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Review of sliding mode control application in autonomous underwater vehicles

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This paper presents a review of sliding mode control for autonomous underwater vehicles (AUVs). The AUVs are used under water operating in the presence of uncertainties (due to hydrodynamics coefficients) and external disturbances (due to water currents, waves, etc.). Sliding mode controller is one of the nonlinear robust controllers which is robust towards uncertainties, parameter variations and external disturbances. The evolution of sliding mode control in motion control studies of autonomous underwater vehicles is summarized throughout for the last three decades. The performance of the controller is examined based on the chattering reduction, accuracy (steady state error reduction), and robustness against perturbation. The review on sliding mode control for AUVs provides insights for readers to design new techniques and algorithms, to enhance the existing family of sliding mode control strategies into a new one or to merge and re-supervise the control techniques with other control strategies, in which, the aim is to obtain good controller design for AUVs in terms of great performance, stability and robustness.

[Keywords: Autonomous underwater vehicle (AUV); Sliding mode control (SMC); Chattering reduction; Robustness]

Introduction

The autonomous underwater vehicle (AUV) was first invented by a group of researchers from University of Washington as early as 1957, which motivated many other researchers to embark in this field of research. Many techniques were proposed to control the motion of the AUV. The AUV is very useful to be used in dangerous and hazardous operations. The oceans cover almost 70% of the earth; therefore, there are many issues related to ocean such as environmental issues, exploitation of the ocean resources, and routine scientific and military tasks that have given a great impetus to the underwater research. Based on the survey carried out in 1990s[1], al more than 30 new AUVs have been developed worldwide. The development of control stability for an AUV has gained much attention amongst many researchers several years ago[2].

The dynamics of AUVs are: Highly nonlinear, coupled, time varying and include the hydrodynamic uncertainty. Fossen in 1994[3] proposed a generic form of motion equation for marine vessels which also include an AUV. The motion of AUVs is expressed in six degree of freedom (6 DOF) and is defined with respect to two coordinate systems: Initial coordinate frame (or earth-fixed frame) attached to the earth, relative to the fixed origin and motion coordinate system (or body-fixed frame) attached to the centre of mass as shown in Figure 1. The generalized coordinates are divided into translational and rotational coordinates being defined as $\eta = [x, y, z, \phi, \theta, \psi]^T$ or in term of motion can be expressed as 'surge', 'sway', 'heave', 'roll', 'pitch' and 'yaw'. The velocity vector in body coordinate is defined as $v = [u, v, w, p, q, r]^T$. The terms are defined according to the notation of SNAME (1950) for marine vessel as shown in Table 1.

For slender bodies, the hydrodynamic coefficient of the AUV can be estimated using strip theory[3,4,5,6,7]. However, in cases where the shapes of the bodies are not slender such as XRay/Liberdade glider, the strip theory no longer can provide approximation of the coefficients. Another approach is to do experimental test either in sea trial or tow-tank experiments[8]. However, experimental test will incur high cost since the trials or testing procedures need to be run several times. Alternatively, the computational method is another option. The computational fluid dynamics (CFD) is the most popular computational method[7]. It involves solving the Navier-Stokes flow equations numerically using a computer. The semi-empirical method is another method used to estimate the hydrodynamic coefficients[9].

The major issues to control the motion of the AUV are due to the fact that the plant is highly nonlinear, time-varying dynamic behaviour in nature, uncertainties in hydrodynamic coefficients, and also disturbances by ocean currents[1]. Various control methods have been proposed by many researchers to overcome aforementioned issues varying from classical proportional integral derivative (PID) controller, optimal controls such as linear quadratic regulator (LQR) right to hybrid methods by combining two or more control methods.

In this paper, a review focusing on sliding mode control (SMC) for AUV is presented. Almost all classes of SMC motion control strategies are reviewed and highlighted. The aim is to provide an overview of the SMC technology and its advancements which have been applied to AUVs since the first introduction of the controller. The review provides significant important insights for readers to design new techniques and algorithms, to enhance the existing family of SMC strategies into a new one or to merge and re-supervise the control techniques with other control strategies, in which, the ultimate aim is to obtain good controller design for AUVs in terms of great performance, stability and robustness.

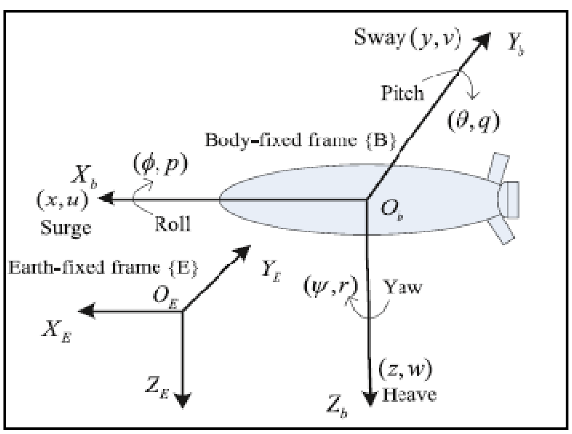

Fig. 1 — Body-fixed and earth-fixed coordinate reference frames

Sliding Mode Control (SMC)

The theory of SMC was first proposed by Emelynov and his team including Utkin and Itkin where the theory was designed based on variable structure control (VSC), in 1960s. However the first journal article was published by Utkin in 1977[10], where he proposed VSC with sliding mode. From there, the SMC approach has attracted many researchers to implement the SMC strategy in many applications such as electromechanical systems and robotics systems. Recently, due to its high robustness against uncertainties/disturbances and parameter variations, many successful practical applications of SMC have been established and the importance of sliding mode theory has mainly developed in the last three decades[11]. The combination of SMC with control techniques also demonstrate better results in both theoretical research and practical engineering[12,13,14,15,16].

The design methodology of SMC comprises two steps: Design of a stable sliding surface that drives the system possess the desired performance (known as reaching phase) and the design of a control law to force the system trajectory onto the chosen sliding surface in finite time and maintain a sliding motion on it thereafter (known as sliding phase)[11,12]. The design of sliding surface should address all the constraints and required specifications; therefore, it should be designed optimally to meet all the requirements. Consider the uncertain nonlinear system is written as

$$\dot{x} = f(x,t)b(x,t,u) + \Delta(x,t) \quad \ldots(1)$$

where f and b are the smooth vectors and the last term is a matched uncertainty. The sliding surface, s is written as

$$s = Cx(t) = c_1x_1 + c_2x_2 + \cdots + c_{n-1}x_{n-1} + x_n \quad \ldots(2)$$

Then the basic SMC control law can be written as

TABLE 1 — THE NOTATION USED FOR MARINE VESSELS [3]

	Description	Parameter	Linear and angular velocity	Position and orientation
1	Motion in the x-direction (surge)	X	u (m/s)	x
2	Motion in the y-direction (sway)	Y	v (m/s)	y
3	Motion in the z-direction (heave)	Z	w (m/s)	z
4	Rotation about the x-axis (roll)	K	p (rad/s)	ϕ
5	Rotation about the y-axis (pitching)	M	q (rad/s)	θ
6	Rotation about the z-axis (yaw)	N	r (rad/s)	ψ

$$u = u_{eq} + u_{dis} \quad \dots (3)$$

u_{eq} is the equivalent control law that is determined based on nominal system that makes the derivative of the sliding surface equals zero to stay on the sliding surface $(\dot{s} = 0)$, and u_{dis} is discontinuous control that rejects the perturbation.

The main drawbacks of SMC is the chattering phenomenon or undesired high frequency oscillations, due to discontinuous switching function (signum) which causes the control signal to oscillate around the sliding mode surface. Another factor contributed to chattering is utilization of digital controllers with finite sampling rate, which causes a so called 'discretization chatter'[17]. This phenomenon can be seen in Figure 2. The chattering phenomenon is harmful because it may deteriorate the control accuracy and system robustness, high wear and tear of moving mechanical components and also energy losses in electrical power circuit.

Several ways are used to overcome the chattering phenomenon. One of them is by replacing the signum function with a smooth function such as saturation or hyperbolic tangent or sigmoid functions considering an ultimate boundedness of the error within some predetermined boundary layer[18,19,20]. Inside the boundary layer, the switching function is approximated by a linear feedback gain. In order for the system behavior to be close to that of the ideal sliding mode, particularly when an unknown disturbance is to be rejected, sufficiently high gain is needed[21].

The ISMC also can be used to reduce the chattering effect. The ISMC was proposed by Utkin and Shi in 1996[22]. In this algorithm, the control law is defined as

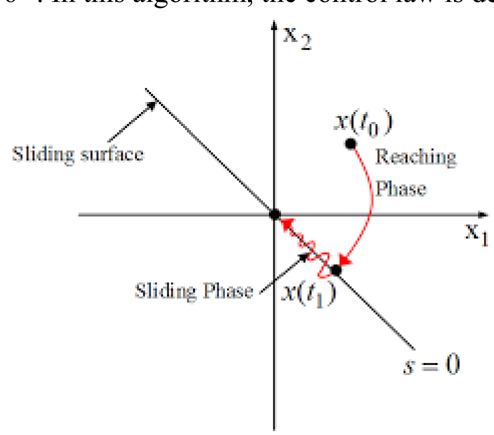

Fig. 2 — The chattering phenomenon near the sliding surface

$$u(x,t) = u_0(x,t) + u_1(x,t) \quad \dots (4)$$

$u_0(x,t)$ is a nominal controller (i.e. the system without perturbation). $u_0(x,t)$ can be designed using any method such as PID, pole-placement, LQR, MPC, etc., $u_1(x,t)$ is composed of an equivalent control, u_{1eq}, and a discontinuous control law, u_{1dis} that rejects the perturbation. The major advantage of ISMC over the conventional SMC is that through this algorithm, a so called perturbation estimator is constructed by removing the discontinuous control action from the real control path and inserting it into an internal dynamic process[22]. Therefore the algorithm is designed without reaching phase[23]. As a result, chattering will not be exited in the controlled plant due to the continuity of the control action, and high degree of robustness and high accuracy of the control can also be preserved. There are many works based on ISMC algorithm[24,25,26,27,28,29].

The higher order sliding mode control (HOSMC) has been used to reduce the chattering phenomenon since it was proposed by Emel'yanov *et al*. in 1996[30]. Later, many researchers employed this approach in many applications[31,32,33,34,35,36]. In HOSMC, the sliding order characterizes the dynamics smoothness degree in the vicinity of the mode. The objective is to keep a constraint given by equality of a smooth function s to zero. The sliding order is known as a number of continuous total derivatives of s (including the zero one) in the vicinity of the sliding mode. Therefore, the r^{th} order sliding mode is determined by the equalities[33].

$$s = \dot{s} = \ddot{s} \dots = s^{r-1} = 0 \quad \dots (5)$$

Among the HOSMC, the second order sliding control (SOSMC) is the most popular used[37,38,39]. The twisting algorithm is another type of SOSMC used for the system with relative degree of two[40]. The super twisting algorithm (STSMC) also falls under second order sliding mode application to system with relative degree of one[41]. It generates the continuous control function that drives the sliding variable and its derivative to zero in finite time in the presence of the smooth matched disturbances with bounded gradient, when this boundary is known. Since STSMC algorithm contains a discontinuous function under the integral, the chattering is not eliminated but attenuated.

Many works have been published based on super twisting algorithm[42,43,44,45,46]. The main drawback of the STSMC is that the knowledge of the boundaries of the disturbance gradients is required. However, in many practical cases, this boundary cannot be easily estimated. Therefore, Plestan *et al.*in [47] has introduced a new algorithm, adaptive STSMC control law so that the perturbed plant dynamics with the additive disturbance/uncertainty of certain class with the unknown boundary can be handled and thus overestimating the boundaries is avoided. Other works related to adaptive STSMC are also found[48,41,49,50,51].

The terminal sliding mode control (TSMC) is another approach used to reduce the chattering effects on the controlled plant. Unlike other SMC strategies, TSMC uses nonlinear sliding surface in its methodology[52,53,54,55]. The sliding surface for TSMC is defined as

$$s = \dot{e} + \beta e^{q/p} \quad \ldots(6)$$

where β is a constant, $0 < q < p$, p and q are odd numbers. When the state of the system is far away from the equilibrium point on the sliding mode surface, the speed of the linear sliding mode surface is higher than the terminal sliding mode surface. On the other hand, when the state of the system is near the equilibrium point, the speed of the terminal sliding mode surface is higher than the linear sliding mode surface. The rational combination of them can make the system acquire a higher speed during the whole stage from any point on the sliding mode surface until the equilibrium point. Nonlinear switching hyperplanes in TSMC can improve the transient performance substantially.

The growth development of digital technology and its widespread use has attracted many researchers to work on the design and implementation of discrete SMC [56]. The discrete SMC was proposed by K. Furuta in 1990[57]. In discrete SMC design, the control is given at every sampling instant defined as $k\Delta$ where Δ is a sampling period. The sliding surface is defined as $s_k = Cx(k)$ or $s_k = Ce(k)$ where $e(k)$ is the error dynamic which is defined as $x(k) - x_d(k)$. Many works have been reported based on discrete SMC[56,58,59]. However, again same as continuous SMC, the discrete SMC is also facing the chattering problem caused by discontinuous control and this may lead to instability of systems because of the sampling rate far away from being infinity, which can be resolved by keeping discontinuous term very small. The summary of SMC strategies is summarized in Table 2.

SMC Implementation in AUVs

The sliding mode control application in AUVs is discusssed here. In 1985, Yoerger and Slotine introduced the basic control strategy using SMC for underwater vehicle due to its robustness towards uncertainty and external disturbances[9]. The SMC was implemented in experimental autonomous vehicle (EAVE) developed by the University of New Hampshire (UNH) simulated based on planar model. In 1988, Dougherty *et al.* also proposed the SMC control strategy which was designed for hovering control of an AUV[60]. The control laws were designed based on nonlinear model[9,60]. Healey and Lienard[8] proposed the SMC control strategy by decoupling the dynamic motion equations into three subsystems: Speed autopilot, steering autopilot, and diving autopilot subsystems.

The SMC control laws were designed for these three subsystems separately. The control law was designed based on AUV linearized model. The performance of the controller was evaluated by simulating in both linearized and nonlinear models. More studies on basic SMC implementation in AUVs were proposed by many other researchers in[61,62,63,64,65,66,67]. In most studies, the motion equations are decoupled into two or three subsystems. The control laws were designed based on the nonlinear equations or based on linearized model with presence of uncertainties and disturbances. As mentioned above the main drawback is chattering phenomena. The approach of using boundary layer to smooth the signum function that caused the chattering phenomenon in tracking problem has been in use[8,60,63,9,68]. The saturation function and hyperbolic function are two common functions used to replace the signum function.

In 1990, Cristi *et al.* proposed the adaptive SMC for dive plane based on linear model that can adjust the changing dynamics and operating conditions[69]. The problem of using the observed state in the control design was addressed. The design was based on input-output signals in terms of dive-plane command and depth measurement. The linear controller was then simulated on a nonlinear model. Later, in 1991, again Yoerger and Slotine improved the previous basic SMC[9] into adaptive SMC[70] and was implemented in underwater vehicle for experimental study. The investigation on the effects of uncertainty of the

TABLE 2 — THE SUMMARY OF SMC CONTROL STRATEGIES FOR A NONLINEAR SYSTEM $\dot{x} = f(x,t) + b(x,t,u) + \Delta(x,t)$

Technique	Sliding Manifold	Control Input
Conventional SMC	Regulation problem: $s = Cx(t) = c_1x_1 + c_2x_2 + \cdots c_{n-1}x_{n-1} + x_n$ Tracking problem: $s = Ce(t) = c_1e_1 + c_2e_2 + \cdots c_{n-1}e_{n-1} + e_n$	$u = u_{eq} + u_{dis}$ where $u_{eq} = -\frac{1}{b}(f + \Delta)$ and u_{dis} can be one of the following: Constant rate: $-k\,sign(s), k \geq 0$ Constant + Proportional rate: $-qs - k\,sign(s), q, k \geq 0$ Power rate: $-k(s)^{\alpha}, \ 0 < \alpha < 1 \text{ and } k \geq 0$
SMC with boundary layer (Quasi Sliding mode)	Same as conventional SMC	Where u_{eq} same as conventional SMC and $u_{dis} = -qs - k\frac{s}{\phi}$
Integral SMC	Same as conventional SMC	$u = u_0 + u_1$ Regulation problem $u_0 = k_1x_1 + k_2x_2 + \cdots k_nx_n$ Tracking Problem $u_0 = k_1e_1 + k_2e_2 + \cdots k_ne_n$ And $u_1 = u_{1eq} + u_{1dis}$ u_{1eq}, u_{1dis}: same as conventional SMC
Dynamic SMC	Same as conventional SMC	$\dot{u}_1 = -q(s - k\,sign(s))$
Twisting SMC	Same as conventional SMC	$u_1 = -k_1 sign(s) - k_2 sign(\dot{s})$ $k_1 > k_2 > 0$
Super-twisting	Same as conventional SMC	$u_1 = -k_1\lvert s\rvert^{1/2} sign(s) - \beta\int_0^t sign(s)$
Terminal SMC	Regulation problem $s = \dot{x} + \beta x^{p/q}$ Tracking problem $s = \dot{e} + \beta e^{p/q}$ $\beta > 0$, p, q are positive odd numbers and $p < q$	u_{eq} , u_{dis}: same as conventional SMC
Fast terminal SMC	Regulation problem $s = \dot{x} + \beta_1 x + \beta_2 x^{p/q}$ Tracking problem $s = \dot{e} + \beta_1 e + \beta_2 e^{p/q}$ $\beta_1, \beta_2 > 0$, p, q are positive odd numbers and $p < q$	u_{eq}, u_{dis}: same as conventional SMC

hydrodynamic coefficients and negligence of cross coupling terms was carried out. After two decades, in 2014, Xiao proposed the adaptive SMC based on backstepping scheme to control a catastrophic course of a high-speed underwater vehicle[71]. The trajectory angle dynamic characteristic was based on the description of the transformed state-coordinates where the nonlinear SMC was designed to track a linear reference model. The adaptive backstepping has improved the robustness against parameter uncertainties and external disturbances.

In a study[72], the combination of SMC with PI (Proportional- Integral) controller was proposed to control the pitch angle and the depth of a STARFISH AUV. The dual loop approach was employed: Inner loop for pitch control and outer loop for depth control. The pitch controller control law was designed based on basic SMC, and the depth controller was designed based on PI algorithm. In this approach, the depth controller generates the desired pitch angle and becomes the input to the pitch controller, where the pitch controller then decides the elevator deflection, based on the desired pitch angle. Shikai *et al.* have proposed the adaptive SMC based on PID[73]. The equivalent control law (u_{eq}) was designed based on PID algorithm and the discontinuous (u_{dis}) was smoothed using boundary layer where the signum function was replaced with saturation function. The sliding mode observer (SMO) is another SMC control strategy used[74]. The controller was designed to deal with sensor faults within the context of navigation controllers for AUV. The proposed SMO with reconfiguration algorithm was tested and the result was compared to SMO without reconfiguration algorithm by looking at the bias error and the heading data loss (completely loss). The robustness of the proposed controller was evaluated in the presence of disturbance.

The HOSMC is another class of SMC used to control the motion of an AUV. Among the HOSMC, the SOSMC is the most popular one[2,75,76,77,78,79,80,81,82]. The SOSMC with switching controller was designed to control surge, yaw, and heave[76]. The simulation result has demonstrated the smallest error as compared to conventional SMC and SOSMC with and without switching controllers. The simulation results were verified with experiment in tow-tank environment with induced of external disturbance and uncertainty. In as another study[77], the SOSMC was proposed to control surge, yaw, and heave. The performance of the proposed SOSMC was compared to the conventional SMC with SOSMC showing chattering reduction through simulation result.

The STSMC which is a sub-class of SOSMC, was proposed for AUV[2,75,78]. The first STSMC was proposed for implementation in AUV by Salgado-Jimenez and Jouvencel in 2003[75]. In this paper, the STSMC control law was designed for diving control of TAIPAN, a torpedo shaped AUV that is developed by LIRMM, University of Montpellier II, France. The control law was designed from the linear equation of diving subsystem. Four types of controllers were designed: PD, conventional SMC, twisting SMC, and STSMC. Later, Ruiz-Duarte and Loukianov[78], also proposed the STSMC control law for diving control. In this paper, a nonlinear observer based on extended STSMC algorithm was designed to estimate the unavailable plant parameters (pitch angle, pitch angular velocity and heave velocity). The controller was designed based on non-minimum phase system with real plant relative degree and simulated in the presence of plant parameter variations and the external disturbances. The STSMC was designed with an objective to make the AUV robust towards external disturbances, such as wind, wave, and ocean currents[2]. The STSMC was designed with the dynamic region concept for an ODIN AUV. In this algorithm, the boundary region was formulated by specifying the region where the ordinary trajectory is replaced with a desired region. The application of boundary region technique has improved the usage of energy. The STSMC with region concept trajectory demonstrated the best performance as compared with STSMC with line trajectory and adaptive region trajectory.

The Terminal SMC (TSMC) is another type of SOSMC employed in AUV control applications. The TSMC was proposed for tracking the horizontal plane of an underwater vehicle in the presence of disturbance and uncertainties[79]. Zhang *et al.*[80] proposed the TSMC to control the longitudinal plane of an AUV. The control law was designed based on the nonlinear equation of longitudinal plane. The non-singular TSMC (NTSMC) for AUV nonlinear system was proposed to overcome the singularity in existing TSMC[81,82]. Elmokadem *et al.*[81] implemented the NTSMC in horizontal plane of the REMUS AUV. The performance of the proposed controller was compared to existing TSMC and fast TSMC (FTSMC). The NTSMC demonstrated the fastest convergence time.

The ISMC was proposed[27] for precise manoeuvring of an AUV with presence of unknown environmental disturbances. The ISMC is effective in compensating for the uncertainties in the hydrodynamic and hydrostatic parameters of the vehicle and rejecting the unpredictable disturbance effects due to ocean waves, tides and currents. The ISMC was designed based on augmented integral sliding surface as proposed by Shi et al.[83] and Utkin and Shi[22]. The controller was simulated in both lateral plane (steering subsystem) and vertical plane (diving subsystem). The ISMC demonstrated the smallest tracking error as compared to PD plus nonlinear cancellation (PD + NC) controller and conventional SMC where the ISMC demonstrated the smallest tracking error in the presence of hydrodynamic uncertainties and unknown disturbances both in simulation and in experimental conditions.

The dynamic sliding mode control (DSMC) offers an alternative approach to reduce the chattering effects. The DSMC was designed based on multiple models switching laws (DSMC-MMSL) for diving plane of the AUV[84]. The control laws were divided into two parts: Depth control and pitching control. The switching control was designed for smooth transition between the two controllers. The proposed controller was simulated and validated through several field tests.

The combination of SMC with fuzzy logic controller is another method used to improve the chattering effects. The combination of fuzzy control with SMC was first proposed by Song and Smith[85]. The fuzzy control using linguistic information possesses several advantages in being model free and robust, applying universal approximation theorem and rule-based algorithm. The fuzzy control was used to estimate the parameters for SMC to ensure the right nonlinear switching curve[85]. The SMC was designed based on fuzzy control for lateral plane to control the line of sight (L.O.S) by tracking the heading error[16]. Later the fuzzy SMC controllers were designed for region tracking where the fuzzy control was used to tune the gain to ensure that the right gain is used and results in reducing the chattering effects[86,87]. The controllers were simulated under various determined disturbances. Later the SMC was designed based on fuzzy control where the fuzzy rules were designed to estimate the switching gain to eliminate the disturbance term and reduce the chattering[88].

The adaptive fuzzy SMC control algorithms were proposed[89,90,91] to improve the performance of fuzzy SMC (FSMC) algorithm. The proposed algorithms were simulated and tested in the presence of uncertainties and external disturbances. The adaptive fuzzy sliding mode controller (AFSMC) was based on the decomposition method using expert knowledge in underwater flight vehicle (UFV) depth control and utilizes a fuzzy basis function expansion (FBFE) and a proportional integral augmented sliding signal[89]. The designing was divided into three phases: Practical generation of the pitch command, use of the expert knowledge in UFV depth control, and design of the AFSMC using FBFEs and proportional integral augmented sliding signals. Adaptive fuzzy SMC was proposed to regulate vertical positioning (depth) in the presence of parametric uncertainty and disturbances[90]. Two fuzzy approximators were employed, one for shape tracking error dynamics in the sliding regime and the second fuzzy approximator to change the supports of the output fuzzy membership function in the defuzzification inference module of (FSMC).

By using these two approximation steps, the best fit curve (slope) and gain are obtained. Later, the fuzzy adaptive SMC (FASMC) was proposed for path following for an AUV[91]. The proposed FASMC is designed based on the following errors of the AUV and the angles between the sliding surface and state vector. The system was decoupled into surge, surge velocity and yaw angle. The thicknesses of the SMC boundary layers were estimated using fuzzy adaptive based on Takagi-Sugeno (T-S) fuzzy model. The performance of the proposed controller in term of robustness towards uncertainties and external disturbances and reducing the chattering effects was compared to conventional SMC. Recently, an adaptive fuzzy SMC was proposed for diving control of an AUV with input saturation constraint where the fuzzy was used to identify the unknown model dynamics[92].

The combination of SMC and neural network (NN) was proposed[13,93,94,95]. The neural network based-time optimal sliding mode control was proposed for heading control[13]. The Pontryagin's maximum principle was used to improve the response of the output. The optimal slope of the output response was estimated using NN. The NN was trained using Levenberg–Marquardt back propagation algorithm. The dynamic inversion-based sliding mode adaptive neural network controller (DI-SMANNC) was proposed for the hybrid visual servo (HVS) control of underwater vehicle[93]. The combination of SMC and feed-forward single hidden layer neural network (SHL) provide robustness against dynamic vehicle's uncertainties. The controller was proposed to control the diving and steering subsystems of the REMUS AUV[94]. The controller was developed using SMC and the radial basis function NN (RBFNN) that consists of input, hidden an output layers was used to estimate the unknown dynamic. Finally, the nonlinear SMC was developed based on NN with a robust exact differentiator which results in chattering reduction and performance improvement[95]. The NN was used to estimate the controller parameters that improve the performance of the proposed controller. The summary of SMC strategies application used in AUVs is given in Table 3.

Potential Development of SMC in AUV Application

Table 3 shows that the application of SMC strategies in AUVs still has potential of implementing other combination of SMC control strategies that may result in reducing the chattering effect, tracking error and increase the controller robustness against perturbations. The combination of the back stepping strategy with integral SMC and super-twisting SMC is one of the potential algorithms. The back stepping strategy is a method that is based on Lyapunov function. The systematic and recursive design methodology has created a great attention to this method. The main advantage of integral sliding mode over conventional SMC is that the system trajectory always starts from the sliding surface and therefore the reaching phase is eliminated. The STSMC is used

TABLE 3 — THE SUMMARY OF THE SMC STRATEGIES USED IN AUVS (Contd.)

Control Technique	Key References	Remark
Conventional SMC	Dougherty et al., 1988 Wang et al., 2002 Akcakaya et al., 2009	Controller developed for MUST AUV. Simulation based nonlinear system. Parameter involved: surge, sway, heave, roll, pitch, yaw Controlled parameter – surge, sway, heave, pitch, yaw. Simulation based on linearized model Controller developed for NPS AUV II. Controlled parameter – sway, yaw. Advantage - Robust against system perturbations and parameter variations Disadvantage - High switching frequency known as chattering phenomena. - Performance is much depend on sliding surface which may lead to instability
SMC (boundary layer)	Tseng & Chen, 2010 Healey & Lienard, 1993 Shi, 2007 Ha & Binugroho, 2008 Akcakaya et al., 2009 Jantapremjit, 2011 Watson & Green, 2014	Controller developed for EAVE AUV. Controlled parameter: surge, sway, yaw Simulation based on nonlinear system. Controlled parameter - Surge, sway, heave, roll, pitch, yaw. Simulation based on linearized model Controller developed for REMUS AUV. Controlled parameter- surge, sway, heave, pitch, yaw. Simulation based on linearized model Controller developed for SNUUV I AUV in National University of Korea. Controlled parameter- heave, yaw. Simulation based on linearized model. Controller developed for NPS AUV II. Controlled parameter – sway, yaw (comparison between boundary layer and conventional SMC). Controller parameter – sway, heave, pitch, yaw. Simulation based on linearized model. Controller developed for micro AUV MK II. Controller parameter- heave. Simulation based on nonlinear model and validated through experimental. Advantage Reduce the chattering effects Disadvantage - loss of invariance property as the control signal is a linear function of the distance between the actual state and the sliding surface within the boundary layer - highly sensitive to the unmodeled fast dynamics and may lead to instabilty
Integral SMC (ISMC)	Kim et al., 2015	Controlled parameter – surge, sway, heave, roll, pitch, yaw. The reaching law is based on boundary layer. Simulation is based on nonlinear model and validated with Cyclops AUV. Advantage - Reduce chattering - Robustness properties against perturbations in the model from the initial time instance, i.e reaching phase is eliminated Disadvantage - Pertubation must satisfy the matching condition.
Dynamic SMC (DSMC)	Zhou et al., 2015	DSMC is implemented based on multi models switching law (MMSL) to control depth of an AUV with presence of external distrbances. Advantage - Reduce chattering effect Disadvantage - The sliding surface is states and input dependent - Increase the complexity of the overall system dynamics
HOSMC	Salgado-Jimenez & Jouvencel, 2003 Joe & Kim, 2014 Ruiz-Duarte & Loukianov, 2015 Ismail & Purtanti, 2015	Controller designed for TAIPAN AUV. Controller designed based on PD, conventional SMC, twisting and super-twisting algorithms. Controlled parameter- heave, pitch. Simulation is based on linearized model and validated with TAIPAN AUV. Controller designed based twisting algorithm with sliding surface is designed using PID technique. Controlled parameter- sway, heave

(Contd.)

TABLE 3 — THE SUMMARY OF THE SMC STRATEGIES USED IN AUVS (Contd.)

Control Technique	Key References	Remark
		Controller designed based on super-twisting SMC. Controlled parameter – heave, pitch. Simulation based on nonlinear model. Use super-twisting reaching law. Simulation based on nonlinear model to control position in x,y,z. Advantage - Reduce chattering - Finite convergence time - Improve transient response - Higher convergence accuracy - Model free control in case of super twisting SMC Disadvantage - The knowledge of the boundaries of the disturbance gradients is required Reduce the robustness
Combination of SMC with intelligent methods	Song & Smith, 2000 Guo et al., 2003 Mokhar & Ismail, 2015 Qi et al., 2016 Kim & Shin, 2005; Lakhekar et al., 2013; Zhang et al., 2015; Chu et al., 2018. Chatchanayuenyong & Parnichkun, 2006; Gao et al., 2017; Geranmehr & Vafee, 2017; Guo et al., 2017	Fuzzy control was used to estimate the parameters for SMC to ensure the right nonlinear switching curve The SMC was designed based on fuzzy control for lateral plane to control the line of sight (L.O.S) by tracking the heading error The fuzzy SMC controllers were designed for region tracking where the fuzzy control was used to tune the gain to ensure the right gain is used and results in reducing the chattering effects The fuzzy control was used to estimate the switching gain to eliminate the disturbance term and reduce the chattering Improve the existing fuzzy SMC which able to adapt the changes in AUV's dynamics and external disturbances Proposed the combination of SMC with neural network (NN). The NN was used to estimate the unknown dynamics and some papers used to tune the gain the controller parameters which improve the performance and reduce the chattering. Advantage - Improve chattering - Dynamics and disturbance adaptation - No need precise dynamic models Disadvantage - High computational time - In case of NN, need training.

to eliminate the chattering effects. The STSMC is also able to drive the sliding surface to zero in finite time. In existing STSMC, the controller only has the discontinuous part; however, with this combined approach, the controller can have both equivalent and discontinuous controls. This may potentially improve the overall SMC performance and will also be able to improve the performance of the AUV overall.

Conclusion

The motion tracking performance of an autonomous underwater vehicle can be assured when its robustness and tracking accuracy are guaranteed. The existence of uncertainties due to hydrodynamics parameters, external disturbance and other system behaviours might cause the degradation of robustness and tracking accuracy. From the literature, it can be concluded that SMC is a significant nonlinear controller. However, discontinuous control action on SMC results in chattering phenomenon which reduces tracking accuracy of the AUVs. The most commonly used is the boundary layer by smoothing the signum function using saturation function, tangent hyperbolic, or sigmoid functions. However, using boundary layer technique has degraded controller accuracy because to obtain the smoother control signal, a larger boundary layer is used and a larger boundary layer width will result in larger error of control signal. Also, the boundary layer will not be effective in reducing the chattering when there is high-level measurement noise and thus degrades the controller robustness[96].

The SMC strategy based on combination of the backstepping, integral SMC and super-twisting algorithm is seen as a good way forward to control the motion of AUV and improve the performance. The goal on chattering reduction, minimal tracking error and robustness against parameter variation and external disturbance will always be the main objective to achieve. The hybrid version of SMC with other intelligent, robust and optimal control method also brings a new perspective in optimizing the controller and the system performance overall. With so many control efforts that have been established in this AUV application nowadays, it is also good to provide a so called meta-heuristic approach among those control strategies. This centralized system will monitor, give command and make decision of which control technique should be utilized every time the expectation is made to the AUV system application.

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