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Terminal sliding mode control for the trajectory tracking of underactuated Autonomous Underwater Vehicles

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ABSTRACT

The aim of this paper is to develop robust control schemes for the lateral motion of underactuated autonomous underwater vehicles (AUVs). The AUV complex dynamics makes their control a challenging task. These challenges include the AUV nonlinear dynamics, unmodeled dynamics, system uncertainties and environmental disturbances. The objective of the proposed control schemes is to solve the trajectory tracking problem of AUVs. These controllers are designed using the concepts of terminal sliding mode control. The control performance of an example AUV (the REMUS AUV), using the proposed control schemes, is evaluated through computer simulations. The simulation results show that the proposed control schemes work well. Moreover, simulation studies are given to evaluate the performance of the proposed control schemes when bounded disturbances are acting on the vehicle. These studies indicate that the proposed control schemes are robust under bounded disturbances.

1. Introduction

In the last decades, autonomous underwater vehicles (AUVs) have been the focus of many oceanic research works due to their emerging applications in many fields. These applications include the exploration of oceans, oceanographic mapping, underwater pipelines inspection, scientific and military missions, and more. These tasks should be performed in an automated way without the interaction of human operators under a variety of load conditions and with unknown sea currents. Therefore, it is necessary to develop robust control schemes that force an AUV to track a desireer to accomplish such hard tasks.

In the literature, the control of AUVs and marine vehicles has been targeted by many researchers. To this end, different control techniques have been used such as sliding mode control (Wang et al., 2012; Yoerger and Slotine, 1985; Healey and Lienard, 1993), higher order sliding mode (Joe et al., 2014), learning control (Yuh, 1994), adaptive control (Qi, 2014; Sahu and Subudhi, 2014; McGann et al., 2008; Antonelli et al., 2003; Do et al., 2004; Li and Lee, 2005), backstepping control (Repoulias and Papadopoulos, 2007), Neural network control (Wang et al., 2014; Yuh, 1990; Fujii and Ura, 1990), fuzzy control (Khaled and Chalhoub, 2013; Wang and Lee, 2003) and suboptimal control (Geranmehr and Nekoo, 2015). However, the control of AUVs continues to be challenging due to the AUV complex dynamics, dynamic effects not known to the controller, system uncertainties and environmental disturbances. Furthermore, most practical AUVs are underactuated where the available actuators are less than the number of degrees of freedom which adds more challenges to the control design. These challenges along with the wide applications of AUVs generate considerable interest on the control of AUVs and serve as a motivation for this work.

Furthermore, the terminal sliding mode control (TSMC) is used for the design to provide robustness against unmodeled dynamics, model uncertainties and external disturbances due to ocean currents and waves. TSMC is known to be superior over the conventional sliding mode control technique in terms of the finite-time convergence and high steady state tracking precision. It has been used in many works in order to achieve fast and finite-time convergence as well as high precision, for example, see (Feng et al., 2002, 2013; Neila and Tarak, 2011; Zou et al., 2011; Wang and Sun, 2012).

Control schemes were developed to tackle the trajectory tracking problem of AUVs. Some of these schemes have drawbacks in their design such as considering the trajectory tracking problem for some special cases of reference trajectories as in (Ashrafiuon et al., 2008; Lefeber et al., 2003; Pettersen and Nijmeijer, 2001; Jiang, 2002). In Ashrafiuon et al. (2008), a sliding mode controller for the trajectory tracking of surface vessels was proposed that can only track special cases of reference trajectories as will be highlighted later. In Lefeber et al. (2003), Pettersen and Nijmeijer (2001) and Jiang (2002), control

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laws are developed for the trajectory tracking of underactuated ships using Lyapunov's theory. However, these controllers cannot provide tracking of straight lines because they have restrictions on the rotational motion of the vehicle. Therefore, the main contribution of this work is to develop terminal sliding mode control schemes to solve the trajectory tracking problem of AUVs in the horizontal plane. These developed controllers overcome the drawbacks of the controllers mentioned above by proposing a new design for the AUV's desired velocities that provides tracking for general cases of reference trajectories.

The organization of this paper is as follows. Section 2 presents a model of AUVs for the lateral motion. In Section 3, the problem of the trajectory tracking control of underactuated AUVs is formulated. Section 4 presents the design of the proposed control schemes using the terminal sliding mode concepts. The performance of these controllers are validated using computer simulations, and the results are given in Section 5. Moreover, Section 6 provides simulation studies in order to investigate the robustness of the derived control schemes under bounded disturbances. Section 7 highlights the conclusions of this work.

2. AUV modeling

Following standard practice, modeling an AUV can be treated by handling two parts which are kinematics and kinetics. The kinematics refers to the study of the geometrical aspects of motion while the kinetics deals with the forces causing the motion (Fossen, 2011). In general, the motion of an AUV involves 6 degrees of freedom (DOFs). These DOFs correspond to the set of independent displacements and rotations which determine the position and orientation of the vehicle, and they are referred to as the surge (longitudinal motion), the sway (lateral motion), the heave (vertical motion), the roll (rotational motion about the longitudinal axis), the pitch (rotational motion about the lateral axis) and the yaw (rotation about the vertical axis) (Fossen, 2002).

In this study, only the motion in the horizontal plane (lateral dynamics) of the AUV is considered which includes the surge, the sway and the yaw. The model for the lateral motion of an AUV can be developed using two special reference frames. These frames are the *Earth-fixed* $\{n\}$ reference frame, which is considered to be inertial and its origin is fixed, and the *body-fixed* $\{b\}$ reference frame, which is a moving frame fixed to the vehicle, as depicted in Fig. 1. The origin of the body-fixed frame is defined usually to coincide with the vehicle's center of mass, and the axes of this frame are chosen along the vehicle's principle axes of inertia.

A complete modeling of AUVs is derived and presented in Fossen (2002) as well as standard models for horizontal and longitudinal motions. The model of the horizontal motion of AUVs is the one considered in this work. The kinematic equations of this model are such that:

$$\dot{x} = u\cos\psi - v\sin\psi\dot{y} = u\sin\psi + v\cos\psi\dot{\psi} = r \tag{1}$$

where u and v are the surge and the sway linear velocities of the AUV respectively, r is the yaw angular velocity of the AUV, x and y express the coordinates of the vehicle's center of mass, and ψ describes the orientation of the vehicle. The position and orientation of the AUV (i.e. (x, y, ψ)) are defined in the earth-fixed frame $\{n\}$ while the linear and angular velocities (i.e. (u, v, r)) are defined in the body-fixed frame $\{b\}$.

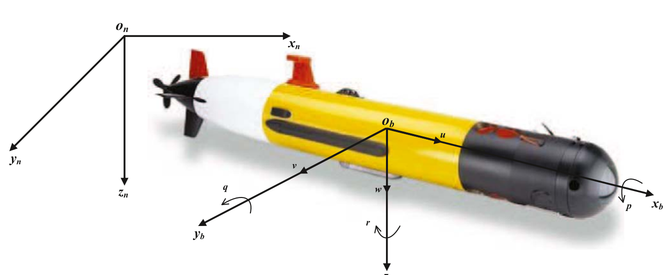

Fig. 1. The earth-fixed and body-fixed reference frames for an AUV.

Consider the following notation: m is the mass of the AUV, I_z is the vehicle's moment of inertia about the z-axis, X_u, Y_v and N_r are negative terms that include the effects of linear damping, and $X_{\dot{u}}$, $Y_{\dot{v}}$ and $N_{\dot{r}}$ are the hydrodynamic added mass terms in the surge, the sway and the yaw directions of motion respectively. By neglecting the heave, roll and pitch motions, the lateral dynamics of an AUV can be represented by:

$$\dot{u} = M_1(X_u u + a_{23} vr + \tau_u)\dot{v} = M_2(Y_v v + a_{13} ur)\dot{r} = M_3(N_r r + a_{12} uv + \tau_r) \tag{2}$$

where $M_1 := 1/(m - X_{\dot{u}})$, $M_2 := 1/(m - Y_{\dot{v}})$, $M_3 := 1/(I_z - N_{\dot{r}})$, $a_{12} := Y_{\dot{v}} - X_{\dot{u}}$, $a_{13} := X_{\dot{u}} - m$ and $a_{23} := m - Y_{\dot{v}}$. The control inputs are the surge force τ_u and the yaw moment τ_r generated by the actuators.

Clearly, the control problem of the AUV model represented by (1) and (2) is considered to be underactuated since actuation forces and moments are generated in the surge and yaw directions only while the sway motion is unactuated .

3. Problem formulation

3.1. Trajectory tracking error coordinates

In order to formulate the trajectory tracking control problem investigated in this work, consider the model of the AUV for the lateral motion given by (1) and (2). Define the following position tracking errors,

$$x_e = x - x_d y_e = y - y_d \tag{3}$$

where x_d and y_d are the coordinates of the desired, time-varying position. The position error dynamics can be obtained by taking the time derivatives of the position errors in (3), and using (1), as follows:

$$\begin{bmatrix} \dot{x}_e \\ \dot{y}_e \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} - \begin{bmatrix} \dot{x}_d \\ \dot{y}_d \end{bmatrix}. \tag{4}$$

Also, let the velocity tracking errors be such that:

$$e_u = u - u_d e_v = v - v_d \tag{5}$$

where u_d and v_d are the desired surge and sway velocities respectively. Taking the time derivative of (5), and using (2), yields the following,

$$\dot{e}_u = M_1(X_u u + a_{26} vr + \tau_u) - \dot{u}_d \dot{e}_v = M_2(Y_v v + a_{16} ur) - \dot{v}_d. \tag{6}$$

3.2. Problem formulation

The trajectory tracking control problem of AUVs refers to the design of control laws so that the vehicle's position (x,y) tracks a desired, time-varying position (x_d, y_d). Fig. 2 shows a block diagram representation of the control problem considered in this work for the AUV trajectory tracking. The formulation of this control problem is such that:

For the AUV model in the horizontal plane described by (1) and (2), derive a control law that computes the applied surge force τ_u and the yaw moment τ_r so that the vehicle's actual position $(x(t), y(t))$ tracks a desired, time-varying trajectory $(x_d(t), y_d(t))$.

4. Control design

4.1. Control design overview

In this section, the proposed control schemes for the trajectory tracking control problem of AUVs are presented. The design is divided into two parts to reduce the complexity of the overall analysis. In the first part, the surge and sway velocities are designed on the kinematic