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Integral Line-of-Sight Guidance of Underwater Vehicles Without Neutral Buoyancy ⋆

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Abstract: This paper analyzes an integral line-of-sight guidance law applied to an underactuated underwater vehicle. The vehicle is rigorously modeled in 5 degrees of freedom using physical principles, and it is taken into account that the vehicle is not necessarily neutrally buoyant. The closed-loop dynamics of the cross-track error are analyzed using nonlinear cascaded systems theory, and are shown to achieve uniform semiglobal exponential stability. Hence, the integral line-of-sight guidance law compensates for the lack of neutral buoyancy, and it is no longer necessary to assume that the vehicle is perfectly ballasted. The exponential convergence properties of the guidance law are demonstrated in simulations of an autonomous underwater vehicle.

Keywords: path following, guidance systems, LOS guidance, underactuated vessel, disturbance compensation, exponentially stable, cascade control

1. INTRODUCTION

Guidance laws for underactuated marine vehicles makes it possible for vehicles equipped with fixed stern propellers and steering rudders to achieve control goals such as path following, tracking and maneuvering, described in Encarnação and Pascoal (2001), Breivik and Fossen (2009) and Fossen (2011). Precise path following is of particular importance in operations such as inspection of submarine pipelines, seabed mapping, and environmental monitoring.

The line-of-sight (LOS) path following principle, used in Healey and Lienard (1993), Pettersen and Lefeber (2001), Fossen et al. (2003), Breivik and Fossen (2004) and Fredriksen and Pettersen (2006), aims the vessel towards a point ahead on the path. Pettersen and Lefeber (2001) proved uniform global asymptotic and uniform local exponential stability (UGAS and ULES, or κ-exponential stability as defined in Sørdalen and Egeland (1995)) of the LOS guidance law in connection with a 3 degrees of freedom (3-DOF) vehicle model. A more complete vehicle model was included in Børhaug and Pettersen (2005) and Fredriksen and Pettersen (2006), while Fossen and Pettersen (2014) proved that the LOS guidance law achieves uniform semiglobal exponential stability (USGES), which gives stronger convergence and robustness properties.

Integral action was added to the LOS guidance law in Børhaug et al. (2008) to compensate for environmental kinematic disturbances such as ocean currents. The resulting integral line-of-sight (ILOS) guidance law for 3-DOF vehicles was proved to be globally κ-exponentially stable in Caharija et al. (2012a) and Caharija et al. (2014), and USGES and UGAS in Wiig et al. (2015).

ILOS guidance was applied to underwater vehicles modeled in 5-DOF in Caharija et al. (2012b) and Caharija et al. (2016), which added an ILOS guidance law in the vertical plane. The system was again shown to achieve κ-exponential stability.

All of the above mentioned works assume that the vehicle is neutrally buoyant, which requires perfect ballasting. In practice this can be difficult to achieve since water density changes with salinity, temperature and depth. This paper investigates the effect of positive or negative buoyancy on an underactuated underwater vehicle controlled by an ILOS guidance law. The 5-DOF kinematic and dynamic model used in Caharija et al. (2012b) and Caharija et al. (2016), which includes kinematic disturbances from constant and irrotational ocean currents, is extended to include effects caused by the lack of neutral buoyancy. The main contribution of the paper is to use the results of Fossen and Pettersen (2014) and Wiig et al. (2015) to prove that the closed-loop cross track error dynamics are

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UGAS and USGES, even when the vehicle is not neutrally buoyant.

This paper is organized as follows: Section 2 gives a description of the vehicle model in 5-DOF, and states the control objective. Section 3 describes the ILOS guidance law and the surge, pitch and yaw controllers that are analyzed in this paper. The stability of the closed-loop system is analyzed in Section 4. Simulations demonstrating exponential stability are shown in Section 5, and some concluding remarks are given in Section 6.

2. SYSTEM DESCRIPTION

2.1 Basic assumptions

The following basic assumptions are used in the modeling and analysis of the system:

Assumption 1. The body-fixed coordinate frame b is located at a point $(x_g, 0, 0)$ from the vehicle's center of gravity (CG), along the center line of the vessel.

Assumption 2. The vehicle is passively stable in roll, and roll motion can hence be neglected.

Assumption 3. The difference between vehicle weight W and buoyancy B, defined as $W_E = W - B$, is assumed known and constant. Furthermore, CG and the center of buoyancy (CB) are located on the same vertical axis in b.

Remark 1. This is a relaxation of the neutral buoyancy assumption in previous works, such as Caharija et al. (2016).

Assumption 4. The vehicle is symmetric in the $x-z$ plane and has a large length to width ratio.

Assumption 5. The surge mode is decoupled from the other degrees of freedom, and only couplings in sway-yaw and heave-pitch are considered.

Assumption 6. The damping is considered linear.

Remark 2. The passive nature of nonlinear damping forces should enhance the directional stability of the vehicle, as noted in Caharija et al. (2016).

Assumption 7. The ocean current $\boldsymbol{v}_c \triangleq [V_x, V_y, V_z]^T$ in the inertial frame i is assumed to be constant, irrotational and bounded. Hence, there exists a constant $V_{\max} \geq 0$ such that $V_{\max} \geq \sqrt{V_x^2 + V_y^2 + V_z^2}$.

2.2 System Model

The vehicle is modeled in 5-DOF with $\boldsymbol{\eta} \triangleq [x, y, z, \theta, \psi]^T$ containing position and orientation in the inertial frame i. The velocity of the vessel in the body-fixed coordinate frame b is represented by $\boldsymbol{\nu} \triangleq [u, v, w, q, r]^T$, where u is surge speed, v is sway speed, w is heave speed, q is pitch rate and r is yaw rate.

The current velocity in the body frame b is $\boldsymbol{\nu}_c = \boldsymbol{R}^T(\theta,\psi)\boldsymbol{v}_c = [u_c, v_c, w_c]^T$, where $\boldsymbol{R}(\theta,\psi)$ is the rotation matrix from b to i given in (3). From Assumption 7 it follows that $\dot{\boldsymbol{v}}_c = \mathbf{0}$ and $\dot{\boldsymbol{\nu}}_c = [rv_c - qw_c, -ru_c, qu_c]^T$.

The vessel model is represented using velocities relative to the ocean current, as described in Fossen (2011). The body-fixed relative velocity is given by $\boldsymbol{\nu}_r \triangleq \boldsymbol{\nu} - \boldsymbol{\nu}_c = [u_r, v_r, w_r, q, r]^T$, where u_r, v_r and w_r are relative surge, sway and heave speed. The 5-DOF model of the vehicle is

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{\nu}_r + \boldsymbol{\nu}_c, \tag{1a}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}}_r + \boldsymbol{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{D}\boldsymbol{\nu}_r + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{B}\boldsymbol{f}, \tag{1b}$$

where $\boldsymbol{M} = \boldsymbol{M}^T > 0$ is the mass and inertia matrix including hydrodynamic added mass, the matrix $\boldsymbol{C}$ contains Coriolis and centripetal terms, and $\boldsymbol{D}(\boldsymbol{\nu}_r)$ is the hydrodynamic damping matrix. The matrix $\boldsymbol{B} \in \mathbb{R}^{5\times 3}$ is the actuator configuration matrix, while $\boldsymbol{f} \triangleq [T_u, T_q, T_r]^T$ is the control input vector with surge thrust T_u, pitch rudder angle T_q and yaw rudder angle T_r. The term $\boldsymbol{J}(\boldsymbol{\eta})$ is the velocity transformation matrix

$$\boldsymbol{J}(\boldsymbol{\eta}) \triangleq \begin{bmatrix} \boldsymbol{R}(\theta,\psi) & 0 \\ 0 & \boldsymbol{T}(\theta) \end{bmatrix}, \tag{2}$$

where $\boldsymbol{T}(\theta) \triangleq \mathrm{diag}(1, 1/\cos(\theta)), |\theta| \neq \frac{\pi}{2}$.

Following Assumption 3, the gravity restoration vector $\boldsymbol{g}(\boldsymbol{\eta}) \triangleq [W_E\sin(\theta), 0, -W_E\cos(\theta), (BG_zW + W_Ez_b)\sin(\theta), 0]^T$, where BG_z is the vertical distance between CG and CB and z_b is the z-coordinate of the center of buoyancy in the body frame. Compared to the gravity restoration vector used in Caharija et al. (2016), the vector $\boldsymbol{g}(\boldsymbol{\eta})$ includes additional forces in surge and heave resulting from W_E, as well as an addition to the moment in pitch.

The matrix $\boldsymbol{C}$ is obtained from $\boldsymbol{M}$ as described in Fossen (2011), while the other system matrices can be expressed as:

$$\boldsymbol{R} \triangleq \begin{bmatrix} c_\psi c_\theta & -s_\psi & c_\psi s_\theta \\ s_\psi c_\theta & c_\psi & s_\psi s_\theta \\ -s_\theta & 0 & c_\theta \end{bmatrix}, \boldsymbol{D}_l \triangleq \begin{bmatrix} d_{11} & 0 & 0 & 0 & 0 \\ 0 & d_{22} & 0 & 0 & d_{25} \\ 0 & 0 & d_{33} & d_{34} & 0 \\ 0 & 0 & d_{43} & d_{44} & 0 \\ 0 & d_{25} & 0 & 0 & d_{55} \end{bmatrix},$$

$$\boldsymbol{M} \triangleq \begin{bmatrix} m_{11} & 0 & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 & m_{25} \\ 0 & 0 & m_{33} & m_{34} & 0 \\ 0 & 0 & m_{43} & m_{44} & 0 \\ 0 & m_{25} & 0 & 0 & m_{55} \end{bmatrix}, \boldsymbol{B} \triangleq \begin{bmatrix} b_{11} & 0 & 0 \\ 0 & 0 & b_{23} \\ 0 & b_{32} & 0 \\ 0 & b_{42} & 0 \\ 0 & 0 & b_{53} \end{bmatrix}. \tag{3}$$

The terms $s_\cdot \triangleq \sin(\cdot)$ and $c_\cdot \triangleq \cos(\cdot)$ are used for brevity.

The structure of the system matrices is justified by Assumptions 2 - 6. The point x_g from Assumption 1 is chosen to lie on the pivot point of the ship, which gives $\boldsymbol{M}^{-1}\boldsymbol{B}\boldsymbol{f} = [\tau_u, 0, 0, \tau_q, \tau_r]^T$, where τ_u is the control force in surge, and τ_q and τ_r is the control moment in pitch and yaw.

2.3 System Model in Component Form

The 5-DOF model in (1) can be represented in component form:

$$\dot{x} = u_r c_\psi c_\theta - v_r s_\psi + w_r c_\psi s_\theta + V_x, \tag{4a}$$

$$\dot{y} = u_r s_\psi c_\theta + v_r c_\psi + w_r s_\psi s_\theta + V_y, \tag{4b}$$

$$\dot{z} = -u_r s_\theta + w_r c_\theta + V_z, \tag{4c}$$

$$\dot{\theta} = q, \tag{4d}$$

$$\dot{\psi} = r/c_\theta, \tag{4e}$$

$$\dot{u}_r = F_{u_r}(\theta, v_r, w_r, r, q) - \frac{d_{11}}{m_{11}}u_r + \tau_u, \tag{4f}$$

$$\dot{v}_r = X_{v_r}(u_r)r + Y_{v_r}(u_r)v_r, \tag{4g}$$