

A DISCRETE-TIME FAST TERMINAL SLIDING MODE FOR DEPTH  
CONTROL OF AUTONOMOUS UNDERWATER VEHICLE

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To my beloved father, late mother, and my lovely kids, thank you.



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## ABSTRACT

The Autonomous Underwater Vehicle (AUV) demonstrates highly nonlinear and complexity in dynamic model coupled with unstructured ocean environment. With limitation of actuator constraints, the only solution for AUV to overcome this challenge is by manipulating the control algorithms. Naturally, Discrete-Time Sliding Mode Control (DSMC) is an appropriate controller for nonlinear systems due to its insensitivity to perturbations. However, the implementation of DSMC on AUV system contribute to chattering effect, which leads to low control accuracy and decreased lifetime of the actuator. For this reason, the reaching law scheme is employed to DSMC law. As a result, the reaching time of state trajectory to sliding surface is prolonged, hence, the robustness of the controller against perturbations is debilitated. Therefore, the Discrete-Time Fast Terminal Sliding Mode Control (DFTSMC) with reaching law schemes is proposed to overcome this issue. DFTSMC is a hybrid form of Discrete-Time Terminal Sliding Mode Control (DTSMC) and DSMC. The combination of nonlinear component from DTSMC and liner component by DSMC guarantee fast and finite error state convergence. While the chattering effect significantly reduced by nonlinear component from DTSMC. A comprehensive simulation showed that DFTSMC is capable of shortening the error state convergence of 65%, the reaching time by 32%, and reducing the chattering effect by 68%, in comparison with DSMC. In other words, DFTSMC offers fast and finite transient response, alleviates chattering effect, and guarantees strong robustness against perturbations in comparison with DTSMC and DSMC. Furthermore, DFTSMC also provides better system response when compared with discrete Proportional Integral Derivative (PID) and Model Predictive Controller (MPC). This indicates that DFTSMC is capable of providing better performance, compared with DTSMC, DSMC, discrete PID and MPC. Therefore, DFTSMC may emerge as one of the preferable controller methods towards improving real AUV system performance.

## ABSTRAK

Kenderaan berautonomi bawah air (AUV) menunjukkan ketidaklurusan yang tinggi dan kerumitan model dinamikanya berserta dengan persekitaran bawah air yang tidak terkawal. Disebabkan keterbatasan system penggerak, pilihan yang di miliki oleh AUV dalam mengatasi rintangan adalah dengan menggunakan strategi algoritma kawalan. Kawalan Ragam Lincir Diskrit (DSMC) adalah pendekatan yang bersesuaian untuk mengawal ketidakpastian sistem yang tidak lurus di sebabkan oleh ketidakpekaan terhadap perubahan parameter dan gangguan luaran. Walaubagaimanapun, pelaksanaan DSMC keatas sistem AUV menghasilkan masalah penggelatukkan yang menurunkan prestasi kawalan and memendekkan jangka hayat penggerak. Oleh itu, hukum jangkauan baharu di formulasi dengan DSMC. Akibatnya, kesan penggelatukkan berkurang tetapi masa jangkauan di panjangkan lalu menurunkan tahap ketahanan terhadap perubahan parameter dan gangguan luaran. Oleh itu, Landasan Pantas Kawalan Ragam Lincir Diskrit (DFTSMC) bersama dengan hukum jangkauan baharu di gunakan untuk mengatasi masalah ini. DFTSMC adalah gabungan antara DTSMC dan DSMC. Gabungan komponen bukan linear dari DTSMC dan komponen linear oleh DSMC memendekkan masa penumpuan ralat dan masa capaian. Kesan penggelatukkan pula dapat di kurangkan dengan ketara oleh komponen tidak linear dari DTSMC. Hasil simulasi menunjukkan DFTSMC memendekkan masa penumpuan ralat sebanyak 65%, memendekkan masa capaian sebanyak 32%, dan mengurangkan penggelatukkan sebanyak 68% di bandingkan dengan DSMC. Ini bermaksud DFTSMC mempercepatkan masa penumpuan ralat dan capaian, mengurangkan penggelatukkan pada kawalan masuk dan menjamin ketahanan yang kuat terhadap gangguan. Malahan, DFTSMC juga memberikan tindak balas sistem yang lebih baik berbanding dengan DSMC, DTSMC, diskrit Proporsional Integral Derivative (PID) dan Kawalan Ramalan Model (MPC). Ini menunjukkan bahawa DFTSMC mampu memberikan prestasi yang baik, di bandingkan dengan DTSMC, DSMC, diskrit PID dan MPC. Oleh itu, DFTSMC boleh dijadikan pengawal yang lebih baik untuk meningkatkan prestasi sistem AUV sebenar.

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## LIST OF ABBREVIATIONS

<i>AD</i>	–	Analogue to Digital
<i>AUV</i>	–	Autonomous Underwater Vehicle
<i>BFF</i>	–	Body Fixed Reference Frame axes
<i>DFS</i>	–	Discrete Fuzzy smoother
<i>DSMC</i>	–	Discrete-Time sliding Mode Control
<i>DTSMC</i>	–	Discrete-Time Terminal Sliding Mode Control
<i>DFTSMC</i>	–	Discrete-Time Fast Terminal Sliding Mode Control
<i>DSMM</i>	–	Discrete-Time Sliding Mode Motion
<i>EFF</i>	–	Earth Fixed Reference Frame
<i>ERL</i>	–	Exponential Reaching Law
<i>EoM</i>	–	Equation of Motion
<i>FLC</i>	–	Fuzzy Logic Controller
<i>GESO</i>	–	General Extended State Observer
<i>ISS</i>	–	Integral Sliding Surface
<i>LSS</i>	–	Linear Sliding Surface
<i>MIMO</i>	–	Multi Input Multi Output
<i>MIT</i>	–	Massachusetts Institute of Technology
<i>MPC</i>	–	Model Predictive Control
<i>NNC</i>	–	Neural Network Controller

<i>NPS</i>	–	Naval Postgraduate School
<i>NSS</i>	–	Nonlinear Sliding Surface
<i>PID</i>	–	Proportional Integral Derivative
<i>PSO</i>	–	Particle Swarm Optimization
<i>QSM</i>	–	Quasi-Sliding Mode Motion
<i>QSMB</i>	–	Quasi-Sliding Mode Band
<i>SMC</i>	–	Sliding Mode Control
<i>SNAME</i>	–	Society of Naval Architecture and Marine Engineers
<i>TDE</i>	–	Time Delay Estimation
<i>UAV</i>	–	Unmanned Ariel Vehicle
<i>VSC</i>	–	Variable Structure Control
<i>6-DoF</i>	–	Six Degree of Freedom



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## LIST OF SYMBOLS

$x$	–	$X$ axes of EFF
$y$	–	$Y$ axes of EFF
$z$	–	$Z$ axes of EFF
$X$	–	Forces along $x$ axes in BFF
$Y$	–	Forces along $y$ axes in BFF
$Z$	–	Forces along $z$ axes in BFF
$K$	–	Moments along $x$ axes in BFF
$M$	–	Moments along $y$ axes in BFF
$N$	–	Moments along $z$ axes in BFF
$\phi$	–	Roll angle in EFF
$\theta$	–	Pitch angle in EFF
$\psi$	–	Yaw angle in EFF
$u$	–	Surge velocity in BFF
$v$	–	Sway velocity in BFF
$w$	–	Heave velocity in BFF
$p$	–	Roll rate in BFF
$q$	–	Pitch rate in BFF
$r$	–	Yaw rate in BFF
$\dot{x}$	–	Linear velocity along $x$ axes of EFF
$\dot{y}$	–	Linear velocity along $y$ axes of EFF

$\dot{z}$	–	Linear velocity along $z$ axes of EFF
$\dot{\phi}$	–	Angular velocity about $x$ axes of EFF
$\dot{\theta}$	–	Angular velocity about $y$ axes of EFF
$\dot{\psi}$	–	Angular velocity about $z$ axes of EFF
$\dot{u}$	–	Time rate of change of velocity along the body longitudinal axis
$\dot{v}$	–	Time rate of change of velocity along the body lateral axis
$\dot{w}$	–	Time rate of change of velocity along the body vertical axis
$\dot{p}$	–	Time rate of change of body roll angular velocity about the body longitudinal axis
$\dot{q}$	–	Time rate of change of pitch angular velocity about the body lateral axis
$\dot{r}$	–	Time rate of change of body yaw angular velocity about the body vertical axis
$\delta_r$	–	Rudder deflection angle
$\delta_s$	–	Stern deflection angle
$n$	–	Propeller revolutions per minute
$\eta_1$	–	Position vector in EFF
$\eta_2$	–	Orientation vector in EFF
$v_1$	–	Linear velocity vector in BFF
$v_2$	–	Angular velocity vector in BFF
$W$	–	Weight of vehicle
$m$	–	Mass of vehicle
$B$	–	Buoyancy of the vehicle
$L$	–	Length of vehicle
$g$	–	Acceleration due to gravity

$\rho$	–	Fluid density
$I_x$	–	Inertia moments along $x$ axes
$I_y$	–	Inertia moments along $y$ axes
$I_z$	–	Inertia moments along $z$ axes
$x_G$	–	$X$ coordinate of $CG$ from BFF
$y_G$	–	$Y$ coordinate of $CG$ from BFF
$z_G$	–	$Z$ coordinate of $CG$ from BFF
$CoB$	–	Center of Body
$CoG$	–	Center of Gravity
$r_g$	–	Distance vector from $CoB$ to $CoG$
$I_b$	–	Inertia matrix of rigid body center of body
$I_g$	–	Inertia matrix of rigid body center of gravity
$A$	–	3x3 nominal system matrix of AUV system
$\Delta A$	–	3x3 uncertainty in system matrix of AUV system
$A_p$	–	4x4 nominal system matrix of AUV system with reference tracking
$\Delta A_p$	–	4x4 uncertainty in system matrix of UV system
$B$	–	3x1 input matrix of AUV system
$\Delta B$	–	3x1 uncertainty in input matrix of AUV system
$B_p$	–	4x1 input matrix of AUV system with reference tracking
$\Delta B_p$	–	4x1 uncertainty in input matrix of AUV system with reference tracking
$f$	–	Total lumped disturbance in continuous time system
$e$	–	External disturbance in continuous time system
$d_T$	–	Total lumped bounded disturbances in continuous time system
$D_T$	–	Total lumped bounded disturbances in discrete-time system

$\Phi$	–	4x1 system matrix in discrete-time state space equation of AUV system
$\Gamma$	–	4x1 input matrix in discrete-time state space equation of AUV system
$C_s$	–	4x1 Sliding mode gain matrix of DSMC
$C_T$	–	4x1 Sliding mode gain matrix of DTSMC
$C_{FT}$	–	4x1 Sliding mode gain matrix of DFTSMC
$Q$	–	Reaching rate of the reaching law
$\varepsilon$	–	Approximation rate of the DSMC reaching law
$\varepsilon_T$	–	Approximation rate of the DTSMC reaching law
$\varepsilon_{FT}$	–	Approximation rate of the DFTSMC reaching law
$T$	–	Sampling time
$S$	–	Sliding surface of DSMC
$S_T$	–	Sliding surface of DTSMC
$S_{FT}$	–	Sliding surface of DFTSMC

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

Most of the earth's surface is covered with water in the form of oceans, rivers, and lakes, and many of which remain unexplored. Other than their traditional significance of being the sources of precious minerals, food, biodiversity, and being directly or indirectly beneficial to mankind, the ecological, economic, and social importance of water bodies are now better understood. The increasing investigation on ocean exploration requires Unmanned Underwater Vehicle (UUV) has reached an impressive technological momentum over the past decades by merging areas such as electrical, mechanical and system engineering. The UUV can be classified into two categories, namely, Autonomous Underwater Vehicles (AUV) and Remotely Operated Underwater Vehicles (ROV). The AUV is further divided into underwater glider, propelled AUV and Biomimetic AUV. The classification of UUV is summarized in Figure 1.1.

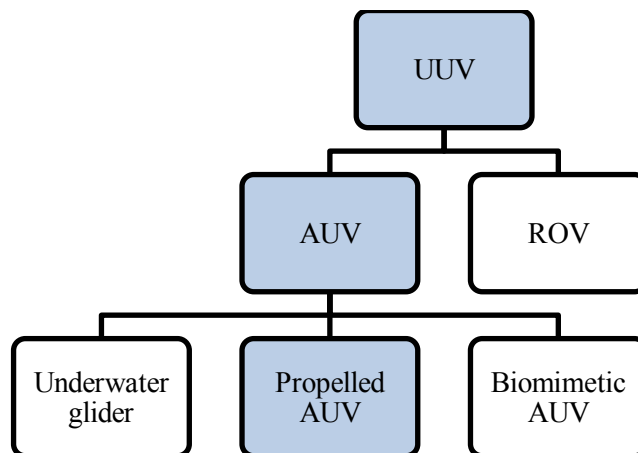


Figure 1.1: The classification of UUV [1]

Over the years, the increasing demand of deep water exploration with higher safety risk have steadily increased from ROV to AUV [2]. Transitioning from ROV to AUV pushed new developments in localization, autonomy, and communications. AUV navigates autonomously relaying on its navigation algorithm and surrounding information. AUV have predefined plan of operations in its system allowing AUV to perform autonomously. Due to versatility, compact size, independence, and covertness, AUV are highly valuable asset in various industries especially in commercial sectors. A chart showing the AUV global demand on commercial sectors starting from 2013 and forecasted for 2022 is presented in Figure 1.2. The pipeline inspection and life of field inspection are expected to witness a higher growth demand over the forecast.

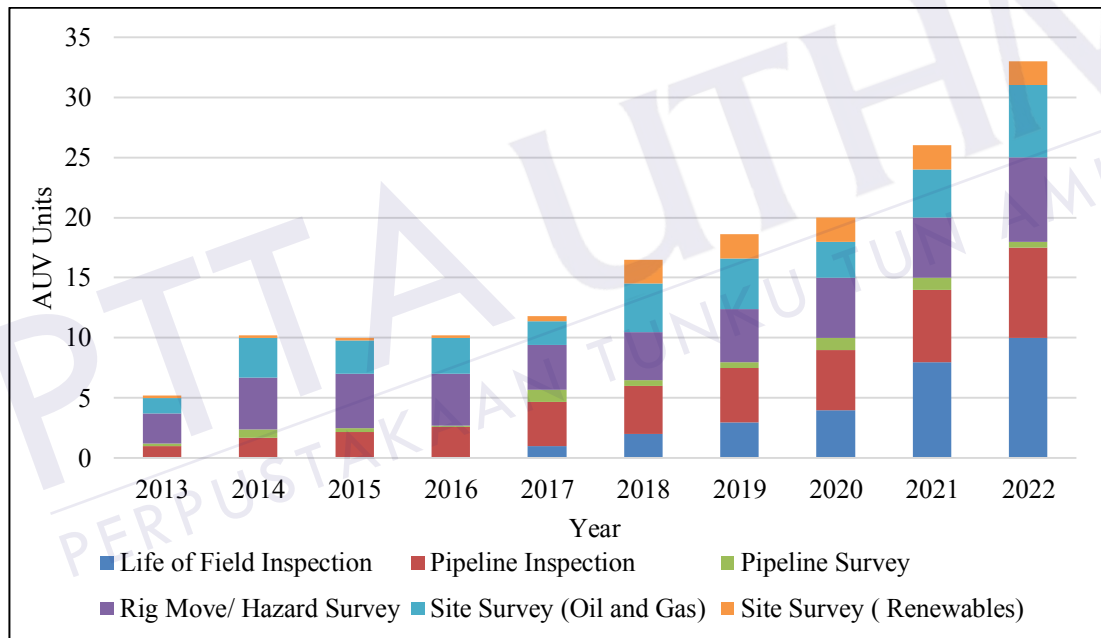


Figure 1.2: Global AUV demand by commercial sector from 2013 and forecasted to 2022 [3]

The past decade has witnessed sustained research activities in achieving high degree of autonomous decision making. However, demanding ocean environments bring many challenges to its autonomy, energy consumption, sensors, and communication. Regardless of the types of control scenarios such as set point regulation, trajectory tracking and path following, the main challenges are highly nonlinear dynamics accompanied with parametric uncertainties [4,5]. Furthermore, with limited state variables and actuator, the only option for AUV to overcome these challenges is by manipulating the control algorithms [6,7]. In this research, robust and

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