Ocean Engineering 133 (2017) 244–252

Contents lists available at ScienceDirect

Ocean Engineering

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

Line-of-sight target tracking control of underactuated autonomous underwater vehicles

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ARTICLE INFO

Keywords:
Dynamic surface control
Model uncertainty
Neural networks
Target tracking
Underactuated underwater vehicles

ABSTRACT

This paper studies target tracking control of underactuated autonomous underwater vehicles in the presence of model uncertainties and environmental disturbances. Dynamic surface control, neural networks and adaptive control techniques are employed to develop a target tracking controller for underwater vehicles in three-dimensional space. Then, a Lyapunov-based stability analysis proves that all signals are bounded in the closed-loop control system and tracking errors converge to a neighborhood of the origin. Following advantages are highlighted in this paper: (*i*) the proposed controller utilizes line-of-sight measurements of range and angle sensors to track a manoeuvring underwater target in three-dimensional space; (*ii*) computational complexities of the traditional backstepping method are greatly reduced via command filtering by employing *dynamic surface control* (DSC) technique; (*iii*) the proposed controller is easily implemented in practice without any prior knowledge of vehicle dynamics, parameters and environmental disturbances. At the end, simulation results demonstrate the tracking performance of the proposed control system for offshore applications.

1. Introduction

The tracking control problem of underactuated autonomous underwater vehicles (AUVs) has attracted many attentions in control engineering during past decades. The design of motion controllers for AUVs is of great importance due to their applications in rescue, search, surveillance, exploration, reconnaissance, ocean floor survey, oceanographic mapping, geological sampling, deep sea archaeology, and minesweeping. The interested readers are referred to the survey paper (Yuh, 2000) and its references for the investigation in the design and motion control of AUVs. The main difficulty in the tracking control of underactuated underwater vehicles is due to the lack of independent propellers and rudders in all degrees of freedom. As a result, the nonlinear tracking controller design is very demanding for such systems in the presence of unknown model parameters, uncertain nonlinearities and environmental disturbances caused by waves and ocean currents. Initial researches on the control of underactuated AUVs have been introduced in Nakamura and Savant (1992), Egeland et al. (1996), Leonard (1995) at the kinematic level. However, underwater vehicles are affected by Centripetal, Coriolis and gravity forces during their manoeuvring such that strong nonlinear couplings are applied to AUV dynamics. Therefore, AUV nonlinear dynamics should not be neglected in practice. There exist different motion controllers for the stabilization and regulation (Pettersen and Egeland, 1999; Zain et al., 2013; Woolsey and Techy, 2009), AUV homing (Batista et al., 2009), path-following (Lapierre and Jouvencel, 2008; Do et al., 2006), positioning and way-point tracking (Aguiar and Pascoal, 2007), trajectory planning and tracking (Repoulias and Papadopoulos, 2007; Bi et al., 2009), output feedback control (Refsnes et al., 2008; Subudhi et al., 2013), coordinated and formation control (Qi, 2014; Cui et al., 2010) in the literature. In Aguiar and Pascoal (2007), Repoulias and Papadopoulos (2007), Bi et al. (2009), Refsnes et al. (2008), Subudhi et al. (2013), Qi (2014), Cui et al. (2010), Xiang et al. (2015); Xu et al. (2015), Glotzbach et al. (2015), Yan et al. (2015), Park, (2015) and Chen et al. (2016), different tracking controllers have been proposed for underactuated AUVs using a 3-degree-of-freedom (DOF) model. For example, a nonlinear controller has been presented in Xiang et al. (2015) for the planar motion control of AUVs by using backstepping technique and Lyapunov's direct method. Adaptive dynamical sliding mode controller has been proposed in Xu et al. (2015) for the planar trajectory tracking of underactuated unmanned underwater vehicles. Line-of-sight (LOS) target tracking control for multiple heterogeneous unmanned marine vehicles has been proposed in Glotzbach et al. (2015) in a planar motion. A globally finite-time tracking controller has been presented in Yan et al. (2015) for underactuated underwater vehicles under constant unknown current and model parameter perturbation in the horizontal plane. Park (2015) has proposed an adaptive formation controller for underactuated AUVs. Chen et al.

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http://dx.doi.org/10.1016/j.oceaneng.2017.02.007
Received 5 August 2016; Received in revised form 7 November 2016; Accepted 12 February 2017
Available online 21 February 2017
0029-8018/

(2016) have presented an adaptive fuzzy inverse trajectory tracking controller for underactuated underwater vehicles. Unfortunately, mentioned works (Aguiar and Pascoal, 2007; Repoulias and Papadopoulos, 2007; Bi et al., 2009; Refsnes et al., 2008; Subudhi et al., 2013; Qi, 2014; Cui et al., 2010; Xiang et al., 2015; Xu et al., 2015; Glotzbach et al., 2015; Yan et al., 2015; Park, 2015; Chen et al., 2016) only considers the motion control problems in the planar motions. In Ismail et al. (2016), Wang et al. (2015), Mukherjee et al. (2015), Gao et al., (2015), Liu et al. (2016), tracking controllers have been proposed for fully-actuated AUVs in three-dimensional space which are not applicable to underactuated ones. Toward this end, the position tracking control of underactuated underwater vehicles have been addressed in (Li et al., 2015) and (Shojaei and Arefi, 2015). The coordination control and formation of underactuated AUVs have been solved in Do (2013) and (Shojaei, 2016a). One interesting solution for the guidance and navigation of marine vehicles is the LOS control which is employed in (Aguiar and Pascoal (2007), Xiang et al. (2015), Glotzbach et al. (2015) and (Børhaug et al. (2008), Caharija et al. (2012, 2016). An integral LOS controller has been proposed in (Børhaug et al. (2008) for the path-following of underactuated marine surface vessels in the presence of constant ocean currents. Then, Caharija et al. (2012, 2016) have extended this approach to the path-following of underactuated autonomous underwater vehicles. In Peng et al. (2015), a containment controller has been proposed by using a neural DSC stratrgy for networked autonomous underwater vehicles in a planar motion. However, all of the above aforementioned control schemes at least suffer from one of the following shortcomings: (*i*) most of previously proposed controllers generally rely on GPS measurements and there are few works to address the target tracking control of AUVs based on LOS measurements; (*ii*) most of previous research works on the tracking control of underactuated AUVs have been done for their planar motion which are not useful for three-dimensional motions; (*iii*) the third problem is related to the inherent explosion of complexity in the standard backstepping design; and (*iv*) previous adaptive tracking controllers often assume that uncertain nonlinearities are "*linear-in-parameter*" (LIP) which is a restrictive assumption in practice. Toward this end, this paper proposes a dynamic surface target tracking controller for underactuated AUVs in three-dimensional space based on LOS measurements which is not addressed sufficiently in the literature (Yuh, 2000; Nakamura and Savant, 1992; Egeland et al., 1996; Leonard, 1995; Pettersen and Egeland, 1999; Zain et al., 2013; Woolsey and Techy, 2009; Batista et al., 2009; Lapierre and Jouvencel, 2008; Do et al., 2006; Aguiar and Pascoal, 2007; Repoulias and Papadopoulos, 2007; Bi et al., 2009; Refsnes et al., 2008; Subudhi et al., 2013; Qi, 2014; Cui et al., 2010; Xiang et al., 2015; Xu et al., 2015; Glotzbach et al., 2015; Yan et al., 2015; Park, 2015; Chen et al., 2016; Ismail et al., 2016; Wang et al., 2015; Mukherjee et al., 2015; Gao et al., 2015; Liu et al., 2016; Li et al., 2015; Shojaei and Arefi, 2015; Do, 2013; Shojaei, 2016a). According to the above discussion, main contributions of this paper are expressed as follows:

(i) this is the first attempt to propose a line-of-sight target tracking controller based on measurements of range and bearing sensors for the tracking of a manoeuvring underwater target in three-dimensional space;
(ii) computational complexities of the traditional backstepping method are greatly reduced via command filtering by employing a DSC technique. A Lyapunov's direct method is used to analyze the stability of the closed-loop control system. It is proved that the target tracking errors are uniformly ultimately bounded and converge to a small neighborhood of the zero;
(iii) neural networks and adaptive robust control techniques are employed to compensate for unknown vehicle parameters, uncertain nonlinearities, unmodeled dynamics, neural network approximation errors and time-varying environmental disturbances which are induced by waves and ocean currents.

The rest of this paper is arranged as follows. The problem statement is presented in the next section where a coordinate transformation is introduced for the line-of-sight design. In Section 3, main results of this paper are presented. Section 4 provides numerical simulations to evaluate the tracking controller performance. Finally, conclusions are drawn in Section 5.

2. Problem statement

2.1. Underwater Vehicle Kinematics and Dynamics

Consider 5-degree-of-freedom (DOF) mathematical model of an underactuated autonomous underwater vehicle which is subjected to environmental disturbances (Do and Pan, 2009):

$$
\begin{aligned}
\dot{x} &= u\cos(\psi)\cos(\theta) - v\sin(\psi) + w\sin(\theta)\cos(\psi),\\
\dot{y} &= u\sin(\psi)\cos(\theta) + v\cos(\psi) + w\sin(\theta)\sin(\psi),\\
\dot{z} &= -u\sin(\theta) + w\cos(\theta),\\
\dot{\theta} &= q,\\
\dot{\psi} &= r/\cos(\theta),
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\dot{u} &= \frac{m_{22}}{m_{11}}vr - \frac{m_{33}}{m_{11}}wq - f_u(u) + \frac{1}{m_{11}}\tau_u - \frac{1}{m_{11}}\tau_{eu}(t),\\
\dot{v} &= -\frac{m_{11}}{m_{22}}ur - f_v(v) - \frac{1}{m_{22}}\tau_{ev}(t),\\
\dot{w} &= \frac{m_{11}}{m_{33}}uq - f_w(w) - \frac{1}{m_{33}}\tau_{ew}(t),\\
\dot{q} &= \frac{m_{33}-m_{11}}{m_{55}}uw - f_q(q) - \frac{\rho g\nabla GM_L\sin(\theta)}{m_{55}} + \frac{1}{m_{55}}\tau_q - \frac{1}{m_{55}}\tau_{eq}(t),\\
\dot{r} &= \frac{m_{11}-m_{22}}{m_{66}}uv - f_r(r) + \frac{1}{m_{66}}\tau_r - \frac{1}{m_{66}}\tau_{er}(t),
\end{aligned}
\tag{2}
$$

where x, y, z, θ and ψ denote positions (i.e. surge, sway, heave displacements), and orientations (i.e. pitch and yaw angles) of the vehicle, respectively, in the earth fixed frame in Fig. 1. The signals u, v, w, q and r show the surge, sway, heave, pitch and yaw velocities in the body-fixed frame and signals τ_u, τ_q and τ_r represent the torque inputs which are provided by propellers and thrusters, $\tau_{eu}(t)$, $\tau_{ev}(t)$, $\tau_{ew}(t)$, $\tau_{eq}(t)$, $\tau_{er}(t) \in \Re$ denote bounded time-varying environmental disturbances which are induced by waves, wind and ocean currents, m_{ii}, $i = 1, \ldots, 5$ are the mass and inertia parameters of the vehicle, and $f_k(k)$, $k = u, v, w, q, r$ stand for unknown nonlinear dynamics of AUV including hydrodynamic damping and friction terms. Other parameters and symbols can be found in Do and Pan (2009) and Fossen (2002).

Remark 1:. The roll dynamics has been neglected in the vehicle

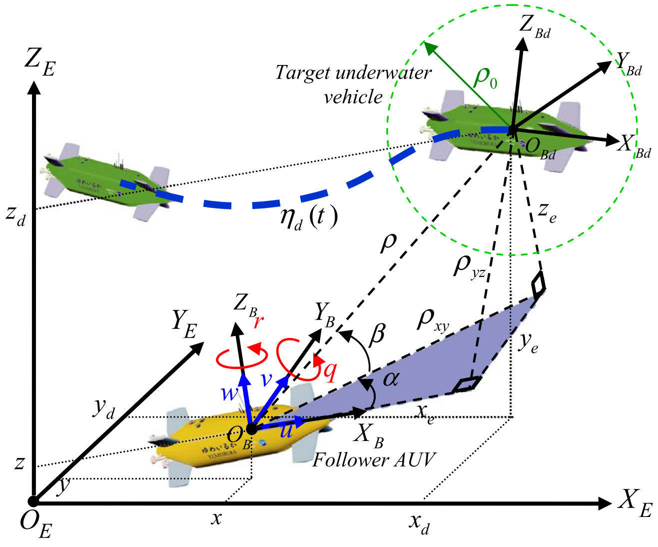

Fig. 1. Target tracking control of underwater vehicles based on range and angles measurements in three-dimensional space.