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Autonomous Homing and Docking Tasks for an Underwater Vehicle

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Abstract

This paper briefly introduces a strategy for autonomous homing and docking tasks using an autonomous underwater vehicle. The control and guidance based path following for those tasks are described in this work. A standard sliding mode for controller design is briefly given. The method provides robust motion control efforts for an underwater vehicle's decoupled system whilst minimising chattering effects. In a guidance system, the vector field based on a conventional artificial potential field method gives a desired trajectory with a use of existing information from sensors in the network. A well structured Line-of-Sight method is used for an AUV to follow the path. It provides guidance for an AUV to follow the predefined trajectory to a required position with the final desired orientation at the dock. Integration of a control and guidance system provides a complete system for this application. Simulation studies are illustrated in the paper.

Keywords:

Autonomous homing and docking, AUV, sliding mode control, vector field, line-of-sight

Introduction

Autonomous Underwater Vehicles (AUVs) are highly efficient which allows for ability to take control actions more accurately and reliably without human intervention. Long-term applications include collecting biological and mineral resources, seabed mapping and surveying, studying underwater and under-ice environments [1]. The power and data storage for current AUV designs do not allow for long-term deployments. Battery-powered can only rely upon for a few hours before power is depleted. In these long-term missions, data storage are also limited. It is therefore obvious that power and data storage are critical factors for all long-term operations. The inherent short operational periods limit the scope of each undersea exploration. In the future applications, an underwater vehicle should be able to operate continuously to complete one or many large mission(s). However, most underwater vehicles are typically only configured of short-term operation. Vehicles require both software and hardware to be turned off before its batteries can be manually recharged or replaced. To overcome the limitations of the onboard battery and data transfer procedure, a floating docking platform is required to extend the scope of potential missions. A focus on homing and docking operations allows a vehicle to come back to the dock to recharge its own battery and exchange data before continuing its operation. To be able to perform its homing and docking mission accurately, the guidance, navigation and control system must be reliable.

This work aims to develop a strategy in the control and guidance system required for a homing and docking strategy for an AUV. A model of an AUV using this strategy is briefly described and used throughout the paper. Homing and docking strategies are detailed. A trajectory planning for a homing and docking problem is formulated. For an assumption used in this paper, the AUV which is equipped with sensor units is able to track position and orientation from the existing sensor networks technology such as a long baseline system in the environment. In the homing stage, the conventional artificial potential field provides the obstacle avoidance. In the docking stage, the vector field provides guidance for a virtual AUV to follow the path to a required position with a final desired orientation. A weighted vector field is a better model to enhance performance in achieving the desired target. The Line-of-Sight technique allows an AUV to follow the predefined path to the dock. For control system design, a standard sliding mode control is presented. The controller utilises sliding surfaces based in time. A discussion on how this controller can be used for tracking errors of desired states is given.

The paper is organised as follows: Section 2 provides a kinematic model of an AUV. The control law using a sling mode control is detailed in section 3. Section 4 presents a guidance law based on the Line-of-Sight and the vector field path generation. The homing and docking strategy are given in section 5. Integration system with simulation studies for a guidance and control is presented in section 6. Finally, section 7 gives a conclusion.

AUV Modelling

Attitude representation of the kinematic AUV model in the global reference frame is defined using Euler angles [2]. The kinematic equation is therefore written as,

$$\dot{\eta} = J(\Theta)\nu = \begin{bmatrix} R(\Theta) & 0_{3\times3} \\ 0_{3\times3} & T(\Theta) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}, \qquad (1)$$

where $R(\Theta), T(\Theta) \in \Re^{3x3}$ and $\eta, \nu \in \Re^{6x1}$,

and,

$$\nu = [u, v, w, p, q, r]^T,$$

$$\eta = [x, y, z, \phi, \theta, \varphi]^T,$$

where $[u, v, w]^T$, $[p, q, r]^T$ are linear and angular velocities in the x-y-z directions and $[x, y, z]^T$ is the position in the x-y-z directions, $[\phi, \theta, \psi]^T$ is the Euler angles parameters (see Figure 1).

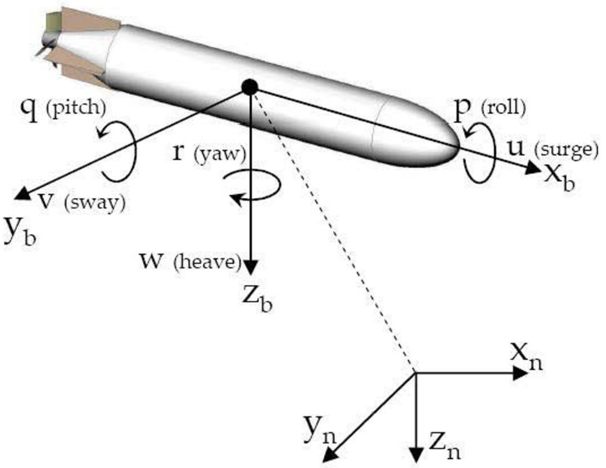

Figure 1 - Six degrees of freedom of an AUV in surge, sway, heave, roll, pitch and yaw motion

Control

Stability schemes in attitude and depth control for nonlinear system [3] are formulated based on the Lyapunov method. The method is a powerful tool for stability analysis which can be used for the design in various nonlinear controllers. One of the most common nonlinear feedback controller designs based on the Lyapunov analysis is the sliding mode control (SMC). It is categorised as a variable structure control system [4]. SMC has been used for AUV control because of excellent stability, robustness and disturbance rejection characteristics. Fundamentally, the sliding mode controller is composed of two main parts, namely the nominal part and also discontinuous terms dealing with uncertainties [5]. The controller with the typical sliding mode drives the system state trajectory onto the sliding surface and maintains that trajectory onto the surface for all times. Thus, the sliding mode becomes insensitive to system disturbances whilst on the sliding surface. Furthermore the significant characteristics of the sliding mode are order reduction and robust stability [5].

Sliding Surface

The sliding surface is designed so that the surface tends to and converges to zero when it satisfies the Lyapunov stability criterion thus the problem of tracking denoted as $x \equiv x_d$ is equivalent to that of remaining on the sliding surface for all time t > 0. The detail of a time-varying sliding surface σ can be found in [6]. The control inputs can be regarded as that for the nominal plant and for the uncertainty of model parameter,

$$u = -kx - K\,\mathrm{sgn}(\sigma) \qquad (2)$$

where K is a constant, corresponding to the maximum value of the controller output. Reducing chattering which is caused by a signum function, a thin boundary layer of thickness around the switching surface is proposed [6],

$$u = -kx - K\mathrm{sat}(\frac{s}{\Phi}) \qquad (3)$$

where the constant Φ defines the thickness of the boundary layer and $\mathrm{sat}(\frac{\sigma}{\Phi})$ is a saturation function that is defined as,

$$\mathrm{sat}(\sigma) = \begin{cases} \frac{\sigma}{\Phi}, & \text{if } \left|\frac{\sigma}{\Phi}\right| \le 1; \\ \mathrm{sgn}(\frac{\sigma}{\Phi}), & \text{otherwise} \end{cases}$$

Subsystems

A controller designed for an AUV control needs to be robust to deal with external disturbance and model uncertainties. However, a simple model is required thus computational time will be relatively short. A controller that is decoupled into two subsystems of heading and depth (see Figure 2) is proposed [6]. An extension version for speed control subsystem is proposed in this work. The sliding mode control law are chosen as,

$$\overline{u}_u = -k_u(u - u_d) + \dot{u}_d \qquad (4)$$

$$\overline{u}_\varphi = \varphi - k_\varphi(u\sin\theta\cos\varphi) - Ksat\left(\frac{\tilde{\varphi}}{\phi_\varphi}\right) \qquad (5)$$

$$\overline{u}_\theta = \theta - k_\theta(u\sin\theta) - Ksat\left(\frac{\tilde{\theta}}{\phi_\theta}\right) \qquad (6)$$

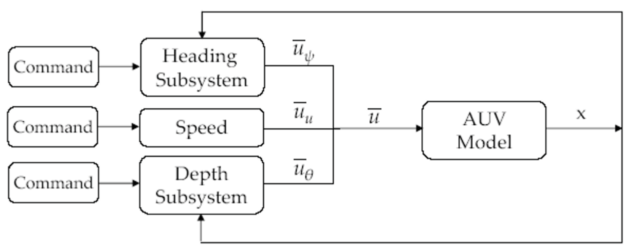

Figure 2 - Subsystems