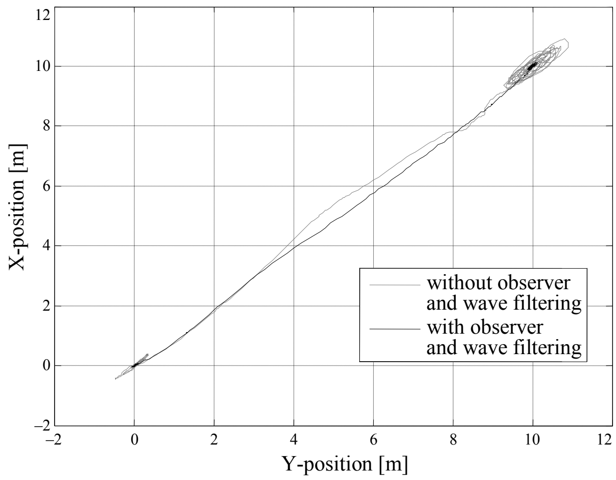

Fig. 4. Actual ship position

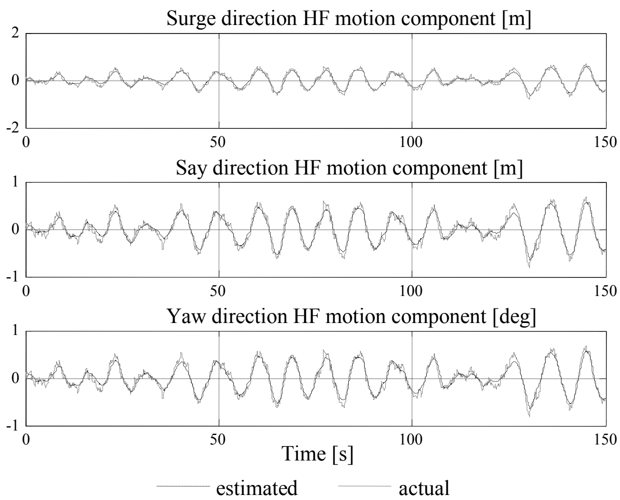

Fig. 5. Actual and estimated HF motion components

The system realizes also estimation of the first order wave motions components that cause oscylatory motion of the vessel. The HF motion components in surge, sway and yaw direction, vessel were presented in a figure 5. We can see that actual HF motion components are fully estimated in each direction.

Conclusions

Ships with DP system are used to perform operations on the sea, especially in the output of crude oil. Functions, that these vessels implement, are able to eliminate the tugs work and are able to quickly respond to changes in weather or operating parameters. This gives the versatility of using this type of vessels.

In this paper the backstepping controller was used to keep fixed position and heading in the presence of wave disturbances. The passive observer was introduced to smooth the measurements and to estimate the velocities needed for the control algorithms. These combinations of controller-observer confirm the good ability of the control system to keep fixed position and heading in the presence of different wave disturbances. The simulation results have shown that these combinations of controller-observer effectively compensate environmental disturbances.

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