Ocean Engineering 105 (2015) 270–274

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Study of 3 dimension trajectory tracking of underactuated autonomous underwater vehicle

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ARTICLE INFO

Article history:
Received 11 September 2014
Accepted 23 June 2015
Available online 15 July 2015

Keywords:
AUV
Underactuated
Trajectory tracking
Backstepping

ABSTRACT

This paper addresses the problem of trajectory tracking control for underactuated autonomous underwater vehicles (AUVs) in 3 dimensions space. Given a smooth, inertial, 3D reference trajectory, in order to make the position error to stay in the neighborhood of zero, the control algorithm uses vehicle's kinematic equation and linear system stability theory to compute the desired body-fixed velocities. Using these methods, the velocity error dynamics are obtained. Backstepping techniques are used, forcing the tracking error to an arbitrarily small neighborhood of zero. Simulation of a spiral trajectory is performed. The result shows that the controller can realize 3 dimensions trajectory tracking effectively.

1. Introduction

Autonomous underwater vehicles (AUVs) are now routinely employed in a wide range of civilian and military applications. For example, AUVs perform long-distance, long-duration oceanographic sampling missions (Bellingham and Rajan, 2007), detect and localize pollutant sources (Farrell et al., 2003), and detect, locate, and neutralize undersea mines. Underactuated AUVs are a kind of AUVs having fewer actuators than its degrees of freedom. Many today's AUVs are underactuted ones because there are some potential benefits over full actuated AUVs. In case of actuator failures, a fully actuated AUV becomes an underactuated one which might be still controlled with a good control scheme for underactuated AUVs. Besides that advantage, with the underactuated property, an AUV can be designed to be more streamlined with the reduction of water resistance. The design of underactuated AUVs can also reduce the weight and cost, at the same time increase the reliability of AUVs (Mehmet Selcuk et al., 2009).

Two main motion control objective of AUVs are path following control and trajectory tracking control respectively. Path following control is to follow a predefined path independent of time (no temporal constraints). Moreover, no restrictions are placed on the temporal propagation along the path. Trajectory tracking is that the position and velocity of the AUV should track desired time varying position and velocity reference signals. Sometimes the trajectory tracking control is based on way-point tracking, since a time varying position can be treated as a moving points.

Way-point tracking has been studied by numerous authors in recent years. For a vehicle with movement in six degrees of freedom, the motion is highly coupled and nonlinear. Thus decoupling the altitude control and the planar way-point tracking control may result in poor performance. For systems experiencing quick maneuvers and high speed movement in three dimensional space, such as autonomous underwater vehicles and unmanned aerial vehicles, a 3-dimensional way-point tracking controller is preferable. Borhaug and Pettersen (2005) presented a control strategy for global k-exponential way-point tracking control of a class of underactuated mechanical systems with movement in six degrees of freedom. They use a cascaded approach and a backstepping-based method for synthesizing controllers that satisfy the developed dynamical constraints.

Do et al. (2004) designed a controller using a Lyapunov's direct method, the popular backstepping and parameter projection techniques. The closed loop path following errors can be made arbitrarily small. It is shown that they developed control strategy is easily extendible to situations of practical importance such as parking and point-to-point navigation.

Alessandretti (2013) addressed the design of Model Predictive Control (MPC) laws to solve the trajectory-tracking problem and the path-following problem for constrained under-actuated vehicles. By allowing an arbitrarily small asymptotic tracking error, they derived MPC laws where the size of the terminal set is only limited by the size of the system constraints. The resulting MPC controllers provide a global solution to the addressed constrained motion control problems. This MPC controllers can be applied to 2-D and to 3-D moving vehicles.

One of the main difficulties in designing a motion controller is that many assumptions are made about mass and damping matrices. For example, some studies assume that the off-

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http://dx.doi.org/10.1016/j.oceaneng.2015.06.034
0029-8018/

Table 1
The main parameters of the test AUV.

m	183	λ_5	86	$X_{\dot{u}}$	−13	$Z_{\vert w\vert w}$	−422
I_x	3	λ_6	86	$Y_{\dot{v}}$	−257	$K_{\vert p\vert p}$	0
I_y	95	X_u	−49	$Z_{\dot{w}}$	−257	$M_{\vert q\vert q}$	−62
I_z	95	Y_v	−243	$K_{\dot{p}}$	0	$N_{\vert r\vert r}$	−78
λ_1	13	Z_w	−230	$N_{\dot{r}}$	−86		
λ_2	255	K_p	0	$M_{\dot{q}}$	−86		
λ_3	255	M_q	−140	$X_{\vert u\vert u}$	−16		
λ_4	2.6	N_r	−160	$Y_{\vert v\vert v}$	−542		

diagonal terms are zero (Pettersen and Nijmeijer, 2001; Jiang, 2002; Lefeber et al., 2003), however, because the bow and the stern are not always symmetric, the off-diagonal terms are not zero. So it is imperative to design a controller which is not very sensitive to off-diagonal terms of the mass and damping matrices.

Bong Seok (2015) presented a formation controller for desired formation of underactuated autonomous underwater vehicles (AUVs). They designed the controller assuming that the mass and damping matrices are not diagonal and that hydrodynamic damping terms are unknown. At the same time, they introduced an additional control input and prove the stability using the Lyapunov stability theory.

In this paper, the problem of trajectory tracking control for underactuated AUVs moving on the desired trajectory is addressed. Given a smooth 3D trajectory, the planning algorithm produces desired velocity of $[u_d, q_d, r_d]$ based on the error of position. Then the control forces and moments of $[X, M, N]$ are generated from the controller. The algorithm is based on velocity error of the AUV. The error of position and velocity are connected into a cascaded system, and using the backstepping method, we are able to come up with the proper control forces and moment $[X, M, N]$ in order to make these error converge to arbitrarily small neighborhood of 0. At last, the trajectory used for the illustration during simulation of the method is a spiral line. Simulation results that demonstrate the performance of the developed control design are presented and discussed.

The main contribution of this work is: using the cascaded system and the backstepping method to design a controller for underactuated AUVs with nonlinear dynamic characteristic to perform trajectory tracking without decoupling and the controller is not sensitive to the term arrangement of the damping and mass matrices.

The remainder of this paper is organized as follows: AUV's kinematics and kinetics equation is derived in Section 2. In Section 3, a controller for trajectory tracking is presented based on the linear system stability theory and a backstepping technique using Lyapunov stability theory. In order to demonstrate the effectiveness of the proposed control scheme, certain simulation results are presented in Section 4. Finally, we make a brief conclusion of the paper in Section 5.

2. Underwater vehicle equations of motion and control objective

The AUV is modeled as a neutrally buoyant, rigid body of mass m. The vehicle is equipped with a single propeller, aligned with the axis of symmetry, and with moment actuators that provide independent control in pitch and yaw. In guidance and control applications, for the representation of rotations, it is customary to use the xyz (roll-pitch-yaw) convention defined in terms of Euler angles. To study the motion, we define an inertial reference frame {I} and a body-fixed frame {B} (Fig. 1). The origin of the {B} frame coincides with the AUV center of mass (CM) while its axes are along the principal axes of inertia of the vehicle assuming three planes of symmetry: x_b is the longitudinal axis, y_b is the transverse axis, and z_b is the normal axis.

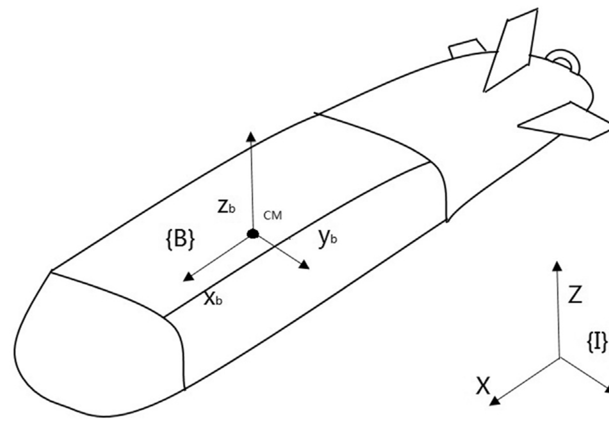

Fig. 1. The underactuated AUV model in plane motion.

The kinematic equations of motion for an AUV in 3 dimension space can be written as

$$\dot{\boldsymbol{\eta}} = J(\boldsymbol{\eta})\mathbf{v} \quad (1)$$

$\boldsymbol{\eta} = \left[\mathbf{p}_{b/n}^{e\ T} \quad \boldsymbol{\Theta}_{nb}^T \right]^T$. $\mathbf{p}_{b/n}^e = \left[x \quad y \quad z \right]^T \in \mathbb{R}^3$ represents the inertial coordinates of the CM of the vehicle, $\boldsymbol{\Theta}_{nb} = \left[\phi \quad \theta \quad \psi \right]^T \in \mathbb{S}^3$ is the orientation of {B} with respect to {I} frame in terms of Euler angles.

$\mathbf{v} = \left[\mathbf{v}_{b/n}^{b\ T} \quad \boldsymbol{\omega}_{b/n}^{b\ T} \right]^T$. $\mathbf{v}_{b/n}^b = \left[u \quad v \quad w \right]^T \in \mathbb{R}^3$ are the surge sway and heave velocities, respectively, defined in the body fixed frame. $\boldsymbol{\omega}_{b/n}^b = \left[p \quad q \quad r \right]^T \in \mathbb{R}^3$ are the body-fixed angular velocities.

$$J(\boldsymbol{\eta}) = \begin{bmatrix} R_b^n(\Theta_{nb}) & 0_{3\times3} \\ 0_{3\times3} & T_\Theta(\Theta_{nb}) \end{bmatrix} \quad (2)$$

where

$$R_b^n(\Theta_{nb}) = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi + \cos\psi\cos\phi\sin\theta \\ \sin\psi\cos\theta & \cos\psi\cos\phi + \sin\phi\sin\theta\sin\phi & -\cos\psi\sin\phi + \sin\theta\sin\psi\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}$$

and

$$T_\Theta(\Theta_{nb}) = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}$$

It follows that the kinetic equations of a rigid body (Fossen, 2011)

$$M\dot{\mathbf{v}} + C(\mathbf{v})\mathbf{v} + D(\mathbf{v})\mathbf{v} + g(\boldsymbol{\eta}) = \boldsymbol{\tau} \quad (3)$$

$$\boldsymbol{\tau} = [X, Y, Z, K, M, N]^T \quad (4)$$

where M accounts for the mass and added mass coefficients, $C(\mathbf{v})$ accounts for the body moments of inertia and added moments of