Ocean Engineering 89 (2014) 69–81

Contents lists available at ScienceDirect

Ocean Engineering

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

Time optimal trajectory design for unmanned underwater vehicle

Mai Ba Loc [a,1], Hyeung-Sik Choi [b,*], Sam-Sang You [b,2], Tran Ngoc Huy [a,3]

[a] Department of Mechanical Engineering, Graduate School, Korea Maritime and Ocean University, South Korea
[b] Division of Mechanical and Energy Systems Engineering, Korea Maritime and Ocean University, South Korea

ARTICLE INFO

Article history:
Received 9 June 2013
Accepted 22 June 2014

Keywords:
Time optimal trajectory
Analytical formulation
Depth control
Sliding mode control
UUV
Uncertainty

ABSTRACT

This paper presents the design of time optimal trajectories for the depth control of an unmanned underwater vehicle. Its approach stems from the fact that the minimum time to destination can be attained when the thruster(s) of the vehicle always operates at maximum thrust levels during the maneuver. Therefore, the nonlinear second order differential equation of depth motion of the vehicle with appropriate constant thrust forces will be analytically solved to find the time optimal trajectories. These resulting trajectories are explicit functions which offer a solution for achieving the shortest travel time provided that a robust trajectory tracking controller is used along. The paper also presents the design of trajectory tracking controller using the sliding mode method. It is shown that this controller forces the vehicle to track the designed time optimal trajectories very well, even with uncertainties. Its robustness can be guaranteed if bounds of the uncertainties are known. The effectiveness of the proposed designs will be demonstrated via simulation results.

1. Introduction

In recent years, a large number of studies on underwater vehicles have been published. However, studies on the optimal control of such vehicles have been rare. It is still a very underdeveloped area (Chyba et al., 2008a). In addition to efficient energy consumption, time optimal maneuver has also become a topic of much interest in optimal control. This paper presents the time optimal trajectories which help the unmanned underwater vehicle (UUV) move to the destination depth as fast as possible. The paper also presents the trajectory tracking controller designed based on the sliding mode method. This controller will force the vehicle to track the desired trajectories.

The most basic depth controller is the regulator, whose input is a constant of destination depth. This controller usually causes sudden changes and unexpected overshoots. The more advanced one is the trajectory tracking controller, whose input is a time-varying position reference signal (trajectory). If the trajectory is well designed (smoothly and feasibly), this controller will perform well, making gradual changes and almost no overshoots. A simple trajectory can be the output of a low-pass filter, whose input is a constant of destination depth, or a polynomial which smoothly connects the departure point with the destination (Fraga et al. 2003). Such trajectories can be easily designed. However, they may not have time (or energy) efficiency. Recently, Chyba et al. presented a numerical method for designing the time optimal trajectory (Chyba et al., 2008b) or the weighted consumption and time optimal trajectory (Chyba et al., 2008a). The numerical method needs a nonlinear optimization solver, which requires discretizing state and control variables of a nonlinear optimization model before using an approximate calculation algorithm to find the time (or/and consumption) optimal trajectories. This method is quite complex and has some weaknesses. The calculation algorithm can only be implemented with a powerful processor and its results take a long time to converge. Because of an offline method, it restricts the controller's automatic ability. The designed optimal trajectories and control forces are given in the form of sequences of discrete values the storage of which requires a large memory. In addition, Chyba et al. (2008a,b) have not been interested in developing a suitable controller which can help the vehicle track the desired trajectories. They presented open-loop controllers, whose inputs are the sequences of predetermined discrete values of control forces. Such controllers cannot ensure a good trajectory tracking performance for the vehicle, as expected, because of the influence of uncertainties such as

* Correspondence to: Room 415, Building A1, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-gu, Busan 606-791, South Korea. Tel.: +82 51 410 4297, mobile: +82 10 5581 2971; fax: +82 51 405 4790.

E-mail addresses: mbloc@hcmut.edu.vn (M.B. Loc), hchoi@kmou.ac.kr (H.-S. Choi), ssyou@hhu.ac.kr (S.-S. You), tran_huy1984@yahoo.com (T.N. Huy).

[1] Present address: Division of Electrical Machines and Apparatus, Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology, 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City 70000, Vietnam. Tel.: +84 8 3864 7256x5746.

[2] Tel.: +82 10 7599 1367.

[3] Tel.: +82 10 6869 7140.

http://dx.doi.org/10.1016/j.oceaneng.2014.06.019
0029-8018/

dynamic perturbations, and disturbances which always exist in the case of underwater vehicles.

In this paper, an analytical method, not a numerical method, is used to find the time optimal trajectories. They are explicit functions given in closed-form expressions, whose formats are unchanged. The use of such functions increases the controller's automatic ability. The proposed controller is a trajectory tracking controller, so it offers optimal time as long as its references (inputs) are the time optimal trajectories, even with uncertainties.

2. Equations of motion

Full equations of motion of an underwater vehicle can be found in Fossen (1994). However, in this paper, because we just consider the design of time optimal trajectories for the depth control of a fully actuated UUV, we only need to consider the body-relative heave velocity w, and the earth-relative vehicle depth z (see Fig. 1). We will set all other translational and rotational velocities to zero, and assume that the roll, pitch and yaw angles of the vehicle always are kept at zero for simplicity. As a result, the mathematical model of depth motion of the UUV is as follows:

$$(m-Z_{\dot{w}})\dot{w}-Z_{w|w|}w|w|=(W-B)+Z_{prop} \tag{1}$$

$$\dot{z}=w \tag{2}$$

where, m: UUV mass, W: vehicle weight, $Z_{\dot{w}}$: added mass coefficient, B: vehicle buoyancy, $Z_{w|w|}$: cross-flow drag coefficient, and Z_{prop}: thrust force.

Substituting Eq. (2) into (1), we have the nonlinear second order differential equation of depth motion as follows:

$$(m-Z_{\dot{w}})\ddot{z}-Z_{w|w|}\dot{z}|\dot{z}|=(W-B)+Z_{prop} \tag{3}$$

Setting $a=m-Z_{\dot{w}}>0$, $b=-Z_{w|w|}>0$, $N=B-W>0$ (net buoyancy), and $u=Z_{prop}$, Eq. (3) becomes

$$a\ddot{z}+b\dot{z}|\dot{z}|+N=u \tag{4}$$

Eq. (4) can be used as a reference model for generating the time optimal trajectories if the values of the parameters a, b, N, u are given. In the next section, the time optimal trajectories are designed by solving Eq. (4) and are given in closed-form expressions.

3. Time optimal trajectory

We will design the time optimal trajectories for a UUV when it moves from the beginning depth z_0 at time t_0 ($z_0=0$, $t_0=0$) to the ending depth z_e at time t_e ($z_e>0$). At both these depth levels, the UUV is at rest, meaning that its velocity is zero ($\dot{z}(t_0)=v_0=0$, $\dot{z}(t_e)=v_e=0$). Depending on the value of the ending depth z_e, there are two plans for the course of the UUV velocity $\dot{z}$. Plan I: if z_e is large, $\dot{z}$ will increase from zero to the critical value v_m (acceleration period); and it will stay at this value for a certain period of time (constant velocity period), and then decrease to zero right at the ending time t_e (deceleration period). Plan II: if z_e is small, $\dot{z}$ will increase from zero to a certain value, not greater than v_m, (acceleration period), and then decrease to zero right at the ending time t_e (deceleration period). Plan II does not have the constant velocity period. In both plans mentioned above, the UUV velocity is always non-negative. So, we can rewrite Eq. (4) as follows:

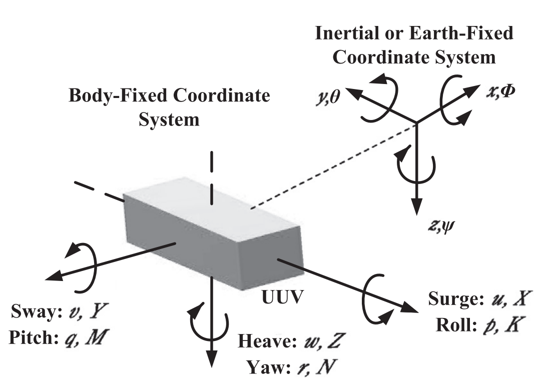

Fig. 1. Body-fixed and inertial coordinate systems.

$$a\ddot{z}+b\dot{z}^2+N=u \tag{5}$$

Setting net force $f=u-N$ (6)

Eq. (5) becomes

$$a\ddot{z}+b\dot{z}^2=f \tag{7}$$

From Eq. (6), if we know the value of the net buoyancy N and the range of the thrust force u, we can calculate the range of the net force f.

Assuming $f_1 \le f \le f_2$, with $f_1<0, f_2>0$, the time optimal trajectories can be obtained by solving Eq. (7) either with $f=f_2$ (corresponding to $u=u_2$) for the constant velocity and acceleration periods or with $f=f_1$ (corresponding to $u=u_1$) for the deceleration period. Here, u_1 and u_2 are the designed constant thrust forces.

3.1. The time optimal trajectories with the constant velocity and acceleration periods

Eq. (7) is rewritten as follows:

$$a\ddot{z}_d+b\dot{z}_d^2=f_2 \tag{8}$$

The constraints for these periods are

$$a,\ b,\ f_2>0 \text{ and } \dot{z}_d,\ \ddot{z}_d \ge 0 \tag{C1}$$

At the beginning time t_0, the initial conditions are

$$\dot{z}_d(t=t_0=0)=v_0=0 \tag{K1}$$

$$z_d(t=t_0=0)=z_0=0 \tag{K2}$$

Here, t denotes the variable of time, and d means 'designed'.

Setting $\dot{z}_d=h(t) \ge 0$ (9)

we have

$$\ddot{z}_d=\frac{dh(t)}{dt} \tag{10}$$

Substituting Eqs. (9) and (10) into Eq. (8) yields

$$a\frac{dh}{dt}+bh^2=f_2 \tag{11}$$

Eq. (11) can be rewritten as

$$a\frac{dh}{dt}=f_2-bh^2 \tag{12}$$

- If $f_2-bh^2 \ne 0$ (acceleration period)
  From Eq. (12), we have

$$a\frac{dh}{f_2-bh^2}=dt \tag{13}$$