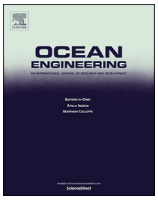
Ocean Engineering 159 (2018) 372–387

Contents lists available at ScienceDirect

Ocean Engineering

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



Disturbance estimator based non-singular fast fuzzy terminal sliding mode control of an autonomous underwater vehicle

B.M. Patre [a,*], P.S. Londhe [b], L.M. Waghmare [a], S. Mohan [c]

[a] *Department of Instrumentation Engineering, Shri Guru Gobind Singhji Institute of Engineering and Technology, Vishnupuri, Nanded, Maharashtra, India*
[b] *Department of Instrumentation Engineering, Government College of Engineering, Chandrapur, Maharashtra, India*
[c] *Discipline of Mechanical Engineering, School of Engineering, Indian Institute of Technology, Indore, Madhya Pradesh, India*

ARTICLE INFO

Keywords:
Autonomous underwater vehicle (AUV)
Finite-time control
Fuzzy logic control
Terminal sliding mode control
Lyapunov stability

ABSTRACT

In this paper, a robust finite time trajectory tracking control approach is proposed for autonomous underwater vehicle (AUV), which belongs to the class of highly nonlinear, coupled dynamics with motion in 6-degrees-of-freedom (DOF). The finite-time error convergence and robust control task is accomplished by designing a non-singular fast fuzzy terminal sliding mode controller (NFFTSMC) with disturbance estimator for the 6-DOF dynamics of an AUV. The proposed NFFTSMC incorporates a non-singular fast terminal sliding mode controller (NFTSMC) which not only assures faster and finite convergence of the tracking errors to the equilibrium from anywhere in the phase portrait but also eliminates the issue of singularity dilemma appeared in conventional terminal sliding mode controller (TSMC); a fuzzy logic control (FLC) tool is employed to generate the hitting control signal in order to reduce chattering in control inputs, which commonly occur in conventional TSMC, and an estimated uncertainty term to compensate for the un-modeled dynamics, external disturbances, and time-varying parameters. Furthermore to investigate the effectiveness of the proposed method, it has been extended to task space control problem of an AUV - manipulator system (AUVMS) employed for underwater manipulation tasks. Simulation studies confirms the potency of the proposed method.

1. Introduction

Over the last few decades, design and development of underwater vehicles for ocean research has gained a huge momentum due to advancement in underwater research. The control system design is one of most active research area in the underwater technology for performing nontrivial underwater missions (Londhe et al., 2017a, 2017b). To ensure operator safety and wide application range, nowadays AUVs are mostly preferred compared to remotely operated vehicles (ROVs) for performing deep and hazardous environmental underwater tasks (Londhe et al., 2017a, 2017b; Jacobi, 2015). To acquire the good quality of data from ocean resources, the accurate position and attitude control of an underwater vehicle is immensely desirable in the existence of highly unstructured ocean environment (Kim et al., 2016; Londhe et al., 2016; Sarhadi et al., 2016). This demands designing of a accurate trajectory tracking control for AUV against the variations in the hydrodynamic coefficients and unknown forces acting on the vehicle due to ocean currents (Londhe et al., 2017c; Ataei and Yousefi-Koma, 2015). Over a period of time, many researchers have been suggested numerous advanced AUV control systems including sliding mode control (SMC), robust and adaptive control, fuzzy logic and neural network control which can accommodate the large perturbations in the AUV dynamics under unstructured ocean environment. Nevertheless, there is still scope to enhance the performance of the AUV's motion when dealing with unstructured and time-varying operating conditions.

Over a few decades, many control methods have been proposed to solve vehicle control issues and can be found in the literature. The linear controllers like proportional-integral-derivative (PID) control were firstly suggested in (Jalving, 1994), designed separately for steering, diving and speed subsystems of the vehicle and subsequently, decoupled proportional-derivative (PD) set-point controller was introduced in (Herman, 2009) for AUVs. However, these controls do not solve the problem of integral windup when actuator goes to saturation. To handle this problem, S. Miyamoto et al. (Miyamaoto et al., 2001) employed a single loop PID structure with an anti-windup technique for maneuvering control of an AUV. As an extension to this, a dual-loop variable

---

[*] Corresponding author.
E-mail addresses: bmpatre@ieee.org, bmpatre@yahoo.com (B.M. Patre), pandurangl97@gmail.com (P.S. Londhe), lmwaghmare@yahoo.com (L.M. Waghmare), santhakumar@iiti.ac.in (S. Mohan).

https://doi.org/10.1016/j.oceaneng.2018.03.082
Received 5 October 2017; Received in revised form 31 January 2018; Accepted 28 March 2018

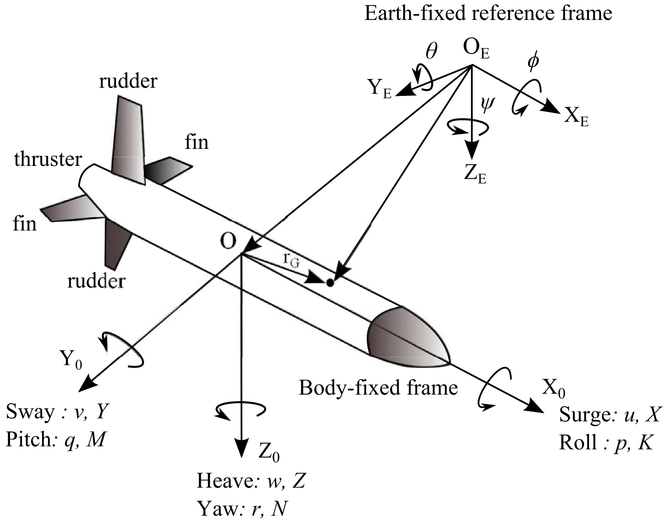


Fig. 1. AUV with body and earth-fixed reference frames.

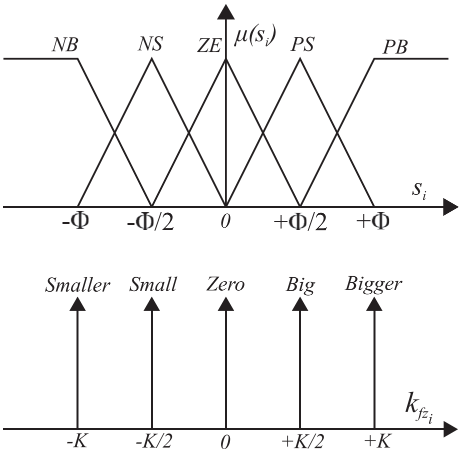


Fig. 2. Membership functions for s_i and.k_{fzi}.

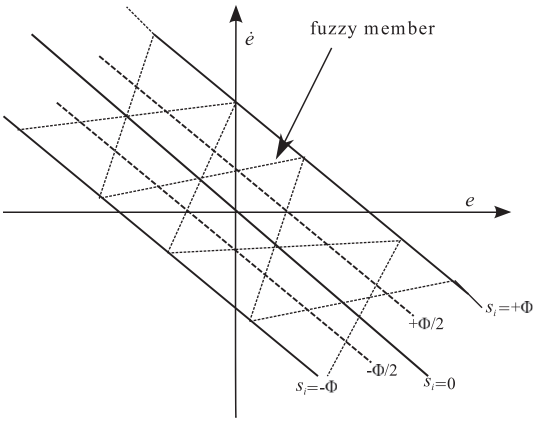


Fig. 3. Fuzzy sliding surface.s_i.

structure-PID controller with the anti-windup technique was adopted in (Kim et al., 2013) for improved performance. The authors in (Feng et al., 2002) and (Roy et al., 2013) proposes a $H\infty$ controller and robust controller respectively in order to deal with hydrodynamic parametric uncertainties and payload variations during path tracking of AUVs.

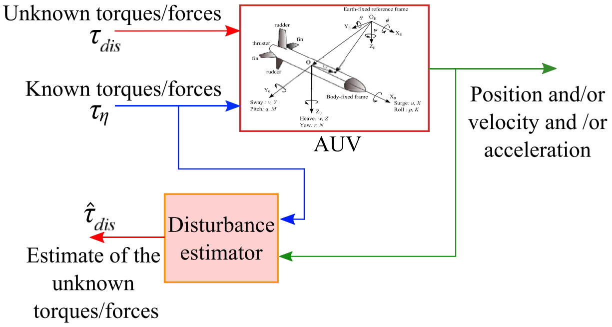


Fig. 4. Concept of disturbance estimator.

Sliding mode control (SMC) technique is one of most efficient and robust control technique due to its invariance properties, like robustness, order reduction and disturbance rejection (Utkin, 1977; Young et al., 1999). Firstly, the SMC was designed for underwater vehicles by Yoerger and Slotine (1985) for robust trajectory tracking control. First experimental results using adaptive SMC were obtained by Yoerger and Slotine (1991) in 1991 and discusses their implementation issues. Furthermore, successful design of decoupled control approaches were proposed by Cristi et al. (1990) using adaptive SMC for AUV in the diving plane and multivariable sliding mode autopilot design by Healey and Lienard (1993) for steering, depth and speed control functions of an AUV. Consequently motion control of an AUV in steering and diving plane was studied in (Rodrigues et al., 1996). Then, in 1999, a discrete-time quasi-SMC was suggested by P. -M. Lee et al. for diving control of an experimental AUV with paramter uncertainties and large sampling interval. Also to strengthen the performance of SMC, a higher order sliding mode control was designed torpedo AUV for diving control (Salgado-Jimenez and Jouvencel, 2003).

The control and coordination of multiple AUVs in horizontal plane have been extensively studied in (Liu and Geng, 2013) by applying finite-time optimal formation control method. However, most of the aforementioned controllers require a full or partial information about hydrodynamic coeeficients and disturbances for the accurate design of control scheme. Additionally, the SMC based control design suffers from the chattering phenomenon. This problem can be overcome by approximating discontinuous term *sgn*() by continouos function like hyperbolic tangent function etc. (Elmokadem et al., 2015). Also, chattering can be reduces by increasing the order of the sliding surface has been successfully examined in (Joe et al., 2014). Furthermore, chattering can be significantly removed by time-delay controller suggested in (Kim et al., 2016; Kumar et al., 2007) and have been successfully applied to tracking control of an AUV. An alternative way to tackle these issue is to use intelligent control approaches like fuzzy logic and neural network control and have been widely applied in control of robotic systems (Chen et al., 2016; He et al., 2016). These intelligent control methods have been successfully applied to the control of underwater vehicles [(Venugopal et al., 1992; Jagannathan and Galan, 2003; Ranganathan et al., 2001; Smith et al., 1994; Song and Smith, 2001)). But, investigating the stability and robustness of these intelligent control methods is found very rigorous and difficult to check (Patre et al., 2015).

Recently, the fusion of soft-computing methodologies like fuzzy logic control (FLC) with sliding mode control becoming a most promising control technique since it gives guaranteed stability and strong robustness against parameter variations (Patre et al., 2015; Kaynak et al., 2001). On the other hand, this fusion attempt to alleviate the implementation issues of the SMC caused due to discontinuous term in the control law of SMC, known as "chattering" (Kaynak et al., 2001). This fusion is commonly termed as a fuzzy sliding mode control (FSMC) in the literature. The main strengths of the FSMC are (Shahraz and Boozarjomehry, 2009): 1) It does not demand full knowledge about the system model because of the qualitative interpretation offered by fuzzy inference