CONTINUOUS ADAPTIVE SLIDING-MODE CONTROL SCHEME FOR AN AUTONOMOUS UNDERWATER VEHICLE WITH REGION-BASED APPROACH

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Dedicated to my beloved family and lovely wife.

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ABSTRACT

Set point method has been typically used for trajectory tracking of Autonomous Underwater Vehicle (AUV). However, this method has several limitations. In this regard, region based method has been applied in trajectory tracking of AUV in order to solve the limitations of set point method. The main idea behind the region-based method is the tracking target of an AUV set as a region, so that the AUV will maintain its position under weak ocean current. This method uses lower energy compared to set point method because the AUV will not turn on its thrusters as long as it maintains its position within the region. Realistically, there is also strong current that can drift vehicle away from the required region. The purpose of the thesis is to develop a robust controller with region-based method. Robust control enables an AUV to reject the disturbance and re-enter the region even under the influence of external disturbance. Based on the literature review, adaptive sliding mode control was chosen as the proposed controller in this study. Sliding mode control is known for its insensitivity towards uncertainty and external disturbance. Adaptive component was introduced to replace switching component. This substitute enables AUV to reject external disturbance better compared to conventional sliding mode control. The stability of the proposed controller was analyzed using Lyapunov function. The energy consumption of region based method was compared with the set point tracking method. It has been shown from this study that the energy consumption for region-based method is indeed lower than set point method. The effectiveness of the proposed controller was compared with adaptive controller using simulation under the influence of ocean current. Underwater vehicle model used in the simulation was Omni Directional Intelligent Navigator (ODIN). It has been proven that the proposed controller performed better compared to adaptive controller. The proposed controller had managed to handle ocean current and re-enter the region.

ABSTRAK

Kaedah titik set kebiasaannya digunakan di dalam penjejakan trajektori oleh kenderaan bawah air automatik (AUV). Akan tetapi, kaedah ini mempunyai beberapa batasan. Oleh itu, kaedah berasaskan kawasan telah digunakan dalam penjejakan trajektori untuk mengatasai batasan kaedah titik set. Teori di sebalik kaedah kawalan berasaskan kawasan ialah sasaran didefinisikan sebagai suatu kawasan, maka AUV akan dapat mengekalkan posisinya walaupun dalam arus laut yang lemah. Kaedah ini juga dikatakan menggunakan tenaga yang lebih rendah berbanding kaedah titik set kerana AUV tidak akan menghidupkan penujah selagi ia dapat mengekalkan posisi di dalam kawasan. Secara realistiknya, terdapat juga arus kuat yang berupaya menghanyutkan kenderaan dari kawasan dikehendaki. Tujuan tesis ini ialah untuk membangunkan pengawal yang tegap menggunakan kaedah berasaskan kawasan. Kawalan tegap membolehkan AUV menolak gangguan dan memasuki semula kawasan walaupun di dalam pengaruh gangguan luaran. Berdasarkan kajian literatur, kawalan mod gelongsor mudah suai telah dipilih sebagai pengawal dalam kajian ini. Kawalan mod gelongsor terkenal dengan ketidakpekaannya terhadap ketidaktentuan dan gangguan luaran. Komponen mudah suai digunakan bagi menggantikan komponen pensuisan. Penggantian ini membolehkan AUV melawan arus yang lebih kuat berbanding kawalan mod gelongsor konvensional. Kestabilan pengawal yang dicadangkan telah dianalisis menggunakan fungsi Lyapunov. Tenaga yang digunakan oleh kaedah kawasan dibandingkan dengan kaedah titik set. Kajian menunjukkan bahawa penggunaan tenaga untuk kaedah kawasan adalah lebih rendah berbanding kaedah titik set. Keberkesanan pengawal yang dicadangkan telah dibandingkan dengan kawalan mudah suai di dalam simulasi di bawah pengaruh arus laut. Kenderaan bawah air yang digunakan dalam simulasi adalah pengemudi cerdas semua arah (ODIN). Telah dibuktikan bahawa pengawal yang dicadangkan memberikan keputusan yang lebih baik berbanding pengawal mudah suai. Pengawal yang dicadangkan dapat menolak arus dan memasuki semula ke dalam kawasan.

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LIST OF ABBREVIATIONS

6-DOF	-	Six Degrees Of Freedom
AUV	-	Autonomous underwater vehicle
CG	-	Centre of gravity
CLF	-	Control Lyapunov Function
DOB	-	Disturbance observer
etc.	-	And so on
i.e.	-	That is
MRAC	-	Model reference adaptive controller
ODIN	-	Omni directional intelligent navigator
PD	-	Proportional derivative
PI	-	Proportional integral
PID	-	Proportional integral and derivative
ROV	-	Remote operate vehicle
SMC	-	Sliding mode control
SMC-PID	-	Sliding mode control- Proportional integral and derivative
UUV	-	Unmanned underwater vehicle
VSC	-	Variable structure control

LIST OF SYMBOLS

$\forall$	-	for all
$\exists$	-	there exists
$\in$	-	belong (s) to
$\Longrightarrow$	-	implies
$\Leftrightarrow$	-	is equivalent to, if and only if
$\rightarrow$	-	tends to, maps onto
$\mathbb{R}$	-	real numbers
$\mathbb{R}_+$	-	non-negative real number
$x \in \mathbb{R}^n$	-	real vector space of dimension *n*
$A \in \mathbb{R}^{n\times m}$	-	set of real matrices of dimension *n x m*
$A \in \mathbb{R}^{n\times n}$	-	square matrix with dimension *n x n*
$A = \{a_{ij}\} \in \mathbb{R}^{n\times m}$	-	diagonal matrix with $a_{ij} = 0$ for all $i \neq j$
$\dot{x}$	-	derivative of ***x*** with respect to time
x_d	-	desired value of the variable ***x***
$\|x\|$	-	Euclidean norm of vector ***x***
x_i	-	*i*th element of the vector ***x***
$x^T\,(X^T)$	-	transpose of the vector ***x*** (matrix *X*)
$\tilde{e}$	-	error variable
$f: X \rightarrow Y$	-	the function f maps the set *X* into the set *Y*
$\sum_v -X_vY_vZ_v.$	-	body-fixed reference frame
$\sum_v -X_iY_iZ_i.$	-	earth-fixed or inertial reference frame
t	-	time (s)
$\eta_1 \in \mathbb{R}^3$	-	position vector in the inertial reference frame (m)
$v_1 \in \mathbb{R}^3$	-	linear velocity vector of the body-fixed frame with

		respect to the origin of the inertial reference frame expressed in the body-fixed frame (m s^{-1})
$\eta_2 \in \mathbb{R}^3$	-	vector of body Euler angle coordinates in the inertial reference frame (rad)
$v_2 \in \mathbb{R}^3$	-	angular velocity vector of the body-fixed frame with respect to the origin of the inertial references frame expressed in the body-fixed frame (rad s^{-1})
$\epsilon \in \mathbb{R}^4$	-	unit quaternion representation
$\tau_{RB} \in \mathbb{R}^6$	-	resultant external forces (N) and moments (N m) of a rigid body
$V(t, x)$	-	Lyapunov function candidate
ρ	-	water density (kg m^{-3})
C_d	-	dimensionless drag coefficient
R_n	-	Reynolds number
m	-	mass of underwater robot (kg)
∇	-	volume of fluid displaced by the robot (m^3)
$I_{n\times n}$	-	identity matrix of dimension *n*
$0_{n\times n}$	-	null matrix if dimension *n*

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The oceans cover more than half of the earth surface compared to land and it has huge source of mineral resources. Ocean also could be linked to tropical storm, tsunami and earthquake. These two reasons could initiate the curiosity of mankind to investigate and explored the abyssal world. Spaces, on the hand, have been successfully intruded by man and man already have stepped on the moon and scientists have already sending their robot as far as Mars. However, journey to undiscovered world of ocean is remaining elusive in the hand of researcher.

Using aircraft or satellite to collect the data of ocean can only work on the surface scope and it is far from the meeting the need for ocean investigation, exploration and exploitation (Zhou, 2004). A manned voyage to deep sea would caused extreme risk as the unknown environment and oceanic environment is not ideal for human as the pressure increases with the depth. On the bright side, if underwater vehicle is used, making it is possible to go far beneath the ocean surface and collect the data firsthand about the unknown ocean world.

Although mankind earliest design of underwater vehicle dated back decades ago, the first unmanned underwater vehicle (UUV) was design in 1958 by US Army (Vervoot, 2008). UUV in the case mention nowadays known as remote operate vehicle (ROV). ROV is used extensively in offshore work however the risk working in ROV is considered working in a hostile situation and also with expensive cost (Zhao and Yuh, 2005).

Therefore, Autonomous Underwater Vehicle (AUV) has been steadily stepped in front of deepwater sea exploration to overcome the deficiencies of ROV. This is crucial since the need of the autonomy in robots and vehicles is becoming more prevalent matter in many situations and environments worldwide (Gonzales, 2004). AUVs are untethered, fully automated submersible platform capable of performing underwater tasks and missions with their onboard sensor, navigation and payload equipments (Xu, 2004). The goal for underwater robotics is to create fully self-contained, intelligent, decision-making AUVs (Yuh, 2000).

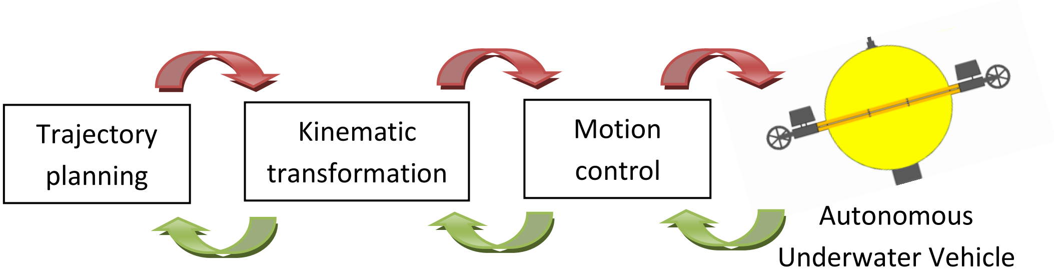

Figure 1.1: Essential part of underwater vehicle system

Figure 1.1 shows the essential part of underwater vehicle system. First part is the trajectory planning. In order to generate reference trajectory, one must first define the path or path planning. Path planning is how ones determined the curve in task space from the initial position until the final position of underwater vehicle while avoiding obstacle if any. Parameterized the curve with time will get us the reference trajectory as it will become the input for underwater vehicle motion. However, before the reference trajectory became the input for motion control, inverse kinematic is used to get time-parameterized for joint space or in this case, underwater vehicle space. The motion controller using the input trajectory to get the forces needed for the underwater vehicle to follow the reference trajectory. In addition, the input or the control variable can be position, velocity and acceleration.

However acceleration seldom used as control variable as the feedback for acceleration usually contains noise.

Usually in underwater vehicle world, there are two control task which is trajectory tracking and regulation control. In trajectory tracking or ones may refer it as motion control, underwater vehicle has to follows the reference trajectory. The reference trajectory is a time-parameterized in joint space or task-space. Regulation control refers as position control or point to point control. In this control task, underwater vehicle has to be in specific point regardless of its initial position and the trajectory to the specific point. The underwater vehicle also has to be at the specific point even in case of external disturbance acted on it. However, the conventional method is consuming a lot of energy. Therefore, Cheah and Sun (2004) suggested a method in order to solve the disadvantages of set point control which is region method. This method will be discussed in detail in Chapter 2.

1.2 Problem Statement

In early years of AUV control, the desired position is always specified as a point which called the set point control. The conventional set point can be seen in Aguiar and Pascoal (2002), Soylu *et al*. (2008), and Sun *et al*. (2012). However, conventional set point method cannot be applied to all AUV applications. There are also AUV applications where the desired position can be specified as a region rather than a point. Thus, Cheah and Sun (2004) proposed a method best suit these applications which called region method. Cheah and Sun (2004) also claims that this method is more energy saving compared to conventional method. This is because the propeller of AUV will not activated in the region even with small current act onto it. In the previous studies using region control scheme, for example in Sun and Cheah (2003), the controller is formulated by only considered the restoring force and in Cheah and Sun (2004) and Li *et al*. (2010), the external disturbance is not even considered. Therefore, this study propose robust control with region formulation as an alternative. Figure 1.2 shows the illustration on the problem statement. The sphere is the required region that the AUV needs to track. However, when ocean current pull out the AUV, if the AUV does not has robust controller, it could not reenter the region under the influence of ocean current.

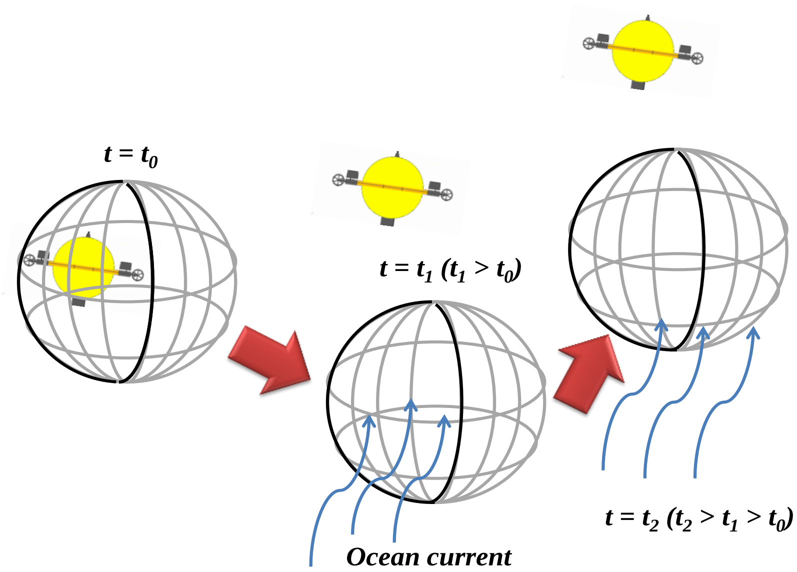

Figure 1.2: Illustration on problem statement

1.3 Objective of Research

The objectives of this research are:

1) To apply adaptive sliding mode control in the proposed dynamic region based control scheme under the influence of ocean current.

2) To formulate dynamic region control schemes with the stability analysis performed using Lyapunov-like function.

3) To investigate the energy usage of the proposed in 1) and compare with set point tracking controller.

1.4 Scope of Research

The scopes of this research covers following aspect. Simulation studies on a spherical shape, omni-directional and fully actuated 6 degree of freedom (DOF) underwater vehicle, Omni Directional Intelligent Navigator (ODIN) will be carried out in order to illustrate the performance of the tracking controller by using Matlab Simulink. Also, the platform of underwater is simulated in controlled environment (e.g swimming pool) where the current also can be controlled and determined. The current of water flowing for this research is assumed to be laminar current. The laminar current refers as movement of the fluid moving in the straight line and in the same direction. The ocean current is assumed unidirectional and constant in the inertial-fixed frame, then the body-fixed current disturbance can be obtained by projecting the constant inertial-fixed current disturbance onto the body-fixed frame in the form of velocity. The stability of proposed controller is analyzed using Lyapunov-like function. The force is calculated using norm method only for XYZ-axis thruster. In this thesis, the term underwater vehicle may refer to both AUV and ROV, however, UUV with manipulator is excluded and not discussed in this thesis.

1.5 Significance of Study

Energy efficiency is very important part in designing AUV as the AUV only have limited supply of energy supply. Most of AUV used various type of battery for power and propulsion. Therefore, the power usage of AUV depending on the limit of the chosen battery. In this thesis, a robust control method is presented that consumed lower energy usage compare to the conventional method. A method that can lower the power usage of limited supply of power in AUV. Knowledge gained from this study will benefit unmanned underwater vehicle industry as it will consume less energy for an AUV to perform the tracking task.

1.6 Thesis Organisation

This thesis is structured in the following manner. The literature review is presented in Chapter 2. The concept of inertial-fixed based and body-fixed based control is briefly introduced. This chapter also highlights the literature review of several control method proposed on underwater vehicle control. The review consist of several type of controller such as adaptive, robust and others such as fuzzy and neural network. The mathematical model of underwater vehicle and novel control designs of task-space tracking control are presented in Chapter 3. The kinematics and dynamics model of underwater vehicle is covered in this chapter along with the related properties. The purpose of this chapter is to give an insight to underwater vehicle and is used in simulation part of this thesis. The related properties is used in designing task-space tracking control. The effectiveness of the proposed controllers is presented using Matlab simulation in Chapter 4 with the discussion. The last chapter, Chapter 5 summarize the whole research with the suggestion for future work.

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