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Path Following of Underactuated Surface Vessels in Presence of Unknown Constant Environmental Forces: Preliminary Results

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Abstract: A disturbance rejection technique for path following applications of underactuated surface vessels, originally designed to compensate for ocean currents, is shown to successfully counteract for wind and wind waves as well. The overall effect of wind and wind waves is modeled as an unknown combination of constant forces and moments acting on the vessel. Disturbances in surge and yaw are canceled through feed-forward and adaptive techniques in the autopilot. However, due to the underactuation, the drifting effect of the environmental forces in the sway direction can not be canceled in this way. In order to eliminate the drifting effect of wind and wave forces in the sway direction, a modified two-dimensional Line-of-Sight (LOS) guidance law with integral action is proposed. The integral effect of the LOS guidance is introduced to counteract slowly varying disturbances like wave drift, wind load and currents. The closed-loop stability analysis reveals global κ-exponential stability properties for the guidance subsystem, where the perturbing effect of the autopilot on the guidance law is neglected. The theoretical results are supported by simulations.

Keywords: path following, LOS guidance, underactuated vessel, disturbance compensation

1. INTRODUCTION

Sailors, seamen, and naval architects have faced challenges represented by wind, waves and sea currents since the early days of coastal navigation, world exploration and merchant shipping. The unavoidable occurrence of dealing with heavy seas and the need to guarantee ship maneuverability as well as safety of the crew on board has lead to improved vessel hulls, smarter navigation techniques and better meteorological/oceanographic forecasts. In particular, the last decades have witnessed an increase in automation and integration of operations at sea. This trend is well established worldwide since any improvements in these fields can significantly increase reliability, safety, sustainability and effectiveness of activities such as offshore hydrocarbon production and exploration, fishing and fish-farming, offshore wind exploitation, seabed mapping and environmental monitoring. As a result, the field of marine control has delivered valuable solutions and ideas on how to handle and reduce sea loads. In particular, effective disturbance estimation techniques and reliable compensation strategies have been introduced to successfully achieve path following tasks as well as station keeping objectives.

Path following is a motion control scenario where a marine vessel has to follow a predefined path without any time constraints and several nonlinear control solutions for path following purposes have been proposed (Aguiar and Hespanha, 2007). The Line-of-Sight (LOS) guidance principle is used in Breivik and Fossen (2004), Fredriksen and Pettersen (2004) and Skjetne et al. (2011) to achieve path following of fully actuated as well as underactuated ships. Ocean currents disturbances are often considered in literature due to their significant effect on marine operations. Observers and adaptive techniques are introduced to compensate for ocean currents and hence achieve different path following and navigation tasks of marine vessels and underwater vehicles in Encarnação et al. (2000), Antonelli et al. (2003), Bakaric et al. (2004), Bibuli et al. (2008), Lapierre and Jouvencel (2008) and Indiveri et al. (2012). To render the popular LOS guidance robust with respect to ocean currents, Aguiar and Pascoal (1997) proposes a modification based on measurements of the vehicle velocity, while integral action is added to the LOS reference generator in Børhaug et al. (2008), Breivik and Fossen (2009), Caharija et al. (2012a) and Caharija et al. (2012c). Furthermore, the use of predictive ocean models embedded into the mission planning strategy of the vehicle for current exploitation is discussed in Jouffroy et al. (2011). Most of the listed contributions consider the ocean current constant and irrotational in the inertial frame - i.e. a pure kinematic drift (Caharija et al., 2012a). This represents a widely accepted model for slowly varying currents. However, wind and waves create kinetic-level forces (Fossen, 2011) and such constant

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dynamic disturbances are taken into account and compensated using adaptive backstepping in Fossen and Strand (2001), to achieve station keeping of fully actuated ships. Prediction, measurement and estimation of environmental disturbances have also improved substantially in the last decades. On-board sensors, motion measurements, weather radars and satellite data are combined to estimate wind and wave forces in Reichert et al. (1999) and Terada and Matsuda (2011). This information can be used as a feedforward and combined with adaptive techniques in the ship autopilot to improve robustness. However, the wind and wave forces cannot be directly compensated in the sway direction if the ship is underactuated and hence, drift will occur unless side-slipping is implemented.

This paper investigates the possibility of compensating also for the drift caused by wind and wind waves by means of the integral line-of-sight (ILOS) guidance law presented in Caharija et al. (2012a) and Caharija et al. (2012c) for underactuated surface vessels. Path following of straight lines is analyzed and the environmental disturbances are modeled as a combination of unknown constant forces and moments acting in the same direction. Their intensity is assumed unknown, while their direction is assumed known since big ships and even small vessels are often equipped with sensors to estimate the wind direction. The effect of swells and ocean currents is not considered in this context. The framework developed in Børhaug et al. (2008), Caharija et al. (2012a) and Caharija et al. (2012c) represents the theoretical background of the foregoing analysis and hence, this paper proves the effectiveness of the ILOS compensation technique, since it is shown that it can counteract for dynamic-level disturbances as well. The closed-loop stability analysis shows uniform global asymptotic stability (UGAS) and uniform local exponential stability (ULES) (alternatively, global κ-exponential stability) for the unperturbed guidance subsystem. Lyapunov theory (Khalil, 2000) is used in the proof. The paper is organized as follows: Section 2 presents the model of the surface vessel and defines the control problem while Section 3 presents the control system that solves the path following task. The stability of the closed loop system is analyzed in Section 4. Simulation results are given in Section 5 and conclusions are given in Section 6.

2. VESSEL MODEL AND CONTROL PROBLEM

2.1 Model Assumptions

Assumption 1. The motion of the vessel is described in 3 degrees of freedom (DOF), that is surge, sway and yaw.

Assumption 2. The vessel is port-starboard symmetric.

Assumption 3. The body-fixed coordinate frame b is located on the center-line of the vessel at a distance x_g^* from the center of gravity (CG), where x_g^* is to be defined later.

Remark 1. The body-fixed coordinate system can always be translated to the required location x_g^* (Fossen, 2011).

Assumption 4. Damping is considered linear.

Remark 2. Nonlinear damping is not considered in order to reduce the complexity of the controllers. However, the passive nature of the non-linear hydrodynamic damping forces should enhance the directional stability of the vessel.

2.2 The Control Plant Model

The state of the vessel is given by the vector $[\boldsymbol{\eta}^T, \boldsymbol{\nu}^T]^T$ where $\boldsymbol{\eta} \triangleq [x, y, \psi]^T$ describes the position and the orientation of the vehicle with respect to the inertial frame i. The vector $\boldsymbol{\nu} \triangleq [u, v, r]^T$ contains the linear and angular velocities of the vessel expressed in the body-fixed frame b, where u is the surge velocity, v is the sway velocity and r is the yaw rate. The class of marine vehicles described by the following 3-DOF maneuvering model is considered (Fossen, 2011):

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu}, \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{B}\boldsymbol{f} + \boldsymbol{w}. \tag{2}$$

The vector $\boldsymbol{f} \triangleq [T_u, T_r]^T$ is the control input vector, containing the surge thrust T_u and the rudder angle T_r. Notice that the model (1-2) is underactuated in its configuration space. The vector $\boldsymbol{w} \triangleq [w_u, w_v, w_r]^T$ is the body-fixed environmental load vector due to wind and waves. The matrix $\boldsymbol{R}(\psi)$ is the rotation matrix from b to i. The matrix $\boldsymbol{M} = \boldsymbol{M}^T > 0$ is the mass and inertia matrix, and includes hydrodynamic added mass. The matrix $\boldsymbol{C}$ is the Coriolis and centripetal matrix, $\boldsymbol{D} > 0$ is the hydrodynamic damping matrix and $\boldsymbol{B} \in \mathbb{R}^{3\times 2}$ is the actuator configuration matrix. For manoeuvring control purposes, the matrices $\boldsymbol{R}(\psi)$, $\boldsymbol{M}$, $\boldsymbol{D}$ and $\boldsymbol{B}$ can be considered as having the following structure:

$$\boldsymbol{R}(\psi) \triangleq \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \boldsymbol{M} \triangleq \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{23} & m_{33} \end{bmatrix}, \tag{3}$$

$$\boldsymbol{D} \triangleq \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}, \quad \boldsymbol{B} \triangleq \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \\ 0 & b_{32} \end{bmatrix}. \tag{4}$$

The Coriolis and centripetal matrix $\boldsymbol{C}$ is obtained from $\boldsymbol{M}$ as described in Fossen (2011). The particular structure of $\boldsymbol{M}$ and $\boldsymbol{D}$ is justified by Assumptions 1-4. The actuator configuration matrix $\boldsymbol{B}$ has full column rank and maps the control inputs T_u and T_r into forces and moments acting on the vessel. Finally, x_g^* from Assumption 3 is chosen so that $\boldsymbol{M}^{-1}\boldsymbol{B}\boldsymbol{f} = [\tau_u, 0, \tau_r]^T$. The point $(x_g^*, 0)$ exists for all port-starboard symmetric vehicles (Caharija et al., 2012b). Notice that wind and wave disturbances show up at the dynamic level (2).

2.3 Disturbance Modeling

Inspired by Fossen (2011), the environmental loads due to wind and wind waves are modeled as a slowly varying combination of the forces F_u and F_v, and the moment M_r. They act in a slowly varying direction β_e, relative to i (see Figure 1). To simplify the problem and given the symmetry properties of the vessel (Assumption 2), it is assumed that there is no sea loads in sway and yaw in presence of head/following sea ($\beta_e - \psi = \pi, 0$), and no sea loads in surge and yaw in presence of beam sea ($\beta_e - \psi = \pm\pi/2$). Therefore, the proposed expression of the body-fixed environmental load vector $\boldsymbol{w} \in \mathbb{R}^3$ is:

$$\boldsymbol{w} \triangleq \begin{bmatrix} F_u \cos(\beta_e - \psi) \\ F_v \sin(\beta_e - \psi) \\ -M_r \sin(2(\beta_e - \psi)) \end{bmatrix}. \tag{5}$$

Remark 3. The distribution of sea loads on marine structures is actually a more complex function of the disturbance attack angle. However, (5) represents a fair approximation for many surface vessels, in particular with respect