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Brief paper

Automatic bottom-following for underwater robotic vehicles[☆]

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ABSTRACT

In this note we propose a solution for the automatic bottom-following problem for a low cost autonomous underwater vehicle. We consider the case that the seabed profile is not known in advance, and we show that it is possible to solve the bottom-following using only one echo sounder and without the need to measure the vertical velocity component (heave velocity). To this effect, we propose an output feedback controller that is obtained by first re-formulating the bottom-following into a trajectory tracking problem, then constructing a reference signal generator (the exo-system) using Fourier series theory, and finally solving the control design problem in the framework of nonlinear output regulation theory. An interesting feature of this approach is that the combination of the Fourier series with output regulation problem allows to bypass the need to compute explicitly the Fourier coefficients. To obtain an approximate solution of the resulting regulator equations we resort to pseudo-spectral methods. Stability analysis that takes explicitly into account the effects of the inner-loop autopilots, disturbances, and measurement noise is presented. Simulation results with real seabed data show the effectiveness of the proposed controller.

1. Introduction

The bottom-following or seabed tracking problem has been identified as one core task in an increasing number of scientific (and military) applications that require autonomous underwater vehicles (AUV) to execute traverses at a constant altitude from the sea bottom.

One of the first works reported in the literature on bottom-following using underwater vehicles can be traced in Bennett, Leonard, and Bellingham (1995) where proportional integrator type controllers are proposed. In Caccia, Bono, Bruzzone, and Veruggio (2003), a Lyapunov based controller for a Remotely Operated Vehicle (ROV) is developed that uses the estimated altitude and seabed slope from the measurements given by two echo sounders. Another method proposed in Silvestre, Cunha, Paulino, and Pascoal (2009) for bottom-following takes into account the terrain characteristics ahead of the vehicle that are also provided by two echo sounders. The main idea amounts to formulate the problem as a discrete time path following control task, where a conveniently defined state error in the space model of the plant is augmented with bathymetric preview data.

This paper is concerned with the case that the seabed profile is not known in advance and with the additional restriction that the proposed bottom-following solution is to be applied to small low cost AUVs that have limited navigation sensors. In particular, we consider the case that there is only a single beam acoustic altimeter sensor, and furthermore, it does not carry on-board a device (e.g., a DVL) that provides the linear heave (vertical) velocity w. It is important to stress that the above mentioned limitations pose considerable challenges for control design and to the best of authors knowledge there are no bottom-following solutions that address such important practical case.

In this note, we design an output feedback bottom-following control algorithm that exploits the output regulation framework and pseudo-spectral methods to approximate the solutions of the regulator equations. To this effect, the main idea is to first re-formulate the bottom-following as a trajectory tracking problem, then construct an exo-system by resorting to Fourier series to approximate the seabed profiles, and finally solve the control design problem in the framework of nonlinear output regulation theory. An interesting feature of this approach is that the combination of

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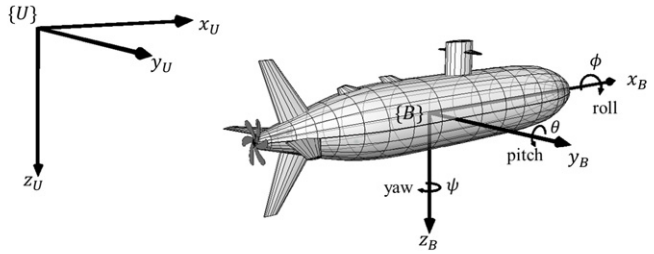

Fig. 1. Coordinate frames, positions and orientations of an AUV.

the Fourier series with output regulation problem allows to bypass the need to compute explicitly the Fourier coefficients, and further, the resulting dynamic controller embodies naturally an observer of the seabed profile. We also consider the practical situation that there exist inner-loop tracking controllers for the linear surge velocity u and pitch angular rate q and take their dynamics explicitly into account in the stability analysis and control design. In particular, we show that the tracking error converges to a small neighborhood of zero, whose size depends on the size of the external disturbances and measurement noise, and also on the fact of not having perfect inner-loop autopilots. With ideal autopilots (infinite bandwidth) and in the absence of disturbances and noise, the error converges to zero.

The paper is organized as follows: Section 2 describes the nonlinear model for the vertical plane dynamics of an AUV and formulates precisely the addressed bottom-following problem. Section 3 states the output feedback controller design procedure, and in Section 4 the stability analysis is discussed. In Section 5, the performance of the proposed control algorithm is evaluated using computer simulations and real seabed data. Section 6 contains concluding remarks. Part of this work was presented in preliminary form in Adhami-Mirhosseini, Aguiar, and Yazdanpanah (2011).

2. Control problem formulation

This section describes the AUV equations of motion used for control design and formulates the bottom-following problem. Fig. 1 illustrates the AUV coordinate frames, position and orientation variables. In general, the motion of an AUV can be described using six degrees of freedom (DOF) differential equations of motion, which can be highly nonlinear and coupled, see e.g., Fossen (1994). In practice, the procedure adopted to simplify the controller design, is to split the equations into two noninteracting models for the vertical and horizontal planes, Jalving (1994). For the bottom-following case and for control design, we are concerned with the vertical plane and we follow the model simplification strategy. Later, it will be shown that this strategy is indeed adequate because the closed-loop system is locally stable as long as the neglected coupling terms are locally bounded. Further, simulation results with the complete six degrees of freedom model show that the impact on the closed-loop performance is almost negligible. In the vertical plane, the kinematic equations take the form

$$\dot{x} = u\cos\theta + w\sin\theta \tag{1a}$$

$$\dot{z} = -u\sin\theta + w\cos\theta \tag{1b}$$

$$\dot{\theta} = q \tag{1c}$$

where u, w and q are the linear and angular velocities of the vehicle, respectively, in surge (x_B), heave (z_B) and pitch (θ) direction of the body-fixed coordinates $\{B\}$. The Cartesian coordinates of the vehicle's center of mass is denoted by x and z, and θ is the pitch angle. Collecting in the vector $\tau_e = (\tau_{e_u}, \tau_{e_w}, \tau_{e_q})$ the effects of the environmental disturbances, neglected coupling terms, and unmodeled dynamics, the simplified equations of motion for surge, heave, and pitch rate when there is no actuated force in Z_B direction (that is, the vehicle is underactuated) yield

$$m_u\dot{u} + m_w wq + d_u(u)u = \tau_u + \tau_{e_u} \tag{2a}$$

$$m_w\dot{w} - m_u uq + d_w(w)w = 0 + \tau_{e_w} \tag{2b}$$

$$m_q\dot{q} + m_{uw}uw + d_q(q)q - z_B B\sin\theta = \tau_q + \tau_{e_q} \tag{2c}$$

where $m_u = m - X_{\dot{u}}$, $m_w = m - Z_{\dot{w}}$, $m_q = I_y - M_{\dot{q}}$ and $m_{uw} = m_u - m_w$ are mass and hydrodynamic added mass terms, $d_u(u) = -X_u - X_{u|u|}|u|$, $d_w(w) = -Z_w - Z_{w|w|}|w|$ and $d_q(q) = -M_q - M_{q|q|}|q|$ are hydrodynamic damping effects, and B denotes the buoyancy. The values of these scalar parameters are listed in the simulation section for a particular AUV. In the equations, and for clarity of presentation, it is assumed that the AUV is neutrally buoyant and that the center of buoyancy can be expressed as $(x_B, y_B, z_B) = (0, 0, z_B)$, where z_B is the metacentric height. The symbols τ_u and τ_q denote the actuated force in surge direction and torque around the y-axis of the vehicle, respectively.

We consider the practical situation that there exist inner-loop controllers in charge of tracking reference signals in u and q, and that these autopilots controllers can be even characterized by an n-order nonlinear dynamics as long as locally the origin of the related linearized unforced dynamics is asymptotically stable. For simplicity, in the paper we will assume that they are locally characterized by first order stable dynamics.

The bottom-following problem can be stated as follows: *consider the AUV vertical model (1) and (2) together with measurements on the depth z and altitude h from the seabed. Derive output feedback control laws for the surge reference velocity u_r and pitch rate reference velocity q_r to drive the vehicle to move along an X_B direction with a desired horizontal velocity V_d at a specified constant height h_d from the seabed.*

3. Controller design

In this section we derive the output feedback control laws to solve the bottom-following problem. In what follows we will neglect the term τ_e and the dynamics of the inner-loop feedback laws. They will be explicitly taken into account in the stability analysis section.

Step 1: *Converting the bottom-following into a trajectory tracking problem*

Let $z_s(x)$ be the (unknown) seabed profile that we would like the vehicle to track and let T_x be a given predefined length. Using Fourier series Steffens (2006), we can approximate z_s by a finite combination of N sinusoidal functions with frequencies $\Omega_i = \frac{2\pi}{T_x}i$, amplitude A_i and phase φ_i, i.e.,

$$\hat{z}_s(x) = A_0 + \sum_{i=1}^{N} A_i \sin(\Omega_i x + \varphi_i). \tag{3}$$

To represent (3) as a function of time, we first compute the surge velocity reference $u_r(t)$ for the speed controller such that the horizontal velocity of the vehicle is regulated to the desired value V_d. In this case, from (1) it follows that

$$u_r = \frac{V_d - w\sin\theta}{\cos\theta} \tag{4}$$

where we have assumed that the pitch angle of the vehicle is not close to the singular points $(2k \pm 1)\pi/2$, which in practice for this type of marine vehicles is a reasonable assumption. Later, u_r in (4) will be redefined to address the fact of not requiring measurements of the heave velocity w.

From (4) we can now conclude that when $u = u_r$ we have $\dot{x} = V_d$ and therefore $x(t) = V_d(t - t_0) + x(t_0)$. Without loss of generality set $t_0 = 0$ and $x(0) = 0$. By this relation between time