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Short Communication

Dynamical sliding mode control for the trajectory tracking of underactuated unmanned underwater vehicles

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ABSTRACT

This paper proposes a novel adaptive dynamical sliding mode control based methodology to design control algorithms for the trajectory tracking of underactuated unmanned underwater vehicles (UUVs). The main advantage of the approach is that the combination of backstepping and sliding mode control enhances the robustness of an UUV in the presence of systematical uncertainty and environmental disturbances. The position and attitude dynamical equations of an underactuated UUV are first represented and analyzed using coordinate transformation with the aid of backstepping technique. Subsequently, the output feedback problem is tackled by employing adaptive sliding mode control to estimate the systematical uncertain states required by the stable velocity tracking controller. The final controlled system can be proved to be globally asymptotically stable based on Lyapunov stability theory. Simulations performed on an underactuated UUV demonstrate the effectiveness of the proposed method.

1. Introduction

Over the last few years, it has witnessed a great amount of research in the area of motion control of underactuated unmanned underwater vehicles (UUVs) (Aguiar and Joao, 2007). However, a control problem of UUVs continues to pose challenges to system designers, since most of them are underactuated, i.e., they have fewer actuators than the number of degrees of freedom, imposing nonintegrable acceleration constraints (Yuh, 2000). In addition, UUVs' kinematic and dynamic models are highly nonlinear and coupled, and the hydrodynamic parameters are often uncertain, especially when the vehicle may subject to unknown disturbances from ocean currents (Fossen, 1994), making trajectory tracking control design a hard work.

Focusing on the motion control of UUVs, trajectory tracking control has received relatively more attention than path following problem, since it is concerned with the design of control laws that force the vehicle to reach and follow a time-varying parameterized trajectory. Currently, different control strategies that are available for the trajectory tracking and path following of UUVs are proposed in the literature.

In Kaminer et al. (1998) and Khac and Jie (2009), a linearization method was proposed to solve the trajectory tracking control, respectively. However, the basic limitation of the approach is that the stability is only guaranteed in a neighborhood of the selected operating points. Moreover, performance can suffer significantly when the vehicle executes maneuvers that emphasize its nonlinearity and cross coupling. On the basis of backstepping and associated Lyapunov functions, some research results were proposed to tackle the control for underactuated UUVs; see for example (Pettersen and Egeland, 1999; Lapierre and Soetanto, 2007; Repoulias and Papadopoulos, 2007). Besides, a current observer was presented based on the Lyapunov stability theory and by using the backstepping technique to estimate the unknown constant ocean current (Bi et al., 2010). However, in most existing backstepping based techniques, these results require a very restrictive assumption that yaw reference velocity must satisfy persistent excitation conditions and thus, it does not converge to zero (Serrano et al., 2014). Consequently, the approach suffers from the drawback that a vehicle cannot track straight-line reference trajectories.

Compared with backstepping, adaptive control is considered to be better for plants with uncertainties because it can improve its performance with little or no information of the bounds on uncertainties. Hence, global output-feedback tracking control (Do et al., 2004a, 2004b; Bidyadhar et al., 2013), model-based output feedback control (Refsnes et al., 2008), and adaptive output feedback control based on DRFNN (Ge and Wang, 2002; Zhang et al., 2009) for underactuated UUVs were proposed, respectively. However, a drawback of these adaptive control approaches is computationally intensive for higher order systems and effective only for constant and slowly varying parameters. Unlike above adaptive

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control, robust adaptive control technique shows the special characteristics in trajectory tracking of underactuated UUVs with unknown parameters and environmental disturbances. A novel method of time delay control that can be thought of as "instantaneous learning" of the system dynamics was proposed in Kumar et al. (2007). Implementation of the control law requires the derivative of the system states to be known, which generally considered as a drawback when it has to be calculated based on the state measurement. In Do et al. (2004a, 2004b), a nonlinear robust adaptive control strategy was proposed by using Lyapunov's direct method, the popular backstepping and parameter projection techniques.

In this paper, a methodology of the combination of backstepping and adaptive dynamical sliding mode control is proposed for underactuated UUVs to deal with the planar trajectory tracking control problem. In such a way, the proposed controller is robust and adaptive to the systematical uncertainty and environmental disturbances. Moreover, the proposed control law adopts virtual velocity error dynamics to represent attitude errors, and thus simplifies the representation of the controller. The position and attitude dynamical equations of an underactuated UUV are first derived and analyzed using coordinate transformation with the aid of backstepping technique. Subsequently, the output feedback problem is tackled by employing adaptive sliding mode control to estimate the systematical uncertain states required by the stable velocity tracking controller. Also, to demonstrate the effectiveness and performance of the developed control strategy, simulation results for the following three scenarios are presented as a circular trajectory with constant velocity, Dubins paths, and a sinusoidal trajectory with time-varying velocity. The main contributions of this paper can be summarized as follows:

(i) A methodology of the combination of backstepping and adaptive sliding mode control is proposed to design control algorithms for the trajectory tracking of underacutated UUVs. Global uniform asymptotic stability of the overall control system is proved in the paper.
(ii) Different from the traditional approach to construct Lyapunov functions, the paper utilizes a virtual velocity variable to represent the attitude error, which can avoid the occurrence of representation singularities and simplify the analytical expression of the controller.
(iii) To enhance the robustness of an underactuated UUV against to model parameter uncertainties and unknown environmental disturbances, the novel sliding surfaces are designed in terms of the velocity errors, position errors and approximate errors. In comparison with the previous work, the controller cannot only realize tracking the trajectories with constant velocity, but also satisfy the constraints with time-varying velocity.

2. Problem formulation

The section describes the kinematic and dynamic models of an underactuated UUV moving in the horizontal plane, and then formulates the problem of trajectory tracking control. The notation is standard.

2.1. UUV modeling

To study the planar motion, the general kinematic and dynamic equations of an UUV moving in the horizontal plane can be developed using an earth-fixed reference frame {E} and a body-fixed reference frame {B} as shown in Fig. 1. Here, we briefly present the mathematical model of a neutrally buoyant UUV under the following assumptions that (i) the center of mass (CM) coincides with the center of buoyancy (CB), (ii) the mass distribution is homogeneous, (iii) the hydrodynamic drag terms of order higher than two are negligible, and (iv) the heave, pitch, and roll motions can be neglected. Then, as by Repoulias and Papadopoulos (2007), the kinematics and dynamics of an underactuated UUV can be expressed by the following differential equations:

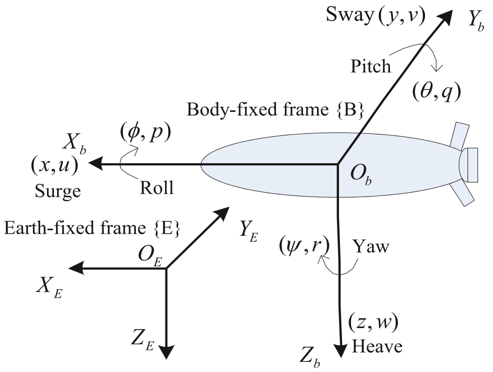

Fig. 1. Reference frames of an unmanned underwater vehicle.

$$\begin{cases} \dot{x} = \cos(\psi)u - \sin(\psi)v, \\ \dot{y} = \sin(\psi)u + \cos(\psi)v, \\ \dot{\psi} = r, \\ \dot{u} = \frac{m_{22}}{m_{11}}vr - \frac{d_{11}}{m_{11}}u + \frac{\tau_u + \tau_{w1}}{m_{11}}, \\ \dot{v} = -\frac{m_{11}}{m_{22}}ur - \frac{d_{22}}{m_{22}}v + \frac{\tau_{w2}}{m_{22}}, \\ \dot{r} = \frac{m_{11} - m_{22}}{m_{33}}uv - \frac{d_{33}}{m_{33}}r + \frac{\tau_r + \tau_{w3}}{m_{33}} \end{cases} \tag{1}$$

where (x, y) denotes the position coordinates of an UUV in the earth-fixed frame, ψ is the yaw angle of the vehicle, and u, v and r are the surge, sway, and yaw velocities, respectively. The surge force τ_u and the yaw torque τ_r are considered as the available control inputs. Parameters m_{ii} and d_{ii} are assumed to be positive constants and are given by the vehicle inertia and damping matrices. Clearly, the UUV is underactuated because the sway force is missing in Eq. (1).

2.2. Control objectives

In order to facilitate the formulation, we first define the actual variables $\mathbf{p} = [x(t), y(t), \psi(t)]^T$ and $\mathbf{v} = [u(t), v(t), r(t)]^T$. Let $\mathbf{p_d} = [x_d(t), y_d(t), \psi_d(t)]^T$ be a given sufficiently smooth time-varying desired trajectory with $\mathbf{v_d} = [u_d(t), v_d(t), r_d(t)]^T$ the reference velocity, and its derivatives with respect to time are bounded. Considering the underactuated UUVs represented in (1), we shall design a controller to render all the tracking errors $||\mathbf{p} - \mathbf{p_d}||$ and $||\mathbf{v} - \mathbf{v_d}||$ converge to a neighborhood of the origin that can be made arbitrarily small. Therefore, in comparison with path-following problem, the control objective to force the underactuated vehicle given in (1) to asymptotically track a smooth time parameterized trajectory by designing the control inputs τ_u and τ_r is considered in the paper. In addition, the control laws should be robust against to model parameter uncertainties and unknown environmental disturbances while guaranteeing a satisfactory performance of the vehicle, so it is desired to design the controller that globally uniformly asymptotically stabilize the tracking errors of an underactuated vehicle with systematical parametric uncertainties and unknown disturbances from the ocean environment (Fig. 2).