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Dynamics of underwater gliders in currents

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ABSTRACT

Although underwater vehicles often operate in time-varying, nonuniform currents, the effect of flow gradients on vehicle dynamics is typically ignored in motion models used for control and estimation. Forces and moments due to a nonuniform flow field are strongest when apparent mass effects are important and flight paths are most sensitive to these disturbances when flow-relative velocities are small – precisely the situation for underwater gliders. This paper presents a nonlinear multi-body dynamic model for an underwater glider operating in an unsteady, nonuniform flow. The eight degree of freedom model incorporates a cylindrically actuated moving mass, a common glider actuation scheme. To illustrate the utility of this full dynamic model, numerical motion predictions are compared with those of simpler models for a variety of nonuniform flow fields. We also demonstrate the use of the full dynamic model for flow estimation using parameter adaptive filtering.

1. Introduction

As applications for autonomous ocean vehicles expand into more dynamic and constrained environments, such as shallow, coastal areas, the benefits of using more precise motion models for control and estimation become more compelling. In typical control applications, either a vehicle's dynamics are ignored completely (a kinematic model) or the attitude dynamics are ignored (a point mass model).

Depending on the problem at hand, simplistic models are sometimes sufficient to capture the effects of a flow field on a vehicle's motion. For synoptic scale path planning (Techy, 2011; Isern-González et al., 2011), for example, it may suffice to use a kinematic particle model, where the vehicle's flow-relative speed is a control input. However, underwater gliders operating in shallow water, such as coastal environments, are subject to time-varying, nonuniform currents which can vary on a scale approaching the vehicle's dimensions. Vehicles operating in nonuniform flow fields are subject to forces that are not captured by kinematic models and moments that are not accounted for in point mass models. A nonlinear dynamic model for a vehicle in an unsteady, nonuniform flow was developed in Woolsey (2011) and Thomasson and Woolsey (2013). The vehicle was modeled as a rigid body and the flow field was assumed to comprise a steady, nonuniform flow component and an unsteady, uniform flow component. These investigations illustrated that the dynamic effects of a flow field can have a significant impact on a vehicle's path, particularly when the flow-relative speed is small and the fluid is dense.

To better appreciate the effect of a nonuniform flow on the dynamics of an underwater glider, and to support motion planning and flow field estimation, we extend the derivation of Woolsey (2011) and Thomasson and Woolsey (2013) to incorporate the multibody dynamics of an underwater glider. Applications of the motion model include simulation of underwater glider dynamics in currents, as well as motion control and state estimator design. To illustrate the utility of this full dynamic model, model predictions are compared with those of simpler models for various nonuniform flow fields. We also demonstrate the use of this full dynamic model for flow estimation using parameter adaptive filtering.

Earlier dynamic models for underwater gliders have incorporated rectilinear motion models for the movable internal mass that provides attitude control (Graver, 2005; Mahmoudian et al., 2010). Here, we adopt a cylindrically actuated moving mass, which matches the mechanization of several existing gliders including *Seaglider* (Eriksen et al., 2001), *Spray* (Sherman et al., 2001), and a glider recently developed at Virginia Tech (Wolek et al., 2012). The control system is a variant of the feedforward/feedback control architecture detailed in Mahmoudian and Woolsey (2013), however, the feedforward term is determined using a

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numerical trim solver rather than the analytical approximation described in Mahmoudian et al. (2010).

The need to measure natural flow fields often arises in the environmental sciences, such as oceanography, meteorology and climatology; see Cuzol et al. (2007), for example. Knowledge of an ambient flow field is also important for autonomous vehicle navigation, as noted in Batista et al. (2009), and for optimal trajectory planning, as noted in Inanc et al. (2005). Remote ocean sensing methods, such as radar or satellite imagery, can provide dense flow measurements at the ocean's surface, but the flow characteristics change dramatically with depth. Measuring or estimating currents is straightforward when vehicle position measurements are available, as from an acoustic positioning system (Batista et al., 2010; Casey et al., 2007; Lee et al., 2007). For a vehicle that obtains GPS updates each time it surfaces, one may determine depth averaged currents based on the dead reckoning error (Petrich et al., 2009; Merckelbach et al., 2008). When absolute position and velocity measurements are unavailable, however, a direct measurement of the flow velocity is impossible.

With an accurate dynamic model for an underwater glider in currents, though, one might identify some flow characteristics even without absolute position or velocity measurements. This information might then be used to enhance dead reckoning performance or to provide additional data for ocean scientists. Because underwater gliders spend most of their time in stable, steady motion (except at the surface or when “pulling up” at the bottom of a dive), these low-cost, long-endurance vehicles offer an opportunity to measure three-dimensional currents. By recognizing the structure of the nonuniform flow perturbation, one may develop a parameter adaptive filter to estimate flow gradients.

The paper is organized as follows. Section 2 presents the multibody dynamic model for an underwater glider, with a cylindrically actuated moving mass, that is operating in an unsteady, nonuniform flow field. In Section 3 we discuss comparisons between the full dynamic model derived here and simpler models (a kinematic and a dynamic particle model) for a variety of different nonuniform flows. In Section 4, we develop and illustrate an adaptive filter for flow gradient estimation. Section 5 summarizes the main contributions and describes some additional applications and avenues for continuing research.

2. Underwater glider dynamic model in nonuniform currents

In this section, we develop a full dynamic model for an underwater glider in an unsteady, nonuniform flow field. We formulate the problem as in Woolsey (2011) and Thomasson and Woolsey (2013), for rigid vehicle motion in a flow field, but we include the multibody effect of a cylindrically actuated movable point mass.

2.1. Kinematics

The eight degree of freedom glider is modeled as a rigid body (mass $m_{\rm rb}$) with a single moving point mass ($m_{\rm p}$) that is offset from the centerline. The point mass can move longitudinally, along the vehicle's length, and can revolve around the vehicle centerline. The vehicle also includes a variable ballast actuator whose effect is represented by a variable point mass ($m_{\rm b}$) fixed at the body frame origin. The total vehicle mass is

$$m = m_{\rm rb} + m_{\rm p} + m_{\rm b},$$

where the rate of change of $m_{\rm b}$ is an input, enabling buoyancy-powered propulsion. The vehicle displaces a (fixed) volume of fluid of mass $\overline{m}$ so that the net mass is $\tilde{m} = m - \overline{m}$.[1] If $\tilde{m}$ is greater than zero, the vehicle is heavier than the fluid it displaces and tends to sink while if $\tilde{m}$ is negative, the vehicle is buoyant and tends to rise.

The vehicle's attitude is given by a proper rotation matrix $\boldsymbol{R}$ which maps free vectors from the body-fixed reference frame to a reference frame fixed in the inertial space. The inertial frame is represented by an orthonormal triad $\{\boldsymbol{i}_1, \boldsymbol{i}_2, \boldsymbol{i}_3\}$, where $\boldsymbol{i}_3$ is aligned with the local direction of gravity. The body frame is defined by an orthonormal triad $\{\boldsymbol{b}_1, \boldsymbol{b}_2, \boldsymbol{b}_3\}$, where $\boldsymbol{b}_1$ is aligned with the body's longitudinal axis. The origin of the body frame sits at the vehicle's center of buoyancy (CB), which remains fixed under our assumptions. While it is straightforward to allow for an offset CB (see Thomasson, 2000, for example), we avoid this additional complication in the interest of clarity. The center of mass (CM) of the glider (neglecting the contribution of $m_{\rm p}$) is located at $\boldsymbol{r}_{\rm rb}$; see Fig. 1. Let the inertial vector $\boldsymbol{X} = [\xi, \eta, \zeta]^T$ represent the position vector from the origin of the inertial frame to the origin of the body frame. Let $\boldsymbol{v} = [u, v, w]^T$ and $\boldsymbol{\omega} = [p, q, r]^T$ represent the translational and the rotational velocity of the body with respect to the inertial frame, but expressed in the body frame. The kinematic equations are

$$\dot{\boldsymbol{X}} = \boldsymbol{R}\boldsymbol{v} \tag{1}$$

$$\dot{\boldsymbol{R}} = \boldsymbol{R}\hat{\boldsymbol{\omega}} \tag{2}$$

where $\hat{\cdot}$ denotes the 3×3 skew-symmetric matrix satisfying $\hat{\boldsymbol{a}}\boldsymbol{b} = \boldsymbol{a} \times \boldsymbol{b}$ for vectors $\boldsymbol{a}$ and $\boldsymbol{b}$.

Following Thomasson and Woolsey (2013), we consider a flow field $\boldsymbol{V}_{\rm f}(\boldsymbol{X}, t) = \boldsymbol{V}_{\rm u}(t) + \boldsymbol{V}_{\rm s}(\boldsymbol{X})$ where $\boldsymbol{V}_{\rm u}(t)$ represents an unsteady, uniform flow component and $\boldsymbol{V}_{\rm s}(\boldsymbol{X})$ represents a steady, circulating flow component. Expressing these two flow components in the body-fixed reference frame, we have

$$\boldsymbol{v}_{\rm u}(\boldsymbol{R}, t) = \boldsymbol{R}^T \boldsymbol{V}_{\rm u}(t) \quad \text{and} \quad \boldsymbol{v}_{\rm s}(\boldsymbol{R}, \boldsymbol{X}) = \boldsymbol{R}^T \boldsymbol{V}_{\rm s}(\boldsymbol{X}) \tag{3}$$

In the moving body frame, the flow field is denoted

$$\begin{aligned} \boldsymbol{v}_{\rm f}(\boldsymbol{R}, \boldsymbol{X}, t) &= \boldsymbol{R}^T \boldsymbol{V}_{\rm f}(\boldsymbol{X}, t) \\ &= \boldsymbol{v}_{\rm u}(\boldsymbol{R}, t) + \boldsymbol{v}_{\rm s}(\boldsymbol{R}, \boldsymbol{X}) \end{aligned} \tag{4}$$

Note that $\boldsymbol{v}_{\rm f} = \boldsymbol{0}$ does not imply that the fluid is at rest. Rather, it implies that the motion of the fluid is due solely to the body's motion through it.

In addition to the six degrees of freedom associated with the vehicle's translation and rotation, there are two degrees of freedom associated with the moving mass, which is modeled as a particle. To describe the point mass position, we define a third orthonormal “actuator” triad $\{\boldsymbol{a}_1, \boldsymbol{a}_{\rm r}, \boldsymbol{a}_\mu\}$, where $\boldsymbol{a}_1$ is parallel to $\boldsymbol{b}_1$. The vector $\boldsymbol{a}_{\rm r}$ points in the radial direction from the vehicle centerline through the point mass; see Fig. 1. The vector $\boldsymbol{a}_\mu$ completes the right handed frame. Let the proper rotation matrix $\boldsymbol{R}_{\rm BP}$ map free vectors from this particle-fixed frame to the body frame:

$$\boldsymbol{R}_{\rm BP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\sin\mu & -\cos\mu \\ 0 & \cos\mu & -\sin\mu \end{pmatrix}$$

Let

$$\tilde{\boldsymbol{r}}_{\rm p} = r_{{\rm p}_x}\boldsymbol{a}_1 + R_{\rm p}\boldsymbol{a}_{\rm r} = \begin{pmatrix} r_{{\rm p}_x} \\ R_{\rm p} \\ 0 \end{pmatrix}_{\rm p}$$

[1] Note that we have defined a fixed control volume around the vehicle, so that the vehicle's mass varies, rather than its buoyancy. Alternatively, one could define a deformable control volume, in which case mass would remain constant and the buoyant force would vary.

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