Tracking Control of Underactuated Surface Vessels Using Hybrid Control Methods

by

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Tracking Control of Underactuated Surface Vessels Using Hybrid Control Methods

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In this thesis, two intelligent control systems are developed for tracking control of an underactuated surface vessel (USV). The studied USV is controlled with uncertain parameters, such as the disturbances from the ocean current. In the first part of this thesis, a new intelligent controller is designed by integrating interval type-2 fuzzy logic control (IT2FLC) with sliding mode control (SMC). Traditional USV trajectory tracking models perform poorly when faced with the dynamic disturbances from wind, wave and airflow. Thus, both kinematic and dynamic USV models are considered in the proposed algorithms. The IT2FLC is utilized to analyze the kinematic model for generating control velocities due to its feature of minimizing the large uncertainties. Then, the IT2FLC is combined with SMC in the dynamic model to generate control law for better tracking performance. In the second part, a hybrid intelligent control system is proposed, which integrates a bioinspired shunting model based backstepping approach and a sliding mode approach. First, the bioinspired backstepping technique is developed to generate virtual velocities based on the kinematic model, which has the capability to resolve the velocity jump problem caused by large initial errors in the conventional backstepping method. Then, the generated smooth velocity signals are used for the dynamic model-based SMC. Furthermore, another bioinspired shunting model is combined with the SMC to provide appropriate control laws for the system to avoid the chattering problem. The effectiveness of the proposed two intelligent controllers is demonstrated through simulation and comparison studies.
Dedication

To my grandparents,
my parents,
my uncles,
my girlfriend,
and
my friend Yin Li
Acknowledgements

First and foremost, I have to thank my parents for their love and support throughout my life. Thank you both for giving me strength to reach for the stars and chase my dreams. My grandparents and uncles, thanks as well.

I would like to express my special thanks of gratitude to my advisor Dr. Simon X. Yang, who pointed me to get my valuable master experience and helped me in doing a lot of research. I came to know about so many new things I am really thankful to him. He gave me so much support not only for the study in university but also my career in Beacon Innovation International Inc.

I would also like to thank my committee member Dr. Mohammad Biglarbegan for looking through my work and giving suggestions.

To all my friends, thank you for your understanding and encouragement in my many moments of crisis. Your friendship makes my life a wonderful experience. I cannot list all the names here, but you are always on my mind.

This thesis is only a beginning of my journey.
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List of Symbols

\( \tilde{A} \) a type-2 fuzzy set

\( A, B, D \) the passive decay rate, and the upper and lower bounds of the neural activity

\( C_m \) the membrane capacitance

\( d_{11}, d_{22}, d_{33} \) the dynamic damping of three degrees of freedom

\( e_\eta \) the tracking errors

\( e_x, e_y, e_\beta \) the errors on \( x, y, \beta \) in local USV coordinate system

\( E_v \) the errors of velocities on surge, sway and yaw

\( E_p, E_{Na}, E_p \) the Nernst potentials for potassium ions, sodium ions, and the passive leak current

\( f(a) \) the excitatory input of bioinspired shunting model

\( \tilde{F} \) the firing level for each fired rules

\( g(a) \) the inhibitory input of bioinspired shunting model

\( g_p, g_{Na}, g_k \) the parameters that conduct potassium, sodium, and passive channels

\( k_1, k_2, k_3 \) the positive constants of bioinspired shunting model

\( m_{11}, m_{22}, m_{33} \) the mass of USV

\( Q_1, Q_2 \) the control gain in sliding mode

\( r \) the USV velocity on yaw

\( \text{sgn} \) the sign function

\( S_1 \) the sliding surface on surge control

\( S_2 \) the sliding surface on lateral motion control

\( u \) the USV velocity on surge
\( v \) the USV velocity on sway
\( V_m \) the dynamic voltage
\( x, y, \beta \) the body fixed inertial frame of USV
\( X_0, Y_0, O_0 \) the earth fixed coordinates of USV
\( y_{\cos(e)} \) the type of Center of Sets
\( \Gamma_{eu}, \Gamma_{ev}, \Gamma_{er} \) the parameters of velocity errors
\( \Gamma_u, \Gamma_v, \Gamma_r \) the virtual velocities on the surge, sway and yaw
\( \lambda_1, \lambda_2 \) the constant parameters in sliding mode
\( \xi_i \) neural activity (membrane potential) of the \( i \)-th neuron
\( \sigma_1, \sigma_2 \) the neural activities
\( \tau \) control variable of forces
\( \tau_r \) the control law on the sway
\( \tau_u \) the control law on the surge
\( \tau_{wu}, \tau_{wv}, \tau_{wr} \) the disturbances of wind, wave and airflow
List of Abbreviations

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<td>AI</td>
<td>Artificial Intelligence</td>
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<tr>
<td>AC</td>
<td>Automatic Control</td>
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<td>DOFs</td>
<td>Degree of Freedoms</td>
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<tr>
<td>FOU</td>
<td>Footprint of Uncertainty</td>
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<tr>
<td>IC</td>
<td>Intelligent Control</td>
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<tr>
<td>IT2FLC</td>
<td>Interval Type-2 Fuzzy Logic Control</td>
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<tr>
<td>LMF</td>
<td>Lower Membership Function</td>
</tr>
<tr>
<td>NB</td>
<td>Negative Big</td>
</tr>
<tr>
<td>NS</td>
<td>Negative Small</td>
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<tr>
<td>OR</td>
<td>Operation Research</td>
</tr>
<tr>
<td>PS</td>
<td>Positive Small</td>
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<td>PB</td>
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<td>SMC</td>
<td>Sliding Mode Control</td>
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<td>SMDC</td>
<td>Sliding Mode Dynamic Control</td>
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<td>T1FIC</td>
<td>Type-1 Fuzzy Logic Control</td>
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<td>USVs</td>
<td>Underactuated Surface Vessels</td>
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<td>UMF</td>
<td>Upper Membership Function</td>
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Chapter 1

Introduction

The unmanned surface vessel is currently a hot topic in robotics, attracting increasing interest from researchers. With the advantage of distributing high-bandwidth wireless data networks, the intelligent sensors greatly improve the performance of intelligent control systems. This function enables the unmanned surface vessel to provide Navy game combat with capability and adaptability. To exploit the ability of the unmanned vessel, the Naval systems research and development team has begun to explore feasible ways to implement and realize the potential functions. The development of aquatic unmanned vessels will undoubtedly continue to grow at a rapid pace in the upcoming decades.

A range of traditional techniques have historically been applied in the automatic control field. Although each approach has individual advantages, several control strategies have failed to achieve perfect performance in specific situations. Most control systems are designed to adapt to known parameters. In addition, ideal responses, stabilities, and efficiencies must be satisfied with specific requirements. As such several disadvantages occur during operational processes that affect the controller which has a poor capability to handle these behaviours. Simple control methods are largely insufficient to satisfy the demands of modern industry. Indeed, it is a challenge to design a controller by using conventional approaches that have the capability to deal with these complex systems. The design of an intelligent controller that considers the various superiorities of each technique and its complementaries is required. Specif-
ically, a hybrid control system is most likely to assure the implementation of high performance control.

The application of unmanned surface vessels (i.e., rather than vessels with manned platforms) for combat operations in high-risk areas is an attractive option to involved parties. This applies not only to individuals who must perform specific combat missions, but also for planners who can be given additional options when choosing more cost-competitive equipment. In perfect working conditions, an advanced unmanned surface vessel should perform autonomously without relying on advanced surface interaction between the operator and the remote control unmanned ship, which may be fragile or even impossible to achieve. Moreover, the vessel is designed to be compatible and adaptive, and it is supposed to be able to perform various functions according to the assessment of various scenarios. All anticipated functions require a high level of reliability and robustness in terms of system performance.

1.1 Problem Statement

Trajectory tracking control is an important research topic in robotics and control system. The aim is to design a motion controller that allows the underactuated surface vessels to track a desired path with high accuracy. Normally, both kinematics and dynamics must be considered to achieve a better tracking performance in various environments. Contrary to fully actuated systems, the underactuated model has smaller inputs accounts, while the controllable objectives usually have more coordinates which need to be considered in such a complex environment. In addition, some research has focused on different systems with either linear or nonlinear parameters; for example, Rugh and Shamma (2000) designed a controller with various linear parameters, and Zhen et al. (2009) introduced a nonlinear path following controller.

Fundamentally, the conventional methods for tracking control include local linearization, Lyapunov based algorithm, the backstepping approach and sliding mode. Although these control methods have been widely applied and studied in the tracking control system, defects in the real time control system are still apparent. For in-
stance, sliding-mode control has an inherent chattering problem, wherein the system suffers uncertain parameters and discontinuous signals. In addition, in the traditional backstepping control system, proper parameters are required to fit the backstepping algorithms. However, finding the suitable parameters in an uncertain situation is a time-consuming process, especially when the system has large initial errors. According to these existed problems that cause inaccurate tracking controls and unstable tracking control systems, two effective solutions are investigated in this thesis to optimize tracking control strategies.

1.2 Motivation

In the past few decades, the control systems of unmanned surface vessels have been developed by many researchers to improve and optimize the designed functions (Roberts, 2005). In most of the classical literature, the controller, which is called an autopilot controller, is designed to help the surface vessel keep a constant speed while sailing in a linear water channel. However, this autopilot controller cannot control high speed small vessels that require autonomous navigation. Consequently, a high-performance controller equipped with the capability of trajectory tracking is expected to be developed for the USV. To accomplish different potential tasks, a reliable controller for USVs is crucial. However, many concerns for the real application of the USV control system still exist due to the effect of unpredictable disturbances in the unknown ocean environment and the lack of a robust system. For the trajectory tracking control, which is considered a necessary and active topic for USV, the controller is designed to generate reasonable velocities and suitable control torques which would enable the surface vehicle to follow a desired path. The tracking control problems for a USV are typically discussed due to these complex nonholonomic systems that may suffer discontinuous feedback. Thus, the motivation of this research is to develop an efficient tool with advanced approaches to solve the existing challenges.

The current study compares different methods to illustrate the various advantages and effectiveness of tracking control for USVs in various situations. The interest in
investigating this topic is based on the requirement for practical capabilities of USVs to both replace and help humans with the risky work.

1.3 Objectives of This Thesis

The aim of this thesis is to develop the intelligent control systems to improve the performance of the USV tracking control. By considering the uncertainties in the dynamics model, the designed methods must consider the powerful ocean disturbances, underactuation of the model, and the nonholonomic constraint in the kinematics. Due to the concern of the dynamic ocean environment, the intelligent systems are developed to have the compatibilities that adapt to the proposed USV models. In addition, the first goal of the designed architecture is to optimize the traditional sliding mode control and to avoid the chattering problem that may affect the control system unstable. Furthermore, the designed intelligent system has to have the capability to fix the speed jump problem of the traditional backstepping approach caused by large initial values in USV tracking control.

1.4 Contributions of This Thesis

This thesis introduces two proposed methods for motion planning and tracking control of underactuated surface vessels: (1) type-2 fuzzy sliding-mode control, and (2) bioinspired backstepping approach-based sliding-mode control. The contributions are summarized as follows.

- A new intelligent method was developed for tracking control of underactuated surface vessels (USV), which integrates interval type-2 fuzzy logic control with a sliding-mode control. Normally, USV trajectory tracking suffers from poor performance due to uncertain model parameters and the dynamic disturbances from wind, wave and airflow. In the proposed control method, the IT2FLC is used to analyze the USV kinematic model for selecting the optimal velocity, as the IT2FLC is an advanced technique to minimize the high uncertainties of the
control system. The integrated IT2FLC-SMC controller is developed with the USV dynamic model to process the applied control torque for better tracking performance. The simulation results demonstrate that the proposed approach is able to handle the system uncertainties better in comparison to the type-1 fuzzy sliding-mode control approach.

- A hybrid control system is developed for the USV, which integrates a bioinspired shunting model with backstepping based algorithms and sliding mode control. Firstly, a bioinspired backstepping approach is used to analyze the USV kinematic model to generate virtual velocities, which efficiently solves the velocity jump issue caused by the large initial values in the conventional backstepping method. Accordingly, the bioinspired algorithm optimizes smooth velocity signals in the sliding mode. Furthermore, a dynamic model based sliding mode controller is combined with the bioinspired model to offer suitable control torques to the USV by avoiding chattering problems. This approach simulates and compares the tracking performance of the proposed method with the aim of improving its efficiency.

1.5 Organization of This Thesis

In this chapter, an overview of the research work examining unmanned surface vessels and intelligent control system is given. The motivation and contributions of this thesis are introduced. The following chapters are organized as follows.

Chapter 2 provides a brief foundational knowledge of the proposed control methods, including type-1 and type-2 fuzzy logic control systems, backstepping approach, sliding mode control approach, and bioinspired algorithms. After that, a review of the related research work is presented.

Chapter 3 presents a new tracking controller that integrates the type-2 fuzzy and sliding mode control for USVs. In the proposed method, both USV kinematics and dynamics are considered. The intelligent controller has the capability to reduce the effect of the uncertainties in the system and can also avoid the chattering problem.
associated with the sliding mode control.

Chapter 4 presents a detailed explanation of the proposed hybrid bioinspired backstepping sliding mode tracking control system. This intelligent control solves the speed jump problem caused by the large initial values in the backstepping approach. Furthermore, the generated smooth velocity signals can avoid the chattering problems of the sliding mode control and generate the stable control laws of the USV.

Chapter 5 summarizes this thesis and explores possibilities for future work.
Chapter 2

Background and Literature Review

The study of unmanned surface vessel can date back to the World War II; however, research projects about this technology only started attracting great attentions until the late of 1990s. For the corresponding supports, this is due to the development of detecting and monitoring technology. The great interest in this unmanned vessel technology promoted the transfer of the Navy pattern, which leads to significant attentions on the coastal war and counter-terrorism missions. The outstanding performance of the unmanned surface vessel in the second Gulf War has made the Navy all of the world even more interested in unmanned vessel projects. In this chapter, the brief introduction of unmanned surface vessel is presented firstly, and the fundamental knowledge about intelligent control system of type-1 and type-2 fuzzy logic control systems, sliding mode control, backstepping approach and bioinspired shunting model are introduced in the meantime.

2.1 Intelligent Control Systems

The field of intelligent control can be regarded as a developing branch of automatic control in advanced level, and it is one of the most attractive and challenged fields at present academic research. It is not unique to define what exactly the intelligent control is, but intelligent control theory is presented by a system that can adapt into some specific environments, and is able to control designed targets or objectives,
which has the ability to handle the complexity and uncertainty. The most common and authoritative explanation from IEEE is “Intelligent control system must have the capabilities of self-learning and adaptation” (CHING et al., 2015). Generally, the intelligent control system should deal with multifarious information to accept different environmental changes, and to reduce uncertain situations as many as possible. Furthermore, the intelligent control theory contains various following comprehensive science knowledge:

- Artificial Intelligence
- Control Theory
- Information Theory
- Bionics
- Neurophysiology
- Evolutionary Computing

All these technologies and theories integrate together and build up the foundations of the intelligent control theory. The first intelligent control theory is published by an American scientist named Wiener in 1948, which introduces the conception of feedback from a system (Wiener, 1961). During the 20th century from 1950s to 1990s, the intelligent control theory has experienced a great deal of significant changes, and the typical evolutionary methods of control structure can be classified as two elements intelligent control structure (II ICS), three elements intelligent control structure (III ICS), four elements intelligent control structure (IV ICS) and multiple elements (tree form) intelligent control structure (Tree ICS). In this section, the two elements and three elements intelligent control structure is briefly introduced.

### 2.1.1 Two-elements Intelligent Control Systems

In 1965, Fu, the professor of American Purdue University, announced the interaction between artificial intelligence (AI) and automatic control (AC), which affected the
research application of intelligent control system (IC) in the recent research (Sun and Cover, 1976). Artificial intelligence is a knowledge process system that has the functions of memorizing, learning, information producing, language forming and inference arouse. On the other hand, automatic control is a dynamic feedback system that describes the characteristics of kinematic models. Fig. 2.1 shows the relationship among these three technologies.

Figure 2.1: Two-elements intelligent control structure. AI: artificial intelligence; AC: automatic control; IC: intelligent control.

### 2.1.2 Three-elements Intelligent Control Systems

Another intelligent control structure is presented by Saridis in 1983; which extended the two elements intelligent control system into a three elements model (Saridis, 1983); and in this model, operation research (OR) was added into the interactive intersection. The structure is displayed in Fig. 2.2. In science, operation research is a quantitative optimization strategy, such as linear programming, network planning, scheduling, management, optimization and etc. It helps intelligent control system runs more efficient and successful.

Two significant control theories related with this thesis are introduced above; and the advantages of intelligent control system are represented based on the applications of using different control structures. For example, ICS has the strong learning ability to recognize an unknown environment, and then improve the self-stability. Meanwhile, like adaptive robustness, well organizing, cooperating via human control, initiative and self-circulation, etc; all of these merits enrich the ICS extensive usage and the
various types of ICS techniques. More specific, there are several main methods can be applied in intelligent control system as follows:

- Fuzzy Logic Control System (Type-1 and Type -2 fuzzy)
- Neural Network Control System
- Genetic Algorithms Control System
- Knowledge-based and Expert Control System
- Neural-fuzzy Control System
- Sensors-based Integration Control System

At present, the application of intelligent control has been widely used in industry, and the technologies are becoming more and more advanced. Researchers have developed diverse soft-computing programs like one typical and well-known high performance visualization numerical software called MATLAB, which was developed by Mathworks. The toolbox of MATLAB can directly take the functions to achieve system designing and simulating. It also has other superiorities, such as wide application, efficient programming, convenient operation and powerful graphics capability. Thus, soft-computing makes the intelligent control system comes true for real application in different area.
Automatic control is one important applied field by using intelligent control theory. Human can apply artificial neural network, fuzzy logic and expert control as the tool to achieve various tasks, such as robot detection, environment modelling, path planning, tracking control and so on. An good example of application is using self-learning strategy of neural network to adjust robotic dynamics. Among the typical approaches, genetic algorithm plays the role of optimization, and it is used to update system programming design to break through the bound of traditional controller. Beside genetic algorithm, the fuzzy logic is another popular applied method to improve the robustness and adaptability of robots.

2.2 Fuzzy Logic Control System

In 1965, fuzzy logic was first proposed by Zadeh of the University of California (Zadeh, 1965). This new control method attracted people’s attention and became popular in a short period. After then on, many researches had focused on this field and develop it to various advanced levels. The fuzzy control theory utilizes the fuzzy controller as a tool that resembles ratiocinative process to implement control theory, which is based on the fuzzy model of control target. The benefit of using fuzzy logic control system is efficiently dealing with the uncertain and inaccurate control system and collecting accurate data by borrowing the experts’ experience. The richer experts’ experience there is, the more effective control will be achieved. In other words, the fuzzy control is an actual system imitating human reactions. Thus, many researchers try to conclude all the accumulated experience into fuzzy logic principles and to make a controller that is based on the principles. After that, the created fuzzy logic language is transformed into algorithmic calculations by four important elements of fuzzy controller, which are the rule base (fuzzy linguistic variables), fuzzification (fuzzy logic theory), fuzzy control inferencing (fuzzy logic inferential information), and defuzzification. The structure of regular fuzzy controller is shown in Fig. 2.3
2.2.1 The Rule Base

A series of fuzzy rules expresses the suitable knowledge to accomplish system control objectives. The rules are totally made by the summation of “IF...THE” sets as the following form:

Within the above database of rules, every single rule is reacted by following the “IF...THEN” form, for example,

\[ R_l^i: \text{IF } x_1 \text{ is } F_{1l}^i \text{ and } x_n \text{ is } F_{nl}^i, \text{ THEN } y_1 \text{ is } B_{ij} \text{ and } y_q \text{ is } B_{lj} \]

where \( l = 1, 2, ..., z \); \( j = 1, 2, ..., q \).

The above rule displays the logic relation that multiple inputs results in multiple outputs. On the other hand, the fuzzy rule base can also have a form that multiple inputs go with one single output.

\[ R_l^i: \text{IF } x_1 \text{ is } F_{1l}^i \text{ and } x_n \text{ is } F_{nl}^i, \text{ THEN } y \text{ is } B_l; \ l = 1, 2, ..., z \]

The rule base is summarized and built based on the comprehension. In research, such comprehension can be obtained through learning process from human on-line or off-line control. Researchers try to conclude intuitionist knowledge via observing the control procedure and to simulate mathematic models. Even though the knowledge found can not be expressed by exact algorithms, it is a way to represent essence of control theory that also shows how the mimetic human intelligent performance responses in a system. Thus, fuzzy logic control rule base is an essential way based on the linguistic variables to implement human decisions and control orders.
2.2.2 Fuzzification

Simply describing the process of fuzzification is a fuzzy controller transforms a large amount of inputs into a degree of membership (contains a small group of fuzzy values), which is comparability matched with the fuzzy logic rules. There are three typical types of fuzzy membership functions display in Fig. 2.4. The actual values of different degrees for each fuzzy rules are identified by truth or not.

![Triangular MF and Trapezoidal MF and Gaussian MF](image)

Figure 2.4: Three different types of fuzzy membership functions.

2.2.3 Fuzzy Inference Engine

This part is used to evaluate which fuzzy rules related with the current conditions and to give the solution from the input to output of the type-2 fuzzy sets. It is a strategy to generate an input state to an output state by using fuzzy logic to compute the
intersections between the sup-star compositions of each type-2 system. The summary of the fuzzy membership functions and rules are transformed into data during this process.

2.2.4 Defuzzification

Due to the output for the system must be an exact value not a fuzzy set, this step contains several methods of defuzzification to produce a final crisp value; such as centre of gravity and so on. Through the defuzzification interface, the fuzzy sets that are the outputs of the inference engine combines each rule to be transformed into a single output set. According to the parameters that belong to the fuzzy set are produced by fuzzy inference engine, the control system needs to use defuzzification find a exact value that is corresponded with the parameters in the set.

This fuzzy logic control system introduced above is called Type-1 Fuzzy Logic Control System (T1FLC), which is widely applied in household appliances, air conditioner, camera and so on. The reason why T1FLCS can work as an efficient control method can be concluded into several advantages: 1. Both the input and output of the system are true value. This design is suitable for engineering application; 2. The procedure runs as the sample rule form “IF ... THEN...”; 3. There are various available fuzzy controllers that has different required combination of fuzzy inference and defuzzification can be selected to solve some specific problems.

Besides, even though in some cases T1FLC is the best selection to be a control strategy, for other conditions it may be not because of the uncertainties. At first, the nondeterminacy of the type-1 fuzzy rules is applied between antecedent and consequent. Furthermore, some uncertain values are existed in consequent especially when all the knowledge comes from different experts’ experience. In addition, in T1FLC, if the signal patches together with noise, the system may lead to unstable work. Hence, according to these unstable situations, the membership functions of fuzzy set stays in an uncertain condition.
Figure 2.5: The structure of type-2 fuzzy controller. (Redraw from Mendel et al., 2007)

2.2.5 Type-2 Fuzzy Logic Control System (T2FLC)

Type-2 fuzzy set is the extension of traditional type-1 fuzzy set, and its characteristic is the membership value. Based on the type-2 fuzzy controller, T2FLCS can deal with the language data and uncertainties effectively at the same time even in highly uncertain situations, which performs better stability than the corresponding of type-1 fuzzy controller. To clarify what uncertainties are, normally two elements need to be considered: linguistics and randomness. Linguistics absolutely relates to the words that have different meanings to different people; thus, according to the different understanding, linguistics is unsure to judge the right or wrong. Meanwhile, T2FLC could handle the randomness by taking the noisy strategies or operations. In addition, the feature of T2FLC is to represent the fuzzy set membership value as another type of fuzzy set; namely, the membership value itself is T1FLC. The T2FLC has enhanced original fuzzy set to improve the ability of dealing with system noise and interference. Due to both of the type-2 fuzzy system and type-2 fuzzy controller use type-2 fuzzy membership function, they could model expert language and data simultaneously to deal directly with the unpredictable effect caused by the fuzzy rules. In addition, T2FLC has absolute advantages in reducing the number of rules, smoothing control output and optimizing response performance. In recent years, T2FLC has become more and more popular on the real application, but it has the capability to solve the control problem in high uncertain control system, such as in
The Type-2 Fuzzy Logic Control (T2FLC) was first presented by Zadeh (Zadeh, 1975). In the proposed scheme, the initiator for sophisticated fuzzy set, which is called as type-2 fuzzy sets, exist as a form of membership function itself. In traditional type-1 fuzzy sets, the membership value is a crisp number in interval 0 to 1; on the contrary, all the elements of membership value belonged to [0, 1] constitute type-2 fuzzy sets, in which the Fig. 2.6 shows a 3 dimensional Gaussian structure for T2FLC membership function. Thus, the T2FLCS that has a wide extension of type-2 fuzzy set performs better on handling noisy inputs and uncertain environment. And also, type-2 fuzzy set is three dimensional, but type-1 is two dimensional, which is shown in Fig. 2.4. To the people who familiar with the basic knowledge of type-2 fuzzy, the rule base of T2FLCS is also described as the form of “IF-THEN”, which the antecedent “IF” and consequent “THEN” are identified by the type of T2FLC. Furthermore, when one or both of the antecedent or/and consequent is/are belong to type-2 set, the system is called T2FLCS. As the example of type-2 fuzzy rule is:
\[ R^l: \text{IF } x_1 \text{ is } \tilde{F}_1^l \text{ and } x_n \text{ is } \tilde{F}_n^l, \text{ THEN } y \in Y \text{ is } \tilde{B}^l. \]

where \( x_1 \in X_1, x_n \in X_n, n \) is the number of inputs, \( l \) is the number of rules, output is \( y \in Y \).

By comparing type-1 and type-2 fuzzy logic systems, the function of inference engine is quite same. T1FLC concludes and transfers all the rules from the input fuzzy sets to the output fuzzy sets, which integrate multiple antecedents into \( t \)-norm (the intersection of sets) and uses the sup-star to connect output sets with membership grades (Karnik et al., 1999). However, in T2FLC, discovering the unions and intersections of type-2 sets is the fundamental condition to successfully work on the procedure. In addition, depending on the structures of both type-1 and type-2 fuzzy in Fig. 2.3 and 2.5, we can easily find that they have similar parts of the control system, where T2FLC has one extra component type-reducer. Type-reducer is focusing on transforming the type-2 fuzzy output sets into type-1 form as well as using the defuzzifier produces a crisp value. Due to a type-reducer of type-2 fuzzy set is a finite interval, the value comes from defuzzification block is the average of the two end-points in this interval. In the academic research area of type-reducer, there are five strategies; one of the most popular methods is Extension Principle that is created by Karnik and Mendel to define the centroid of T2FLC (Karnik and Mendel, 2001). Although this algorithm is repeated when it runs, it is still time-saving than others.

### 2.3 Sliding Mode Control

Sliding mode control is a typical variable structure system that has the features of robustness, accuracy and so on (Zinober, 1990). It is a nonlinear control approach that has amount of feedback control laws. The control laws have the capability to drive the system state to a desired surface in the state space, in which the surface is called sliding surface. Sliding mode technique can keep the control state staying on the sliding surface when it reaches. Meanwhile, the state feedback control laws can convert the signals from one to another closed one that is depended on the real-time requirement in the space. This function benefits the flexibility of the control system.
to handle dynamic parameters by switching the variable structures. Furthermore, the response of switching functions results in an insensitive environment to confront uncertainties. This feature is utilized to effectively make the unpredictable parameters and disturbances stay in boundary.

Considering a single input nonlinear dynamic system as:

$$\dot{x} = f(x, t) + g(x, t)u(t), \quad (2.1)$$
$$y = h(x, t), \quad (2.2)$$

where $x \in \mathbb{R}^n$ represents the state vector; $u \in \mathbb{R}^m$ and $y$ are the scalar input and output variable, respectively. The task of the control is to make the output variable to track the specific desired state, which means the tracking error must tend to zero. Both of the function $f(x)$ and $g(x)$ are unknown in the equation, but the continuous vector $x$ is known.

To design a sliding mode control system, there are two steps: firstly, to select a certain system state that makes the system reactions to be restricted; secondly, to find a control law that drives the system reach the sliding surface, which takes the error variable to zero in a finite time. Specifically, the SMC trajectory normally begins with the non-zero initial condition, the dynamic switching sliding surface steers it to stay on the state once it reaches. The switched control is defined as

$$u(t) = [u_i(t, x)], \quad (2.3)$$

and

$$u_i(t, x) = \begin{cases} u^+_i(t, x), & s_i(x) > 0 \\ 0, & s_i(x) = 0 \\ u^-_i(t, x), & s_i(x) < 0 \end{cases} \quad (2.4)$$

where $i = 1, ..., m$, the order of the switching functions is less than the order of plant. Meanwhile, the sliding mode is affected by the parameters of the switching functions. If one system has $m$ switching functions, it has $m$ inputs and $2^m - 1$ sliding surfaces.

In addition, the second phase for sliding mode control is to generate a suitable control law to reach the sliding surface and stay on it. Once the trajectory reaches
the sliding surface, the following equation is the structure of the controller, which is:

\[ u(t) = k \text{sgn}(s) + u_{eq}(t), \quad (2.5) \]

where \( k \) is a control gain that affects the output value, \( u_{eq}(t) \) is equivalent control that makes the derivative of the sliding surface converge to zero to stay on the surface, and \( s \) is the switching function that has been introduced above. The corrective control \( u(t) \) quickly switches the functions and drives the state to a specific switching surface. To guarantee the system path catch the sliding surface in finite time, the Lyapunov function approach is applied to the control strategy. Define

\[ V(x) = \frac{1}{2} s(x)^T s(x), \quad (2.6) \]

and the derivative of \( V(x) \) is gotten as

\[ \dot{V}(x) = s(x)^T \frac{ds(x)}{dx} \left[ f(x, u) + B(x)u(t) \right] < 0, \quad (2.7) \]

the value of the \( u(t) \) is modified for a negative definite \( \dot{V}(x) \), and the large input is chosen to ensure the function keeps on negative definite for \( f(x) \).

Even though the sliding mode control is an efficient approach, it still has the shortage caused by the negative influence of the features itself. Due to the various structures for switching the functions in high finite frequency, some unsatisfactory behaviours will happen in the procedure that causes the phenomenon of oscillations and amplitude. This situation is called chattering that is the major problem occurs in SMC. The chattering problem is caused by discontinuous signals from control activities when the control system has the fast changing dynamics without modelling. The reason that chattering occurs in the system is because the controller has restricted capability of sampling rate. In the theory, the ideal sliding mode controller is able to deal with infinite high frequency, which seems impossible to implement in real applications. The major effects of the chattering problem make the entire control system run with very low accuracy actions, and sometime affect the power circuits lost.

To easily solve the chattering problem, the system is better to add a continuous control component. Due the major effect of the high frequency switching functions,
the sgn function can be modified or optimized by other effective strategies. There are various methods and strategies to be implemented with sliding mode control for improving the system capability of dealing with discontinuous signals and switching frequency. More details about the reviewed work are discussed in Chapter 3.

2.4 Backstepping Approach

Backstepping control is a method widely used for nonlinear dynamical system. It is designed as a feedback mathematical model in 1980s, using for stabilizing control with the various structures of subsystems (Kokotovic, 1992). The basic idea for this technique is to build a known state first and to make the new progress run back to the previous stage stably. With the circular structures, the control system asymptotically studies the controlling parameters until the final stage is reached. Normally, backstepping approach is designed with Lyapunov function to guarantee the system stability, which automatically neglects the unknown cross-coupling factors. This feature provides the flexibility for the control system to model nonlinearities and some specific terms of restricted linearization. The capability of stabilization allows the control system to handle more nonlinearities and put them into the recursive equations to avoid the risk of the unpredictable parameters.

Considering a nonlinear control system

\[ \dot{z} = f(z) + g(z)x_i, \quad (2.8) \]
\[ \dot{x}_i = u, \quad (2.9) \]

where \( u \) is the control input, and \( z = (x_1, x_2, ..., x_i)^T \). To design a feedback control system, in which \( x_i = u(z) \) and \( i = 1, 2, ..., n \), the subsystem of \( z_1 \) becomes

\[ z_1 = f(z) + g(z)u. \quad (2.10) \]

To use the Lyapunov function to define

\[ V_1(x_1, z_1) = V_1(x_1) + \frac{1}{2}(z_1 - u)^2, \quad (2.11) \]
and to ensure the subsystem of \( \dot{z} \) stays in a stable condition, which defines \( V_1 > 0 \) and gets

\[
\dot{V}_1 = \frac{dV_1}{dz} \left[ f(z) + g(z)u(z) \right],
\]

(2.12)

which is negative as the stable condition.

Denote \( \beta \) as estimated error and \( \beta = x_i - u(z) \), and rewrite the (2.9) to

\[
\dot{z} = f(z) + g(z)u(z) + g(z)\beta, \quad \quad (2.13)
\]

\[
\dot{\beta} = u - \dot{u}(z). \quad \quad (2.14)
\]

Define the Lyapunov function of

\[
V_2(z, \beta) = V_1(z) + \frac{\beta^2}{2},
\]

(2.15)

then get

\[
\dot{V}_2 = \frac{dV_1}{dz} \left[ f(z) + g(z)u(z) \right] + \frac{dV_1}{dz}g(z)\beta + \beta\dot{\beta},
\]

(2.16)

where choosing \( \dot{\beta} = -\frac{dV_1}{dz}g(z)\beta - k\beta \), and \( k \) is a positive constant, in which the origin of the system is stable asymptotically. Meanwhile, the control law of the system is chosen as

\[
u(z, x_i) = \dot{\beta} + \dot{u}. \quad \quad (2.17)\]

Normally, for a rigorous standard feedback nonlinear system, two and more steps are designed to select the control input. In the first subsystem, \( x_2 \) is chosen as an expected value that is described by the function of \( x_1 \) to ensure the previous step stable, and it satisfies the stability of the Lyapunov function in

\[
\dot{V}_1 = \frac{dV_1}{dz} \left[ f_1(x_1) + g_1(x_1)u_1(x_1) \right].
\]

(2.18)

In the second step, denote the \( x_3 \) as the virtual input to the subsystem based on the state \( x = [x_1, x_2]^T \), and define

\[
x_3 = \frac{1}{g_2(x_1, x_2)} \left[ u_1 - f_2(x_1, x_2) \right],
\]

(2.19)

and the control system of state \( x \) is becoming

\[
\dot{x}_1 = f_1(x_1) + g_1(x_1)x_2, \quad \quad (2.20)
\]

\[
\dot{x}_2 = u_1, \quad \quad (2.21)
\]
According to the equation (2.17), the control parameter $u_1$ is calculated as

$$u_1 = \frac{dV_1}{dx_1} g_1(x_1) - k_1[x_2 - u(x_1)] + \frac{du}{dx_1} \left[ f_1(x_1) + g_1(x_1)x_2 \right],$$  \hspace{1cm} (2.22)

and the corresponding Lyapunov function is

$$V_2(x_1, x_2) = V_1(x_1) + \frac{1}{2} \left[ x_2 - u_1(x_1) \right]^2.$$  \hspace{1cm} (2.23)

Therefore, the virtual input $x_3$ is gotten by take the equation (2.22) back to the equation (2.19). This procedure is described as the backstepping algorithm, which treats the desired output as the input of the first phase and uses the virtual parameter to calculate the actual value by taking back-step to the entire system.

The main idea of the backstepping approach is introduced above. It is obviously to find that this technique implements the control system based on the recursive strategy. Both of the feedback control laws and Lyapunov functions are integrated into systematic system, and several individual subsystems has the capability to deal with amounts of nonlinearities, in which the system stability is guaranteed meantime.

### 2.5 Kinematic and Dynamic Models of an USV

Marine surface vessels are regularly comprised of six DOFs (degree of freedoms) within the earth-fixed ($X_o, O_o, Y_o$) and body-fixed ($X, O, Y$) frames. Normally, the tagged motion coefficients are composed by surge, sway, yaw, heave, roll and pitch, which build the intact model of USV to accomplish the position tracking behaviour and orientation. In Fig.2.7, only three components of the USV are sufficient for the system based on the two-dimensional simulation; these are surge, sway and yaw. The model of heave, roll and pitch is neglected in order to simplify the structure of the controller, which is a stable loop. Thus, three individual velocities are defined as $V = [u, v, r]$ in the direction of surge, sway and yaw, respectively. In addition, the actual position of the ship in inertial frame is $\eta = [x, y, \beta]^T$, which is described in Fig. 2.8.

Then, the kinematic model of USV is expressed as

$$\dot{\eta} = J(\beta) V,$$  \hspace{1cm} (2.24)
and
\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\beta}
\end{bmatrix} = \begin{bmatrix}
\cos \beta & -\sin \beta & 0 \\
\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
u \\
v \\
r
\end{bmatrix},
\]

where \( J \in \mathbb{R}^{n \times n} \) is the transformation matrix between earth-fixed and ship body-fixed frame; \( x \) and \( y \) represent the actual position of the surface vessel in the earth-fixed frame and \( \beta \) is the orientation in the \( X_o-Y_o \) coordinate. Furthermore, the desired posture of the trajectory is constructed by a series of points that are \( \eta_d = [x_d, y_d, \beta_d]^T \). Meanwhile, the referenced equation can be written the same as replacing the parameters of equation (2.25) in which excepts the velocity on sway is zero due to the underactuated vessel system.

According to all the explanations above, the position errors \( \eta_e \) can be easily computed as \( \eta_e = \eta - \eta_d = [x_e, y_e, \beta_e] \). In order to consider system dynamics, the body-fixed frame based velocities of tracking errors \( e_x, e_y \) and \( e_\beta \) are respectively defined as
\[
e_\eta = \begin{bmatrix}
e_x \\
e_y \\
e_\beta
\end{bmatrix} = \begin{bmatrix}
\cos \beta & \sin \beta & 0 \\
-\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x_e \\
y_e \\
\beta_e
\end{bmatrix}.
\]

Figure 2.7: A 2D USV with three degrees of freedom.
The dynamic model of the USV is a non-linear system that is described based on the motion of surge, sway and yaw. The dynamic equation is expressed as (Fossen and Johansen, 2006)

\[ M \ddot{V} + C(V)\dot{V} + D(V)V = \tau + \tau_w, \]

where \( M \in \mathbb{R}^{n \times n} \) is the moment of inertia, \( C \in \mathbb{R}^{n \times n} \) represents the centripetal and Coriolis forces, \( D \in \mathbb{R}^{n \times n} \) is the damping matrix, \( \tau \in \mathbb{R}^{n \times n} \) is the control variables of forces, and \( \tau_w \in \mathbb{R}^{n \times n} \) represents the unknown parameter of the disturbances (wave, wind and airflow) from the external environment.

According to the proposed underactuated ship model, the control forces only exist on the surge \( \tau_u \) and yaw \( \tau_r \), in which there is no input on sway moment. To simplify the control model of the system, this method assumes that the disturbances can be neglected on the dynamic model.

### 2.6 Potential Applications

A typical application of the unmanned surface vessel in the military field is the underwater robot, which is to complete the task of detection and surveillance operations in
the open sea and coastal areas. In these operations, unmanned surface vessel can provide the real-time environmental information to the remote station. In theory, those real-time caught information will be more accurate and updated than those that from conventional manned equipment. The remote control centre of the unmanned surface vessel can be set as various types, such as ships, aircrafts, and ground bases. No matter the kind it exists, the construction needs be autonomous. At transmission level, the unmanned surface vessels can transfer photos, videos or electronic data back to the remote control centre that is either located on ground, in the air or on the ship. The power plant of the unmanned surface vessel can be a diesel engine, an electrical motor, or even a power generator of wind driven (Luh and Lin, 1982). In addition, the unmanned surface vessel can be designed specifically for the high-speed and long-distance operations. Most of the unmanned surface vessels are equipped with marine surveillance appliance, such as infrared ray, thermal imaging, and real-time camera. These devices can provide the real-time information to the remote control centre via satellite or radio transmission. Since the unmanned surface vessel does not require any individual to operate on-site, it is possible to decrease the cost of human and financial resources to carry out interception of the target of interest. In such cases, those expensive ships, helicopters and aircrafts, which may be still under directly control of human operators, can be arranged to perform other special operations.

Unmanned surface vessel can play a vital role in the territorial security, drug control, search and rescue missions. It can deliver patrol management to any site around the coast, ports and vulnerable equipment. Furthermore, the unmanned surface vessels can also perform an applicable supervision on the transportation of those medications prohibited by law. By cooperating with the manned or unmanned aircrafts, the unmanned surface vessel can provide with real-time and actuate monitoring of the significantly important locations and channels on the sea. Under the active observation, these important notifications of any hostile or illegal activity can be delivered to the remote control centre as early as possible. Not limited as above, the unmanned surface vessel can also protect the sovereignty of the distant territory (IEEE Control Systems Magazine, 2007). A colony of unmanned surface vessels can be applied to
participate in the onerous task of long-distance search and rescue.

To liberate human from danger, the unmanned surface vessel can be applied to replace those manned vessels in terms of completing high-risk operations. For example, during the time of missile firing, it is highly required to ensure the safety of launch centre. It will be extremely dangerous if manned vessels, helicopters or aircrafts are implemented in such circumstances. In comparison, the unmanned vessel is able to accomplish this kind of tasks without risking the personnel to face up with unsafe conditions. For the government and research institute, the unmanned vessels can be appointed to check unlicensed vessels and endangered marine species in a targeted area. When deployed in such tasks, the unmanned vessel can provide real-time video stream and other useful data based on the its ability of precise location within its own self-defence range. With unmanned vessel working in such way, it realizes the aim to reduce the danger level of the staff and eliminates the need to install expensive observation platform.

Another important application of the unmanned surface vessel is to provide with anti-mine measures. The region where has already been cleared with no mines still has to be closely monitored to ensure that no fresh mines leak or expose to this area again. Since the compactness, it is found that the light noise can easily escape from the detection of radar and other electronic equipment. For this situation, the unmanned vessel is pretty applicable to be deployed. It can conduct monitoring tasks in those sensitive areas, such as the sea lanes, the entrance of harbours and the seacoast. Such tasks will no longer endanger the operation personnel since no physical appearance of them is required on the unmanned surface vessel.

A great number of potential applications of unmanned vessel can be designed in terms of being applied in the civilian aspects. For example, it can provide help with the protection of the marine industry assets and important cargo as well the protection of marine oil and gas exploration platform. It is also able to aid accomplishing marine survey, nautical charting, data acquisition and marine biological research. Moreover, the unmanned vessel can be applied to the fisheries and even to the entertainment ships. By now, a large number of business groups receive and plan the deep-sea
engineering projects, and they have a lot of valuable movable or fixed assets (such as container ships, tanks,). The unmanned vessel is able to provide with services in monitoring the shipping channel and sensitive sea area of the maritime mobile assets, as well as in ensuring the safety of fixed assets. The above mentioned applications are highly dependent on the advanced sensor that unmanned vessel is equipped with. These sensors can provide real-time image and perception of information, which allows the control centre to be aware of any potential threat. The unmanned surface vessel provides with a great deal of help to offshore industry in terms of the development offshore oil and mineral exploitation. Prior to any marine exploitation, the task of mapping the seabed topography is of great importance, which requires the help of sound waves to accomplish. This mapping process requires the specific period, during which the unmanned vessel will strictly comply with a predetermined procedure that can be suitably carried out using the high-precision navigation system of the unmanned vessel. As a consequence, the unmanned surface vessel is regarded as a very superior tool for terrain mapping works. In addition, the unmanned vessel does not require an anchor or rope to stay a long time in the set point. This merit allows the unmanned vessel to be implemented as a mobile weather station that is applied to collect meteorological and hydrological data, or support the marine survey. The great support that the unmanned vessel offers for fishery industry is another aspect of its main applications. The unmanned vessel equipped with sonar sensors can be used to accomplish search tasks in large sea area with complex ecosystems. After location of a shoal with fish, the unmanned vessel can directly go to the water region with great density of fish. Similarly, the unmanned vessel can be employed to monitor the water regions where fishing is forbidden and to notify the superior with illegal fishing activities, resulting in offering great help for the protection of ecosystems.

2.7 Literature Survey

Unmanned surface vessels have become more and more popular as the attractive research objectives around the world because of the commercial values and the capabil-
ities of implementing some difficult tasks (Aguiar et al., 2003). One of the important research interests about USV is motion control, which is typically performed as trajectory tracking. In the tracking control system, the USV is designed to catch and follow a desired path considering both positions and steering. Normally, the error between the actual ship position and the desired trajectory is the significant element for studying the tracking problem. In addition, the speed and the force on thruster of the USV are also considered as two important factors in tracking control. Meanwhile, the various control methods are designed based on considering either or both of kinematic model and dynamic model of USV.

Many approaches are widely developed for improving the tracking control systems in past decades. A detailed introduction about the course keeping control of USV was explained in Azzeri et al. (2015). Numerous control strategies were designed and utilized to compensate and to reduce the tracking errors in positions. The brief introduction of course keeping control structure is shown in Fig. 2.9. The typical methods are PID control (Parra-Vega et al., 2003), sliding mode control (e.g. Wang et al., 2007; Martinez et al., 2008), backstepping algorithms (Godhavn et al., 1998), adaptive fuzzy control (Zhen et al., 2009), Lyapunov-based method (Ma and Xie, 2013), and hybrid control theory (Chen et al., 2009), and so on. In research Al-Hiddabi and McClamroch (2002), a feedback linearization method is applied to a tracking system; however, because of the limitations of control conditions, the system stability is not guaranteed. Besides, Reyhanoglu and Bommer (2006) proposed an integrated intelligent controller by using backstepping approach and switched feedback control loop, which is designed based on the global stability. Furthermore, Ghommam team developed another global exponentially stabilization tracking controller; the systematic framework provides a smooth control feedback under the dynamic situation. The external disturbances are controllable in this tracking system, where the Lyapunov-based backstepping method is utilized (Ghommam et al., 2010). In addition, a bioinspired neural dynamics-based controller is designed by (Pan et al., 2015) for marine ship trajectory tracking. The strategy was developing a combined system with integrating three neural dynamic models and a bioinspired shunting model,
where the stability of the system is approved as well. The experiment indicates that the proposed controller is effectively to deal with the external disturbances in an unknown ocean environment.

In the following sections, many academic studies are briefly introduced, which are related with this research, such as hybrid sliding mode control, type-2 fuzzy logic theory, bioinspired algorithm, backstepping method, etc.

### 2.7.1 Sliding Mode Control

One of the most common methods for tracking control is sliding mode control (SMC), which is designed by the features of high simplicity and robustness. The basic idea of using SMC method is to build a sliding surface for driving the tracking system stays on it. Meanwhile, SMC is a nonlinear control strategy that applies discontinuous signals to the nonlinear system, which always forces the trajectories along to the bounded controllable plates. The characteristic of SMC is the insensitive respond that is excellent for modelling uncertainty parameters and disturbances. Due to this feature, many researches utilize the SMC to deal with unknown system models and parameters for achieving robust control.

The multiple structures of SMC can be used to USV tracking control system. Cheng et al. (2007) proposed a SMC controller with variable structures, in which the control law is proved by Lyapunov as stable. Ashrafiuon et al. (2008) introduced a SMC method and designed a control law that utilizes a first-order and second-order
sliding surface to deal with tracking errors on surge and lateral motion errors respectively. The reaching conditions of trajectories to the sliding surfaces are bounded that is proved by using Lyapunov as well. The simulation studies are applied on a ship with two DC propellers in room by tracking a straight line and a circle. Similarly, Wei and Guo (2009) developed a nonlinear SMC system for USV tracking control, which is also considered by using the first-order surface and second order surface to compute the tracking errors. Also, in the research of Fahimi and Van Kleeck (2013), a nonlinear sliding mode tracking controller was designed for an underactuated model, in which the outdoor experiment is simulated to test the robustness of the system with disturbances. Furthermore, considering the advantage features of the robustness for uncertainties and disturbances, the sliding mode control is also widely used in the research (e.g. Soltan et al., 2009; Young et al., 1999; Serrani et al., 2001).

In order to use SMC efficiently, an important factor is necessarily concerned, which is the drawback may result in an unstable control system. Due to the high frequency of sliding mode real-time control, uncertain and dynamic parameters may cause controller sustaining a high-order sliding surface, in which the situation is normally called chattering. This problem leads the SMC to implement discontinuous signals that probably damage the system temporally. Based on this main defect, numbers of researches about the solution are presented; for example, Some researches developed several useful strategies to avoid SMC chattering problem (e.g. Shim et al., 1995; Allen et al., 2000; Levant, 2003). Furthermore, many hybrid control systems are widely designed to enhance the SMC at the same time in (e.g. Ho and Niu, 2007; Lefeber et al., 2003). A typical research that introduced an efficient approach by Hwang et al. (2009), the main idea is to design a controller combine fuzzy control and sliding mode, which could provides the larger outputs than inputs to the system. The simulation work is analyzed by considering dynamic parameters and disturbances of wind and wave; based on the designed conditions and the optimized inputs, the control performance is better approved.
2.7.2 Type-2 Fuzzy Control and Bioinspired Neural Dynamic Model

Fuzzy system has been investigated for decades as an efficient logic control, due to its capability of computational reducing. In normal situation, uncertainties and vague systems are simply handled by using fuzzy logic control system, which are conducted as numbers in the interval between 0 and 1 (Coupland and John, 2008). Nevertheless, the demand of control plant accuracy is much higher especially in realistic control; in some cases, the type-1 fuzzy controller is not efficient to implement a better performance (Lee et al., 2003). Thus, the type-2 fuzzy is needed to deal with more types of uncertainties. By using type-2 fuzzy control system, vague information and unpredictable elements are effectively modelled due to its enhance features of linguistics and the function of fuzzy sets (Zadeh, 1975).

Type-2 fuzzy logic system has been paid many attentions in the application of intelligent control; in many researches, it has been reviewed for comparing the difference with type-1 fuzzy and describing the applications (Wu and Mendel, 2002). Meanwhile, some control problems are also presented in some researches that indicate the regular concerns in the application of type-2 fuzzy (e.g. Chen and Tan, 2010; Hagras, 2004). For a type-2 fuzzy system in a real-world control, Wagner and Hagras (2007) proposed a genetic algorithm to optimize the type-2 fuzzy inputs and to drive the system with controllable uncertainties. Meanwhile, Mohammadi et al. (2010) introduced another method about type-2 fuzzy logic system optimization that the nonlinear system inputs are optimized by the evolved type-2 membership function. To deal with the nonlinear system uncertainties, Lee and Lin (2005) developed a type-2 fuzzy neural network approach that is combined with adaptive filter. This system has the capability of approximating the unknown parameters and learning the effect of disturbances. In the work of Chen and Tan (2010), an adaptive type-2 fuzzy controller is designed to resolve the tracking problems of surface vessels. The comparison of indirect and direct adaptive type-2 fuzzy systems is studied by considering the hydrodynamic coefficients. The stability is proved that makes the tracking errors converge to zero, and
the controller is simulated based on a robust performance.

In recent year, bioinspired approach has been researched as an updated type of optimized technique for improving control strategies in complex systems. By comparing with type-2 fuzzy logic control system, bioinspired method has the similar capabilities to seek the appropriate parameters for complex systems to accomplish risky tasks. A typical membrane model of biological neural system is firstly proposed by Hodgkin and Huxley in Hodgkin and Huxley (1952). Yang and Meng (2000) developed an efficient controller for dynamic robot motion planning based on using the membrane model integrated with Grossberg’s shunting model in Grossberg (1988). Meanwhile, this approach is widely applied as an efficient control system in intelligent control. Yuan et al. (2001) designed a novel tracking control system for a mobile robot based on the bioinspired shunting model strategy; the simulation result performs better than the traditional backstepping method. Afterwards, a neural dynamic based algorithm for real time robot path planning is represented by Luo and Yang (2008), where the proposed algorithm is effectively tested for robot navigation in an unknown environment. Furthermore, Pan et al. (2013) introduced a bioinspired neural dynamics method for autonomous surface vessels tracking control, where the velocity value is optimized for a stable manipulation. The control method was designed by integrating the backstepping approach and the neurodynamics shunting model. The tracking errors of the surface vessel were derived by the proposed controller as inputs. Firstly, two steps of the backstepping based control algorithms were developed. And the velocities \( u \) and \( r \) are defined as

\[
\begin{align*}
  u &= \bar{v}_d \cos \phi_e - k_1 z_x, \\
  r &= \frac{k_3 z_v + e_y + W}{k_2 \sigma},
\end{align*}
\]

(2.28)

(2.29)

where \( v_d \) is the desired virtual control parameter, \( z_x \) and \( z_v \) represent the errors on the motion of the surface vessel, and \( k_1, k_2, k_3 \) are constants.

Secondly, by considering the speed jump problems, this research utilize the shunting model to replace the control parameters \( z_x \) and \( z_v \) by \( v_{s1} \) and \( v_{s2} \), in which the
shunting models are defined as

\begin{align}
\dot{v}_{s1} &= -A_1v_{s1} + (B_1 - v_{s1})f(z_x) - (D_1 + v_{s1})g(z_x), \\
\dot{v}_{s2} &= -A_2v_{s2} + (B_2 - v_{s2})f(z_v) - (D_2 + v_{s2})g(z_v).
\end{align}

The stability of the proposed control algorithms are approved by using multi-Lyapunov functions, and the simulation results indicate that the effectiveness of this method. However, this approach is only considered the speed vector, the control laws of the model and the control force on thruster are neglected, which are significant elements for practical control.

### 2.7.3 Backstepping Approach

The backstepping method is widely used in the nonlinear tracking control system based on the Lyapunov theory due to its outstanding features of systematic and recursive structure for feedback control. The design flexibility of the backstepping algorithm has contributed to provide the unlimited restriction conditions to the researchers for designing a control system. The main idea of backstepping approach is to divide the whole system into two series subsystems, in which the outputs or results computed from the first stage are the factors for the next stage. The effective way to recognize the backstepping approach is to obtain a control signal that is studied by the first subsystem and then transferred to the second subsystem. The second subsystem provides a state-feedback plant to build a closed-loop system with stability. Normally in automatic surface vessels tracking control systems, the first step is to study the varying knowledge in order to realize the desired structures, and the generated signals are transferred to the next subsystems.

Many papers are published in the world to discuss about the application of backstepping approach in various control system, especially for surface vessels tracking control. Do and Pan (2005) proposed a backstepping algorithm based control system to investigate the trajectory tracking of the underactuated surface vessels. The experiment is implemented with environmental disturbances, and the ship model is not required to be specific on a reference trajectory. The dynamic structures were studied
in this research. Additionally, a marine vessel path following strategy is introduced by Zhen et al. (2009). This model is presented as four degrees of freedom nonlinear, and the backstepping based controller was designed for the feedback dominance. Even though the proposed method has been approved the robustness for the uncertainty, the underactuated feature is difficult to achieve with restricted control laws.

A typical study of underactuated ship tracking control is presented by Pettersen and Nijmeijer (1998), only two motion controls were considered on surge and yaw. The proposed model is restricted to be transferred to chained form. However, the coordinate transformation of the ship is still accepted to combine with backstepping algorithm to generate control laws for the control system. To continue this study, in 1999, they developed an extended model by integrating the backstepping approach with averaging technique and global stabilization strategy (Pettersen and Nijmeijer, 1999).

In recent years, many researches about backstepping approach become more and more attractive. For example, Chen and Tan (2013) developed an adaptive backstepping controller for an actuated surface vessel by considering the hydrodynamic disturbances. They also applied the type-2 fuzzy logic control into the system to observe and choose the high gain as the output for feedback control. The stability is approved by Lyapunov functions to ensure the system efficiency. In addition, another effective tracking controller of underactuated surface vessel was designed by Sonnenburg and Woolsey (2013). The possibilities of this model under the various situations with a wide range of control values were presented in this study. Meanwhile, this research provided the multiple structures and the options of parameters to generate on the dynamic trajectories, which indicated using backstepping approach is an effective tool to solve the tracking control problem. Furthermore, a backstepping based course controller was designed by Witkowska and Smierzchalski (2007), the main idea of this research was to build a automatic steering system to control the ship to follow a desired path. The ship’s motion was controlled by steering machine with bounded rudder, and the control rules were generated by the calculation of the backstepping algorithms. The structure of the control is displayed in Fig. 2.10, and $x$, 

34
$y$, and $\psi$ represent the posture of the ship. In addition, the input signals transferred from the autopilot, which were defined as a set of rudder angle $\delta_Z(t)$. The output $\delta(t)$ represented the real-time rudder angle, and it was bounded in a certain interval. The simulations were approved that backstepping approach is an effective strategy to implement tracking control of surface vessels.

![Control Structure](image)

Figure 2.10: The control structure of steering the movement of ship. (From Witkowska et al., 2007)

To deal with nonlinear control system, adaptive backstepping plays a very significant role to conduct the feedback parameters. The effectiveness and the outstanding advantages are illustrated by many researches. Li et al. (2011) developed a robust adaptive controller for backstepping tracking control, which has the capability to drive the ship to the desired trajectory with the system uncertainty. In addition, another adaptive backstepping course keeping controller was designed for USV model. This controller has no requirement for the priori information about surface vessels, which can ensure the ultimate uniform boundedness of the signals in closed-loop system (Ren and Zhang, 2013).

In a word, the backstepping approach is utilized to design a stable system for nonlinear control, and the progress of each subsystem is guaranteed by using Lyapunov function to stabilize the entire system. The various structures of the backstepping algorithm provide unlimited possibilities for different types of the complex systems.
Chapter 3

An Integrated Type-2 Fuzzy Sliding Mode Controller for an USV

In this chapter, a new intelligent method is developed for tracking control of under-actuated surface vessels, which integrates interval type-2 fuzzy logic control with a sliding-mode control. Normally, USV trajectory tracking suffers from the poor performance due to uncertain model parameters and the dynamic disturbances from wind, wave and airflow. In the proposed control method, the IT2FLC is used to analyze the USV kinematic model for selecting the optimal velocity, as the IT2FLC is an advanced technique to minimize the high uncertainties of the control system. The integrated IT2FLC-SMC controller is developed with the USV dynamic model to process the applied control torque for better tracking performance. The simulation results demonstrate that the proposed approach is able to handle the system uncertainties better in comparison to the Type-1 fuzzy sliding-mode control approach.

3.1 Introduction

Marine surface vessels have been investigated widely in recent years because of their increasing commercial and industrial values. For tracking control, the accuracy of
position is one of the most challenging topics for unmanned surface vessels and is studied using various methods. However, even though many methods have been introduced to enhance real-time control strategies, the environmental disturbance and input noise still obstinately exist to affect tracking performance. Due to this issue, an effective control strategy is required to deal with all kinds of uncertainties and to track the desired path smoothly. Normally, six independent coordinates of the underactuated surface vessel is the condition required to track the movements in position and orientation; these coordinates are surge, sway, heave, roll, pitch and yaw. Somehow, researchers adopt only three significant coordinates: surge, sway and yaw to build a general model of USV because it satisfies the model that can be simply tested with different controllers. Therefore, in this paper USV is modelled as a rigid body with three degrees of freedom.

Many approaches have been developed on USV tracking control using the kinematic model in the recent decade, such as feedback linearization (Fjellstad and Fossen, 1994), nonlinear Lyapunov-based control (e.g. Ghommam et al., 2010; Bi et al., 2010), and neural network based control (e.g. Chen et al., 2009; van de Ven et al., 2005). The traditional feedback linearization (or dynamic inversion) is popularly accepted as a tool of localization that handles tracking error via a time constant linear system. While this seems attractive, the system must start with a small initial value of tracking error in order to allow this method to be utilized under a stable condition. In addition, neural network is an efficient method for handling uncertain nonlinear systems because it employs large-range calculations. However, the required training process is time consuming, and the learning algorithms are complicatedly to simulate in the system. Moreover, a controller that runs the control theory with only kinematic USV is not able to satisfy reality under atrocious conditions. Hence, it is imperative to develop an effective controller with the suitable control method, which takes both dynamic and kinematic models into consideration. To deal with the unstable system problem caused by the environmental complexity, Hwang introduced a fuzzy-sliding model controller to reduce the effect of the disturbance in ambient situations (Hwang et al., 2009); and the result of interference reduction is better performed than the tra-
ditional terminal sliding mode controller (Chen and Tan, 2013) and adaptive-sliding mode (Fang et al., 2004). Nonetheless, a general fuzzy logic system of type-1 form is processed based on the expert experience and knowledge, which is not such a useful strategy to solve control problem of handling complexity and uncertainties.

Type-2 fuzzy logic control, which becomes a popular research topic in recent years, performs exceptional capability than type-1 fuzzy on facing the system issues of disturbances. T2FLCS was first presented by Zadeh the initiator for sophisticated fuzzy set, which exists as a shape of membership function itself. Different from type-1 fuzzy control, all the elements of membership value belonged to [0, 1] constitute type-2 sets. T2FLCS performs a 3D membership function that contains a footprint of uncertainty. Thus, T2FLC that has a wide extension of type-2 fuzzy set performs better on dealing with system noisy inputs and uncertain components (Karnik et al., 1999). To well understand FOU, two bounding functions are important: lower membership function and upper membership function, which are type-1 fuzzy sets. They make a simple step to build an IT2FLC that has the similar characteristics of T1FLC. Furthermore, similar with type-1 fuzzy control system, T2FLC is consisted of fuzzifier, rule base, fuzzy inference, type reducer, and defuzzifier. Meanwhile, it has absolute advantages in reducing the number of rules, smoothing control output and optimizing response performance.

Sliding mode control represents a method of discontinuous and nonlinear control, which is suitable to collect diverse parameters and to reject disturbance without requiring an exact mathematic model (e.g. Ashrafuon et al., 2008; Chwa et al., 2002; Nguyen et al., 2007). It has a state couple back law to adjust the system control states running on sliding surface. The benefit of using SMC is because of its insensitive and robustness, it could adapt to the T2FLC system for handling high disturbances. The proposed controller that combines an interval-T2FLC and SMC theory is introduced, which controls USV tracking a curve smoothly. Both of kinematic and dynamic model are analyzed by using proposed method, and the value of the tracking error is approximated to 0.
3.2 The Proposed Type-2 Fuzzy Kinematic Controller for an USV

In this section, a type-2 fuzzy kinematic model is designed for the IT2FLC method, in which the kinematic model of USV has been introduced in Chapter 2.

In order to reduce the system uncertain effects of using sliding model technique cooperates efficiently with USV kinematic model, a controller is designed by type-2 fuzzy control, which has several inputs and one output.

Firstly, some main ideas about IT2FLC controller is briefly introduced. Basically, type-2 fuzzy logic is mainly similar as type-1. In T2FLC, a is the primary value, which are different points contained in the membership functions b (Karnik and Mendel, 2001). A type-2 fuzzy set $\tilde{A}$ is described by

$$\tilde{A} = \{(a, b), \mu_{\tilde{A}}(a, b) | \forall a \in X, \forall b \in J_a \subseteq [0, 1])\}, \quad (3.1)$$

where $X$ is the primary variable and $J_a$ is the primary membership. The secondary set $\mu_{\tilde{A}}(a, b)$ is in the interval of [0,1], which has the same range with $J_a$. When the set $\mu_{\tilde{A}}$ of second level equals to 1, the interval T2 fuzzy set uses all units of primary memberships to indicate the uncertainty - FOU. The standard shape of the FOU performs the overall fuzzy sets, and it means two significant components that are an upper membership function $\overline{\mu}_{\tilde{A}}(a) = \text{FOU}(\tilde{A})$ and a lower membership function $\underline{\mu}_{\tilde{A}}(a) = \text{FOU}(\tilde{A})$.

**IT2FLCKM Fuzzifier**

In this controller, the type-2 singleton fuzzifier is used in a singleton fuzzification, where the tracking errors $e_\eta$ and the corresponding velocity vectors of $\dot{e}_\eta$ are the inputs for the system (Hsiao et al., 2009). A triangular shape membership function in Fig. 3.1 determines the uncertain range that relates to upper bound and lower bound membership function.
Figure 3.1: Interval Type-2 triangular shape contains Type-1 (dotline) based fuzzy logic bounded by lower membership function and upper membership function.

Figure 3.2: The fuzzy rules of the proposed type-2 fuzzy system.
The form of rules is similar between type-1 and type-2 fuzzy, the rule base of T2FLCS is also described as the form of “IF-THE”, which the antecedent “IF” and consequent “THEN” are identified by T2FLC. While one or both of the antecedent or/and consequent is/are belong to type-2 set, the system is T2FLC.

\[ R^l: \text{IF } e_1 \text{ is } \tilde{F}_1^l \text{ and } e_2 \text{ is } \tilde{F}_2^l, \text{ THEN } y \text{ is } \tilde{G}^l, \quad l = 1, \ldots, m. \]

where \( e_1, e_2 \) and \( y \) represent the inputs and output of the IT2FLC, and \( \tilde{F}_i^l, \tilde{G}^l \) are the fuzzy sets defining the space of input and output. Meanwhile, \( e_1 \) and \( e_2 \) represent the tracking errors and the derivative of errors belong to \( e_\eta \) and \( \dot{e}_\eta \), respectively. \( m \) is the number of the total fuzzy rules. The summary of rules is concluded in Fig. 3.2, and the related membership functions are shown in Fig. 3.3, 3.4, and 3.5, respectively.

**IT2FLCKM Inference Engine**

In the IT2FLC, the inference engine integrates fuzzy rules and provides the sets from input to output. The important strategy finds intersections is described by extended sup-star compositions as

\[
\mu_{P^l} = \left[ \bigcap_{i=1}^{n} \mu_{\tilde{F}_i^l} \right] \cap \mu_{\tilde{G}^l},
\]

where \( \cap \) is defined as the intersections, \( n \) is the amount of inputs, and also the fire set is \( \tilde{F}^l(e_i) \). Thus, the consequence is the interval fuzzy set that becomes type-1 model.
Figure 3.4: Triangular type-2 fuzzy membership function with the middle point of uncertainties.

Figure 3.5: Singleton type-2 fuzzy membership function with the centre of points.
by computing the firing level for each fired rules, i.e.

\[ \tilde{F} = [f^l, \bar{f}] \]  

(3.3)

**IT2FLCKM Type Reducer and Defuzzifier**

Type Reducer is the most important part of the type-2 fuzzy logic system, which is produced by following the principle of extension (Zadeh, 1975). It drives the system from type-2 form into type-1 by the end points from left $y_l$ to right $y_r$ in the interval set. To calculate the T2FLC consequents of each rule, two variable parameters $y^l_l$ and $y^r_l$ are defined. For widely applied method of type reducer, the type of Centre-of-Sets is used as an efficient tool that is defined as

\[ y_{\text{cos}}(e) = [y_l, y_r], \]  

(3.4)

where $y_{\text{cos}}(e)$ is a set for output that is calculated by its smallest point $y_l$ and largest point $y_r$ on both left and right, which are expressed as

\[ y_l = \min_{\forall f^l \in [f^l, \bar{f}]} \left[ \frac{\sum_{i=1}^{M} f^l_i y^l_i}{\sum_{i=1}^{N} f^l_i} \right], \]  

(3.5)

\[ y_r = \max_{\forall f^l \in [f^l, \bar{f}]} \left[ \frac{\sum_{i=1}^{M} f^l_i y^r_i}{\sum_{i=1}^{N} f^l_i} \right]. \]  

(3.6)

Getting the value of $y_l(e)$ and $y_r(e)$ must use the Karnik-Mendel iterative procedure (Karnik and Mendel, 2001). Furthermore, the interval set is defuzzified to calculate the average of $y_l$ and $y_r$, which is

\[ V = \frac{y_l + y_r}{2}, \]  

(3.7)

down there, kinematic output $V$ represents a crisp value that drives the tracking error approximating to zero.

**3.3 The Proposed Type-2 Fuzzy Dynamic Sliding-mode Controller for an USV**

The second important component of the proposed control system is the dynamic sliding-mode control that combines with IT2FLC technique, which is shown in Fig. 43.
3.6. The details of this designed controller are introduced in this section.

3.3.1 USV Dynamic model

To analyze the ability of proposed method for dealing with system uncertainties, both of damping coefficients and ocean environmental disturbances are concerned in this model. Thus, the dynamic model of USV (Siramdasu and Fahimi, 2013) is defined as

\begin{align}
\dot{u} &= \frac{m_{22}}{m_{11}} vr - \frac{d_{11}}{m_{11}} u + \frac{1}{m_{11}} \tau_u + \frac{1}{m_{11}} \tau_{wu}, \\
\dot{v} &= \frac{m_{11}}{m_{22}} vr - \frac{d_{22}}{m_{22}} v + \frac{1}{m_{22}} \tau_{wv}, \\
\dot{r} &= \frac{m_{22} - m_{11}}{m_{33}} uv - \frac{d_{33}}{m_{33}} r + \frac{1}{m_{33}} \tau_r + \frac{1}{m_{33}} \tau_{wr},
\end{align}

where \( u, v \) and \( r \) represent the velocities on surge, sway and yaw; respectively, \( m_{11}, m_{22}, \) and \( m_{33} \) are the mass of the surface vessel that is set based on the realistic value; \( d_{11}, d_{22}, \) and \( d_{33} \) are the dynamic damping of three degree freedoms. In order to simplify the simulation work, the higher nonlinear damping should be neglected. Furthermore, \( \tau_u \) and \( \tau_r \) are the surge control torque and lateral motion control torque, which are estimated coefficients. \( \tau_{wu}(t), \tau_{wv}(t) \) and \( \tau_{wr}(t) \) are the disturbances of wind, wave and airflow, and they satisfy the conditions, which are given by \(|\tau_{wu}(t)| \leq \tau_{wu\text{max}}\), \(|\tau_{wv}(t)| \leq \tau_{wv\text{max}}\), and \(|\tau_{wr}(t)| \leq \tau_{wr\text{max}}\). The actual values of these three disturbances are lower than the maximum estimation.

Considering about the tracking control problem, the desired dynamic model are necessarily to be defined to get the trajectory errors of ship body frame based three degrees of freedom. Differently than the USV dynamic model above, the desired dynamic model only contains two expected parameters on the surge and lateral di-
rections $\tau_{ud}$ and $\tau_{rd}$. Meanwhile, the errors of velocities on surge, sway and yaw are defined as $E_v = [e_u, e_v, e_r]^T$. Thus, some important factors are expressed as:

$$e_u = u - u_d, e_v = v - v_d, e_r = r - r_d, \tau_{eu} = \tau_u - \tau_{ud}, \tau_{ev} = 0, \tau_{er} = \tau_r - \tau_{rd}.$$ 

Take these velocity errors to the dynamic model of the USV, then the tracking error dynamic model could be obtained as

$$
\begin{align*}
\dot{e}_u &= \frac{m_{22}}{m_{11}} (v_r - v_d r_d) - \frac{d_{11}}{m_{11}} e_u + \frac{1}{m_{11}} \tau_{eu} + \frac{1}{m_{11}} \tau_{wu}, \\
\dot{e}_v &= \frac{m_{11}}{m_{22}} (u_r - u_d r_d) - \frac{d_{22}}{m_{22}} e_v + \frac{1}{m_{22}} \tau_{wv}, \\
\dot{e}_r &= \frac{m_{22} - m_{11}}{m_{33}} (u_v - u_d v_d) - \frac{d_{33}}{m_{33}} e_r + \frac{1}{m_{33}} \tau_{er} + \frac{1}{m_{33}} \tau_{wr}.
\end{align*}
$$

### 3.3.2 Dynamic Sliding-mode Controller for the USV

The general SMC of USV dynamic model is briefly described in this part in order to combine with type-2 fuzzy system that involves in the proposed USV control. Due to the characteristics of surface vessels, two important control torques of sliding-mode $\tau_u$ and $\tau_r$ must be designed. In the normal situation, $\tau_r$ indirectly motivate the lateral motion control.

**Surge Control Torque $\tau_u$**

Firstly, the tracking error $e_u(t)$ is utilized to define a gradual stable sliding surface $S_1$, which is a first-order system expressed as

$$
S_1 = e_u + \lambda_1 \int_0^t e_u(\tau) d\tau, \lambda_1 > 0.
$$

Next, the surge tracking error equation could be substituted into (3.14), and then taking the time derivative of $S_1$. Sliding surface is calculated by

$$
\dot{S}_1 = e_u + \lambda_1 \dot{e}_u = 0.
$$

As the $e_u$ has been defined on the above, taking the equation into time derivative sliding surface to get

$$
\dot{S}_1 = \frac{m_{22}}{m_{11}} (v_r - v_d r_d) - \frac{d_{11}}{m_{11}} e_u + \frac{1}{m_{11}} (\tau_u - \tau_{ud}) + \frac{1}{m_{11}} \tau_{wu} + \lambda_1 e_u.
$$
Once the controller is able to drive the system to the sliding surface, then, \( \dot{S}_1 = 0 \). Meanwhile, to solve the control problem, the equivalent control torque \( \tau_u \) should be defined for the nominal model as

\[
\dot{\tau}_u = -\hat{m}_{22}(vr - v_d r_d) - (\hat{m}_{11} \lambda_1 - \hat{d}_{11})e_u,
\]

where \( \hat{\cdot} \) is used to define the estimated parameters for simulating, and they have bounded conditions as

\[
|m_{ii} - \hat{m}_{ii}| \leq M, |d_{ii} - \hat{d}_{ii}| \leq D_{11}, i = 1, 2, 3.
\]

In addition, the equivalent control torque \( \dot{\tau}_u \) is not guaranteed to perform a successful control because of various unpredictable impact factors exist. Therefore, an discontinuous assistant parameter \( \tau_1 \) to represent the effect of disturbances is necessarily projected as

\[
\tau_1 = -Q_1 \text{sgn}(S_1),
\]

where \( Q_1 \) is defined as a control gain that belongs to the range near sliding surface. To determine the value of \( Q_1 \), the interval section uses the equation (3.18) to set boundaries. Then, \( Q_1 \) is given by (Ashrafiuon et al., 2008)

\[
Q_1 = \lambda_1 M_{11} |e_u| + M_{11} |\dot{u}_d| + D_{11} |u| + M_{22} |vr|.
\]

Thus, the surge control torque is gotten by integrating \( \dot{\tau}_u \) and \( \tau_1 \); where, this non-linear system is fully considered about both of uncertainties and stable conditions. The final equation is expressed as

\[
\tau_u = \dot{\tau}_u - Q_1 \text{sgn}(S_1).
\]

**Lateral Motion Control Torque \( \tau_r \)**

Based on the error from the direction of sway, the second sliding surface is defined as a second-order system, which is written by

\[
S_2 = \ddot{e}_v + 2\lambda_2 e_v + \lambda_2^2 \int_0^t e_v(\tau)d\tau, \lambda_2 > 0.
\]
In order to get the solution of tracking control problem; similarly as $S_1$ above; when $S_2$ equals to zero, the trajectory is able to keep on the sliding surface. Taking the derivative of this equation, then get

$$\dot{S}_2 = \ddot{e}_v + 2\lambda_2 \dot{e}_v + \lambda_2 e_v = 0. \quad (3.23)$$

Depending on the dynamic equations of errors, the parameter $\dot{e}_v$ is calculated by

$$\ddot{e}_v = -\frac{m_{11}}{m_{22}}(\dot{e}_u r_d + e_u \dot{r}_d) - \frac{m_{11}}{m_{22}} \dot{e} u_r - \frac{d_{22}}{m_{22}} e_v + \frac{1}{m_{22}} \dot{\tau}_{uv} - \frac{m_{11}}{m_{22}} \dot{u} e_r, \quad (3.24)$$

and define

$$I = -\frac{m_{11}}{m_{22}}(\dot{e}_u r_d + e_u \dot{r}_d) - \frac{m_{11}}{m_{22}} \dot{e} u_r - \frac{d_{22}}{m_{22}} e_v + \frac{1}{m_{22}} \dot{\tau}_{uv}, \quad (3.25)$$

then the equation (3.23) becomes

$$\dot{S}_2 = I - \frac{m_{11}}{m_{22}} u \dot{e}_r + 2\lambda_2 \ddot{e}_v + \lambda_2^2 e_v. \quad (3.26)$$

In addition, two parameters $p$ and $b$ are defined as

$$p = m_{22} m_{33} I - m_{11}(m_{11} - m_{22}) u (uv - u_d v_d) \quad (3.27)$$

$$+ m_{11} d_{33} u e_r + m_{22} m_{33} (2\lambda_2 \ddot{e}_v + \lambda_2^2 e_v),$$

$$b = m_{22} u_d - m_{11} u. \quad (3.28)$$

The lateral motion control torque is procured under the condition $\dot{S}_2(t) = 0$, which drives the error stay on the sliding surface, which is expressed as

$$\dot{\tau}_r = \tau_{rd} - \tau_{wr} + \frac{\dot{p}}{b}, \quad (3.29)$$

where $p$ and $b$ are estimated parameters that are calculated by the equations (3.27) and (3.28). In addition, the reaching control is necessarily to be accepted in this part as well, which is defined as

$$\tau_2 = -\frac{Q_2 \text{sgn}(S_2)}{b}. \quad (3.30)$$

Thus, integrating all the control torques and getting the force of turning vessel in lateral motion; then, the control torque is re-written as

$$\tau_r = \tau_{rd} - \tau_{wr} + \frac{\dot{p} - Q_2 \text{sgn}(S_2)}{b}. \quad (3.31)$$
IT2FLC-SMDC Design for the USV

Similar as the IT2FLC kinematic model, the second type-2 fuzzy controller chooses sliding surface to be a single input. The fuzzy rule of the IT2FLC-SMDC is described as

\[ R^l: \text{If } S_j \text{ is } \tilde{S}^l, \text{ then } Q_j \text{ is } \tilde{Q}^l, \quad l = 1, \ldots, M, \; j = 1, 2. \]

To enhance the tracking performance, \( Q \), the gain of control action, is a significant parameter to be adjusted in real-time. As shown above, the sliding surface \( S \) is the element of type-2 fuzzy controller to affect the speed parameter \( Q \). Although underactuated surface vessel control is considered by surge torque and lateral torque, which have two different sliding surfaces defined, the result of tracking purpose is equivalent. Therefore, two sliding surfaces and control gains could be combined as

\[
S = \begin{bmatrix} S_1 & 0 \\ 0 & S_2 \end{bmatrix}; \quad Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}, \quad S > 0.
\]

The IT2FLC controller of this part helps the velocity raises up when the sliding surface has a long distance with the actual position. Besides, the \( Q \) gradually reduces to close to the tangent plane. This controller not only benefits the low time consuming, but also causes a weak system buffeting, which achieves a fast and stable tracking control. Thus, the five rules for IT2FLC-SMDC is shown in table 1, which contains Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS) and Positive Big (PB).

Table 3.1: The Rule Base of the IT2FLC-SMC. \( S \): Sliding Surface; \( Q \): Control Gain; NB: Negative Big; NS: Negative Small; ZO: Zero; PS: Positive Small; PB: Positive Big.

| \(|S|\) | NB | NS | ZO | PS | PB |
| --- | --- | --- | --- | --- | --- |
| \( Q \) | NB | NS | ZO | PS | PB |

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3.4 Simulation Studies

To validate the proposed method, this section has displayed two type fuzzy logic system simulations for underactuated surface vessel tracking control. As this chapter desired at the beginning, IT2FLC-SMC controller has better performance on dealing with ocean current disturbances and control system itself. It can optimize the damping coefficients and model parameters so that the system causes less time varying to against uncertainties. The simulation work in this part is compared with conventional SMC method and T1FLC-SMC method.

![Comparison of tracking a line](image)

**Figure 3.7**: The comparison of tracking a line by using the IT2FLC-SMC method and the T1FLC-SMC method.

Based on the computer simulations, the model parameters of the underactuated surface vessel are consulted in (Ashrafiuon et al., 2008). The IF and THEN fuzzy membership function is taken by five equal separations in both types of fuzzy controllers. Then, $m_{11} = 1.956 \pm 0.019$, $m_{22} = 2.405 \pm 0.117$, $m_{33} = 0.043 \pm 0.0068$, $d_{11} = 2.436 \pm 0.023$, $d_{22} = 12.992 \pm 0.297$ and $d_{33} = 0.0564 \pm 0.00085$. Firstly, a straight line is used as a desired path that sets $y_d = 3$ and $x_d = 0$ in MATLAB.
workspace. Therefore, the desired speed is \( u_d = 0.1 \text{m/s} \). Meanwhile, the initial posture for USV is [0,0,0]. Due to the underactuated model, the USV starts with zero velocities on surge, sway and yaw. In addition, all other control parameters are selected as \( \lambda_1 = 0.5, \lambda_2 = 1 \), and assuming that the disturbances of the ocean environment \( \tau_{wu}(t) = \tau_{wv}(t) = \tau_{wr}(t) = 0.5 + 0.1 \times \sin(t) \).

![Figure 3.8: The comparison of posture errors by using the T1FLC-SMC method (a) and the IT2FLC-SMC method (b).](image)

The simulation result by tracking the straight line is shown in Fig. 3.7. It is obvious to observe that the controller of IT2FLC-SMC has a better tracking performance by comparing with T1FLC. Even though USV uses T1FLC-SMC method to catch up the desired path with short time, the tracking path is not perfect to land on it. By contrast, the IT2FLC-SMC method drives the USV smoothly to catch the desired path and stay on it after reaching the path. More details about related posture errors, velocities and torques by using two controllers are compared in Fig. 3.8, 3.9 and 3.10. As the coefficients of disturbance are added into the control system, the velocities and torques are quite different between these two methods. IT2FLC-SMC controller has a better capability to deal with the system uncertainties and noises, which is effectively approved by simulation study of tracking a line.

In the second case, a typical circular path has been designed for studying the performance of each methods. To well illustrate the performance of the proposed controller, the tracking control is compared by considering the conventional sliding
Figure 3.9: The comparison of the USV velocities by using the T1FLC-SMC method (a) and the IT2FLC-SMC method (b).

Figure 3.10: The comparison of torques by using the T1FLC-SMC method (a) and the IT2FLC-SMC method (b).
mode control and T1FLC-SMC method at the mean time. Assuming the desired circular path is \( (x-1)^2 + (y-1)^2 = 1 \), and the start posture of USV is \([0, -0.6, 0]\) with zero initial velocities. Other control parameters are as same as the first tracking case. The simulation results are shown from Fig. 3.11 to 3.14. The performance of proposed controller is most effective than other two methods. Meanwhile, the indication of chattering problem appeared in conventional SMC controller, but not happened in IT2FLC-SMC system. The comparison of this phenomenon has obviously approved that IT2FLC system can effectively optimize the control signals to avoid amplitude of sliding mode approach. In addition, although type-1 fuzzy control also has the capability to deal with chattering problem, the effectiveness is not good than type-2 fuzzy logic control.

Figure 3.11: The comparison of tracking a circular trajectory by using the conventional SMC method, the T1FLC-SMC method and the IT2FLC-SMC method.
Figure 3.12: The comparison of posture errors by using the T1FLC-SMC method (a) and the IT2FLC-SMC method (b).

Figure 3.13: The comparison of velocities by using the T1FLC-SMC method (a), the conventional SMC method (b) and the IT2FLC-SMC method (c).
Figure 3.14: The comparison of torques by using the T1FLC-SMC method (a), the conventional SMC method (b) and the IT2FLC-SMC method (c).

At last, an elliptic path is chosen as an uncommon way to simulate, which is defined as $(x - 4)^2/9 + (y - 4)^2/4 = 1$. The trajectory initial position is desired as [4, 2, 0]; meanwhile, the initial status of surface vessel system are $\eta_d = [2, 0.8, 0]$ and the velocities of surge, sway and yaw are zero because of the underactuated model. In addition, all other control parameters are reset as $\lambda_1 = 1, \lambda_2 = 3$.

The compared trajectories of actual positions between type-1 and type-2 fuzzy controller are shown in Fig. 3.15, which drive the USV to follow the reference elliptic path. Due to the effect of uncertain parameters, the surface vessel performs a slow tracking at the beginning. However, the proposed method takes smoother and faster movement to catch the desired trajectory than T1FLC-SMC method, and it drives the system based on a stable condition. Fig. 3.16 represents the curve of three posture errors for both two different methods. It is clearly shown that the prior errors are large, but stay in a bounded area. Obviously, IT2FLC-SMC costs less error than
Figure 3.15: The comparison of tracking an elliptic trajectory by using the T1FLC-SMC method and the IT2FLC-SMC method.

T1FLC-SMC, which means the designed control system has a better capability on handling USV tracking problems of uncertainties and disturbances. Also, Fig. 3.17 shows the velocities $u$, $v$, and $r$ of the USV with the correspond torques of IT2FLC-SMC controller; the speed attempts to increase to track the path and then tends toward stability.

### 3.5 Summary

This chapter presents an approach that combines interval type-2 fuzzy control and sliding-mode control for solving the tracking problems of underactuated surface vessels. Both of kinematic and dynamic models are considered and analyzed in details for the proposed new control design. The proposed controller can reduce the risk caused by the uncertain model parameters and disturbances of ocean environment, where the controller can choose the optimized variable values. The simulation results show that the type-2 fuzzy control is better than type-1 sliding-mode tracking control and conventional sliding mode control.
Figure 3.16: The posture errors of tracking an elliptic trajectory in surge, sway and yaw by using the T1FLC-SMC (a) and the IT2FLC-SMC (b).

Figure 3.17: The velocities (upper) and torques (lower) of tracking an elliptic trajectory by using the IT2FLC-SMC method.
Chapter 4

A Hybrid Bioinspired Backstepping Sliding Mode Tracking Control Method for an USV

In this chapter, another hybrid control system for tracking control of underactuated surface vessels is developed. This tracking controller integrates a bioinspired shunting model with backstepping based algorithms and sliding mode control. Firstly, a bioinspired backstepping approach is used to analyze the USV kinematic model to generate virtual velocities, which effectively solves the velocity jump issue caused by the large initial errors in the conventional backstepping method. Accordingly, the bioinspired algorithm smooths the velocity signals for the sliding mode controller. In addition, a dynamic model based sliding mode controller combines with a bioinspired model to offer suitable control torques to the USV with avoiding chattering problems. Simulation and comparison studies are conducted to demonstrate the efficient tracking performance of the proposed method.
4.1 Introduction

Unmanned surface vessels have been widely investigated in recent years as a tool to accomplish various risky tasks while superseding humans. It is valuable to explore more efficient strategies to control autonomous surface vessels in order to reach a high level of accuracy to satisfy the precise requirements of arduous objectives (Manley, 2008). Thus, researchers have begun to investigate the control problems of unmanned surface vessels; especially in regards to real-time control. Normally, surface vessel systems are considered underactuated systems that suffer uncertain hydrodynamic factors due to their highly nonlinear systems. In addition, it is unavoidable to neglect the disturbances from ocean currents and other noises in the control system.

One method frequently used to study USV control is to create a tracking control condition with a tracking controller. The issues related to real-time control are available to be learnt during the process of USV tracking a desired path. Many research studies have been proposed to analyze the nonlinear parts on the surface vessel dynamics and uncertainties. To deal with uncertain situations in an unknown environment, sliding mode control is an effective strategy to be considered a priori because of its insensitivity to changeable parameters and its robustness to disturbances. Particularly, the control gain of the sliding mode system is adapted to large initial values when the boundary is uncertain. On the other hand, the inputs of sliding mode control have the capability to force the system to reach and stay on the prescribed surface, which can drive the designed object to catch the trajectory quickly. Unfortunately, even though it has many outstanding characteristics, the main disadvantage of the sliding mode is that it still results in a discontinuous control system due to its high frequency oscillations, which may cause system instabilities or control system damage (Levant, 2007). Therefore, to deal with this problem, numerous methods have been introduced for designing a continuous sliding control system. Yoo and Ham (1998) also introduced an adaptive fuzzy sliding mode control to improve the conventional fuzzy logic system. This strategy combines both advantages of fuzzy logic control and sliding mode control, which implements a formulation of translating the sliding
mode to be processed as linguistic based on the fuzzy rules. However, the rule base of the fuzzy system is normally very complex, and a large computation time is required to achieve each task.

In addition to the sliding mode control, a backstepping algorithm is another similar control approach widely used in USV tracking control. The backstepping control is a nonlinear control method based on the Lyapunov theorem, which offers a continuous system that is both recursive and flexible for nonlinear feedback control. Nevertheless, the visible shortage that is velocity jump affects the system unstable, due to large initial errors exist in the tracking control (Zhu and Sun, 2013). During the process of USV tracking, large acceleration and forces are initially required, and the control law of the system will respond quickly once the state errors have occurred. The speed jump problem may happen in unpredictable situations when the tracking system has a sudden error, which would cause the system to be impractical. According to this issue, other approaches such as fuzzy logic and neural networks are presented that combine with the backstepping method to smooth the large initial signals. However, these ideas are not extremely efficient due to the resistance of each system. Fuzzy linguistic rules are constructed based on the human experience, and it is impossible to fully describe the large value of USV velocities accurately. For the neural network strategy, the backstepping algorithms need to be learnt and trained, which resulting in a complex computation. Thus, depending on the problems described above, a practical method is required to entirely consider both the velocity jump problem and thrust status.

The motivation of this paper was to design a system that not only integrates the advantages of the backstepping technique and sliding mode control, but also seeks a suitable strategy to overcome the shortages of this method. According to the reality of USV tracking control, it is necessary to handle the numerous uncertain parameters and disturbances through the advanced features of the robust sliding mode; meanwhile, using a Lyapunov-based backstepping approach to ensure the stabilization of the systematic system. Moreover, a bioinspired neural dynamics model is utilized to focus on resolving the speed jump problem and the chattering problem caused by
the variables. The most significant feature of the bioinspired model is that it has a smooth and bounded dynamic interval, and the output of the shunting model will not be affected by input sudden changes. Compared to the fuzzy logic and neural networks, the bioinspired model is more efficient in terms of computation, and especially economically in that it does not require requested learning steps for the simplified USV model. The proposed method herein is an integrated approach of the backstepping algorithm, the sliding mode and the bioinspired shunting model, which applies to both the kinematics and dynamics of the underactuated surface vessel. The tracking performance is demonstrated via a simulation study, ensuring that the system has the capability to eliminate the velocity jump caused by the sudden error changes. In addition, the chattering problem is effectively prevented, resulting in smooth and continuous signals.

4.2 The Bioinspired Shunting Model

In this section, bioinspired approach is explained in detail, which is a significant method in proposed control system. The knowledge of kinematic and dynamic models of USV in Chapter 2 are needed for the preparation of designing the control system.

The proposed tracking controller integrates both the backstepping algorithm and the sliding mode approach. As mentioned earlier, the backstepping method has a typical problem of sharp speed jumps; meanwhile, the sliding mode suffers a chattering problem during the system tracking procedure. To resolve these problems, the
controller is optimized by using bioinspired shunting model that provides a sufficient modification for a smooth trajectory. This model was developed by Grossberg as an effective strategy to learn the system real-time behaviour in a complex and dynamic environment. In 1952, Hodgkin and Huxley introduced a biological neural system contains a patch of membrane, which uses electrical circuit elements (Hodgkin and Huxley, 1952); and this is widely used on the mobile robot control field (e.g. Yang and Meng, 2001; Yang et al., 2012). The dynamics of the voltage \( V_m \) crosses the membrane that is defined as

\[
C_m \frac{dV_m}{dt} = -(E_p + V_m)g_p + (E_{N_a} - V_m)g_{N_a} - (E_k + V_m)g_k,
\]  

(4.1)

where \( C_m \) is the membrane capacitance; \( E_p, E_{N_a} \) and \( E_k \) are the Nernst potentials (saturation potentials) for potassium ions, sodium ions, and the passive leak current in the membrane, respectively; \( g_p, g_{N_a}, \) and \( g_k \) are the parameters that conduct potassium, sodium, and passive channels, respectively. Moreover, the shunting model is represented based on modification of the equation (4.1), setting \( C_m = 1 \) and replacing \( \xi_i = E_p + V_m, A = g_p, B = E_{N_a} + E_p, D = E_k - E_p, [\psi_i]^+ = g_{N_a} \) and \( [\psi_i]^− = g_k \); then getting

\[
\dot{\xi}_i = -A\xi_i + (B - \xi_i)[\psi_i]^+ - (D + \xi_i)[\psi_i]^−,
\]  

(4.2)

where \( \xi_i \) is the neural activity (membrane potential) of the neuron; \( A, B \) and \( D \) are the passive decay rate, and the upper and lower bounds of the neural activity, respectively; and \( [\psi_i]^+, [\psi_i]^− \) are the variables of the excitatory and inhibitory inputs respectively, which drive the neural activity to stay in a finite bounded interval \([-D, B]\) (Grossberg, 1988). An advantageous feature of the shunting model is that the input factors force the output of the shunting model to stay in a stable bound, which ensures that the system will produce smooth output. As a result, the tracking problems of the proposed controller are sufficiently addressed.
4.3 The Proposed Controller

This section briefly describes the hybrid control method used to solve the USV tracking problems. The control loop of the system displayed in Fig. 4.1 contains two main components. The first part utilizes the backstepping based algorithm to measure errors of the actual position and orientation; the resulting parameters transfer the velocity vector to the second part of the sliding mode to obtain the control torque. The shunting model is applied to optimize significant parameters.

4.3.1 Backstepping-based Formulation

The backstepping approach is used to measure the velocity state vector in this proposed method; as such a virtual controller is required. By comparing with the conventional backstepping strategy, the elements of the new backstepping control are simply enhanced by the shunting model, and the algorithm is more suitable to be integrated with the sliding mode to force a USV tracking a desired path. Since the movement of the USV is standard on a horizontal plane, the control system is simulated horizontally.

The term $\eta_d$, $\eta$, $\eta_e$ and $V$ are defined based on the description of the USV kinematic model in Chapter 2. In order to achieve a perfect tracking, the basic idea is to make the $\eta_e$ zero by the motivated forward and angular velocities. As in the tracking movement of the USV model explained in Chapter 2, the actual velocity frame can be defined as $\omega_1$ and $\omega_2$, which are calculated by the referenced velocities; assuming that $\omega_1 = u_d \cos(e_\beta) - v_d \sin(e_\beta)$ and $\omega_2 = u_d \sin(e_\beta) + v_d \cos(e_\beta)$. Therefore, the backstepping based virtual velocity controller is expressed as

$$\Gamma_V = \begin{bmatrix}
\Gamma_u \\
\Gamma_v \\
\Gamma_r
\end{bmatrix} = \begin{bmatrix}
k_1(e_x \cos \beta + e_y \sin \beta) + \omega_1 \\
k_2(-e_x \sin \beta + e_y \cos \beta) + \omega_2 \\
r_d + k_3 e_\beta
\end{bmatrix},$$

(4.3)

where $k_1$, $k_2$ and $k_3$ are positive constants; $\Gamma_u$, $\Gamma_v$ and $\Gamma_r$ are the virtual velocities on the direction of surge, sway and yaw; and $e_x \cos \beta + e_y \sin \beta$ and $-e_x \sin \beta + e_y \cos \beta$
represent the transformation of the tracking errors between earth-fixed and body-fixed coordinates, respectively.

### 4.3.2 Bioinspired Backstepping Controller

The proposed bioinspired shunting model was briefly introduced in the Background; this model is mainly used to solve the velocity jump problem in the first control section. The virtual velocity controller for the backstepping approach is decided by the factor of tracking errors; thus, the related parameters can be optimized by using the bioinspired model. As the explanation of the shunting model equation in the above section, the parameters $e_x$, $e_y$ and $e_\beta$ are replaced by $\xi_x$, $\xi_y$ and $\xi_\beta$ to optimize the backstepping system. Then the new bioinspired backstepping controller is computed as

$$
\Gamma_V = \begin{bmatrix}
\Gamma_u \\
\Gamma_v \\
\Gamma_r
\end{bmatrix} = \begin{bmatrix}
k_1(\xi_x \cos \beta + \xi_y \sin \beta) + \omega_1 \\
k_2(-\xi_x \sin \beta + \xi_y \cos \beta) + \omega_2 \\
r_d + k_3\xi_\beta
\end{bmatrix},
$$

(4.4)

where the neural activities $\xi_x$, $\xi_y$ and $\xi_\beta$ are generated by equation (4.2) with parameters $A_1$, $B_1$ and $D_1$ respectively, which are expressed as

$$
\dot{\xi}_x = -A_1\xi_x + (B_1 - \xi_x)f(e_x) - (D_1 + \xi_x)g(e_x),
$$

(4.5)

$$
\dot{\xi}_y = -A_1\xi_y + (B_1 - \xi_y)f(e_y) - (D_1 + \xi_y)g(e_y),
$$

(4.6)

$$
\dot{\xi}_\beta = -A_1\xi_\beta + (B_1 - \xi_\beta)f(e_\beta) - (D_1 + \xi_\beta)g(e_\beta),
$$

(4.7)

where define the excitatory inputs $f(a) = \max\{a, 0\}$, and the inhibitory inputs $g(a) = \max\{-a, 0\}$.

The output of the virtual velocity is bounded in a finite interval, which is improved by using a shunting model even though the system suffers from large initial coefficients. Thus, the first section of the tracking control system is efficiently improved.

### 4.3.3 The Bioinspired Sliding Mode Controller

In the second part of the control system, an inner loop of the sliding mode control is utilized to handle the input variables of control forces through time-varying. Due
to the characteristics of surface vessels, only two control torques are applied in the system, \( \tau_u \) and \( \tau_r \), in which lateral motion control is regularly motivated by \( \tau_r \). Therefore, the actual velocities of the USV are resulted by the control \( \tau \) via dynamic sliding mode. Meanwhile, the bioinspired shunting model is applied to reduce the chattering problem caused by the speed of change of the propellers.

### Surge Motion Control

Firstly defining the sliding surface \( S_1 \) by using the parameter of \( \Gamma_{e_u} \) that is the parameter of velocity error, where \( \Gamma_{e_u} = \Gamma_u - u \). Then, the sliding surface on surge is expressed as

\[
S_1 = \Gamma_{e_u} + \lambda_1 \int_0^t \Gamma_{e_u}(\tau)d\tau, \lambda_1 > 0. \tag{4.8}
\]

Taking a time derivative of \( S_1 \) equation, and getting:

\[
\dot{S}_1 = \lambda_1 \Gamma_{e_u} + \dot{u} - \dot{u}_d = \frac{1}{m_{11}} (\lambda_1 m_{11} \Gamma_{e_u} + \tau_u + m_{22} vr - d_{11} u - m_{11} \dot{u}_d), \tag{4.9}
\]

where \( \dot{S}_1 = 0 \) when the controller drives the system to the sliding surface without considering the uncertain factors. Thus, the equivalent control effort is represented by

\[
\tau_u(t) = -\lambda_1 \hat{m}_{11} \Gamma_{e_u} - \hat{m}_{22} vr + \hat{d}_{11} u + \hat{m}_{11} \dot{u}_d, \tag{4.10}
\]

where \( \dot{\cdot} \) is illustrated by the estimated parameters. In addition, because of the discontinuous coefficients, the tracking performance is unstable by chance. Thus, another control effort \( \tau_{u_1} \) is designed to represent the perturbations, which is defined as:

\[
\tau_{u_1} = -Q_1 \text{sgn}(S_1), \tag{4.11}
\]

where \( Q_1 \) is the control gain to reach the sliding surface. Normally, the chattering problem of the sliding mode appears due to effect of the \( \text{sgn} \) function. In order to avoid this, the \( \text{sgn} \) function can be replaced by the shunting model. According to the equation (4.2), the \( \text{sgn}(S_1) \) is replaced by the neural activity \( \sim \text{shunting model}(\sigma_1) \), and get

\[
\frac{d\sigma_1}{dt} = -A_2 \sigma_1 + (B_2 - \sigma_1) f(S_1) - (D_2 + \sigma_1) g(S_1), \tag{4.12}
\]

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where the excitatory input is the function of $f(S_1)$, and the inhibitory input is the function of $g(S_1)$. Therefore, the surge motion control torque is concluded as

$$\tau_u = \bar{\tau}_u - Q_1 \sigma_1. \quad (4.13)$$

**Lateral Motion Control**

The lateral sliding surface is determined by the tracking error on yaw, which is a second-order system, due to the fact that there is no control force on the sway. The equation is defined as

$$S_2 = \dot{\Gamma}_e + 2\lambda_2 \Gamma_e + \lambda_2^2 \int_0^t \Gamma_e(\tau)d\tau, \lambda_2 > 0. \quad (4.14)$$

To drive the system to reach the sliding surface, $S_2$ needs to be zero, similar to $S_1$. Taking the time derivative, the equation (4.14) becomes

$$\dot{S}_2 = \ddot{\Gamma}_e + 2\lambda_2 \dot{\Gamma}_e + \lambda_2^2 \Gamma_e = 0. \quad (4.15)$$

Considering the $\Gamma_e$ is also the velocity error between virtual and actual, the calculation is represented as

$$\dot{\Gamma}_e = -\frac{m_{11}}{m_{22}}(\dot{\Gamma}_e r + \Gamma_e \dot{r}) - \frac{m_{11}}{m_{22}} \dot{\Gamma}_e - \frac{d_{22}}{m_{22}} \Gamma_e - \frac{m_{11}}{m_{22}} \dot{r} \dot{r}, \quad (4.16)$$

where $\Gamma_e = \Gamma - r$. Then, the equivalent control torque is concluded as

$$\bar{\tau}_r(t) = \frac{\dot{p}}{b}. \quad (4.17)$$

where $p$ and $b$ are estimated parameters that are modelled by

$$p = d_{22}m_{33} \dot{v} + m_{11}m_{33} \dot{u}r - m_{11}d_{33}ur - m_{11}(m_{22} - m_{11})u^2v + m_{22}d_{33}udr,$$

$$+ m_{22}(m_{22} - m_{11})uv + m_{22}m_{33}(2\lambda_2 \Gamma_e + \lambda_2^2 \Gamma_e) \quad (4.18)$$

$$b = m_{22}ud - m_{11}u. \quad (4.19)$$

Similar to surge motion control, the reaching control function $\tau_{r_1}$ is defined as

$$\tau_{r_1} = \frac{-Q_2 \text{sgn}(S_2)}{b}. \quad (4.20)$$
In order to optimize the sgn function, switching $\text{sgn}(S_2)$ with the neural activity $\sigma_1$, the new lateral motion control torque is calculated as

$$\tau_r = \tau_r + \tau_{r_{\text{new}}} = \dot{p} - \frac{Q_2 \sigma_2}{b}. \quad (4.21)$$

As introduced in the shunting model equation (4.12), $\sigma_2$ can be defined as same as $\sigma_1$; then, the second bioinspired equation of the lateral motion becomes

$$\dot{\sigma}_2 = -A_2 \sigma_2 + (B_2 - \sigma_2)f(S_2) - (D_2 + \sigma_2)g(S_2). \quad (4.22)$$

In this section, the proposed neural activities $\sigma_1$ and $\sigma_2$ are two significant parameters to help sliding mode control avoid chattering problem.

### 4.4 Simulation Studies

To indicate the effectiveness of the proposed method, the experiment of USV tracking control is implemented in this section. The conventional backstepping approach and the hybrid bioinspired system are simulated for comparison. The backstepping theory based kinematic controller combined with the shunting model not only simply calculates the virtual velocity and transfers it to the dynamic sliding mode to generate the control forces, which eliminates the traditionally complex calculations, but also solves the system velocity jump problem. Meanwhile, the robust sliding mode also provides smooth control efforts with avoiding the chattering issue by using bioinspired strategy. The tracking performance of the proposed controller is demonstrated by comparing it with traditional backstepping.

The simulation work was processed in MATLAB. Some review work of other tracking controllers that normally suffer from the speed jump problem, which may happen when the big initial error appears in the backstepping control system. Moreover, some underactuated ships are not able to track a line due to the fact of zero speed on yaw, and some systems may have the big value of tuning radium. In order to produce better results, some system data is consulted from Chwa (2011). In the first case, a trajectory of line is designed to study the difference between conventional
backstepping approach and the hybrid bioinspired backstepping method. The second
part of the proposed controller sliding mode controller is temporarily neglected at this
moment. The line path is defined as \( y = 2x - 2 \), and it starts at the position \([1, 0, \pi/3]\). The desired posture of USV is \([1.2, -1.5, 1]\) with zero velocities on surge, sway
and yaw due to the underactuated model. The control parameters are \( m_{11} = 120, m_{22} = 172.9, m_{33} = 636, d_{11} = 215, d_{22} = 97, d_{33} = 802, \lambda_1 = 0.1, \lambda_2 = 1, k_1 = 3,
k_2 = 3 \) and \( k_3 = 10 \). Meanwhile, the parameters of the bioinspired model are chosen
as: \( A_1 = B_1 = D_1 = 1 \).

<table>
<thead>
<tr>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( A_1 )</th>
<th>( B_1 )</th>
<th>( D_1 )</th>
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<tr>
<td>3</td>
<td>3</td>
<td>10</td>
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The simulation results of tracking a line path are shown in Fig.4.2, 4.3 and 4.4. In
the conventional approach, the USV tracking speed has a sudden change at the
very beginning, which not happens by comparing with the bioinspired method. The
velocities changed more smooth with the optimized function of shunting model. This
result illustrates that it is necessary and effective to integrate the bioinspired shunting
model with backstepping approach for improving the USV tracking control perfor-
mance. According to the proposed control method, the effectiveness of the first part
of the control system has been approved.

In the second case, the proposed controller has been fully considered, and a circular
trajectory is designed as \( x^2 + y^2 = 1 \), in which the desired velocity of radius is \( 1m \).
The initial posture of the USV is set as \([1.5, -0.5, 1]\), and the initial path reference
is \([1, 0, 0]\). The control parameters of the controller are same except some changes
for \( k_1 = 1.5, k_2 = 1.5 \) and \( k_3 = 3 \). In addition, the parameters of the two shunting
models are chosen as: \( A_1 = 2, B_1 = D_1 = 1 \) and \( A_2 = 0.1, B_2 = D_2 = 1 \).

The circular trajectory tracking performance of the USV displayed in Fig. 4.5
illustrates the proposed controller and tracks the desired path more smoothly and
gently than the conventional backstepping controller. Although it seems that the
Figure 4.2: The comparison of tracking a line by using the conventional backstepping approach and the bioinspired method.

Figure 4.3: The posture errors comparison of tracking a line by using the conventional bioinspired method (a) and the backstepping approach (b).

Table 4.2: Control Parameters for Tracking a Circular Trajectory.

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<td>$k_1$</td>
<td>$k_2$</td>
<td>$k_3$</td>
<td>$A_1$</td>
<td>$B_1$</td>
<td>$D_1$</td>
<td>$A_2$</td>
<td>$B_2$</td>
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<td>2</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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Figure 4.4: The velocity comparison of tracking a line by using the bioinspired method (a) and the conventional backstepping approach (b).

Figure 4.5: The comparison of tracking a circular trajectory by using the conventional method and the proposed controller.
Figure 4.6: The velocity comparison of tracking a circular trajectory by using the conventional method (a) and the proposed controller (b).
Figure 4.7: The torques of tracking a circular trajectory by using the conventional method (a) and the proposed controller (b).
The proposed method takes longer to track the trajectory, the behaviour of the USV performs stably staying on the path after it is reached. In Fig. 4.6, the backstepping approach based virtual velocity of two different controllers are compared; the speed jump problem clearly occurs in the backstepping controller, which is caused by large initial errors. However, the bioinspired backstepping algorithm generates smooth velocities on sway and yaw when faced with the same situation. Moreover, the USV requires large control efforts to satisfy the sudden speed change; it is probably difficult to generate enough value for the control constraint of the control system. By comparing the control torques in Fig 4.7, the bioinspired sliding mode control provides stable forces moments to make the USV run normally. Meanwhile, the effective hybrid controller ensures that the control torques of the system work without the chattering problem.

Figure 4.8: The comparison of tracking an elliptic trajectory by using the conventional method and the proposed controller.
Table 4.3: Control Parameters for Tracking a Ellipse Trajectory.

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<th>$k_3$</th>
<th>$A_1$</th>
<th>$B_1$</th>
<th>$D_1$</th>
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<th>$D_2$</th>
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<td>5</td>
<td>18</td>
<td>18</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
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</table>

In the final case, a complicated ellipse trajectory is designed for investigating the effectiveness of the proposed controller. The path is described by \((x - 1)^2/1.5^2 + (y - 1)^2 = 1\), and the initial position is \([1,0,0]\). The desired position for USV is \([0,-0.6,0]\), and no desired velocities. In addition, the control parameters \(k_1 = 3\), \(k_2 = 4\) and \(k_3 = 1\), and the parameters for shunting model are \(A_1 = 5\), \(B_1 = 18\), \(D_1 = 18\) and \(A_2 = 3\), \(B_2 = 1\), \(D_2 = 1\). The simulation results are displayed in Fig. 4.8, 4.9, 4.10, and 4.11.

Figure 4.9: The posture errors comparison of tracking a elliptic trajectory by using the proposed controller (a) and the conventional method (b).

According to the comparison between conventional method and proposed method in Fig. 4.8, it is obvious to indicate that the proposed hybrid control method performs better on tracking the desired ellipse trajectory. In this case, conventional based tracking controller takes a longer to catch the desired path, and the velocities of USV are generated irregularly, in which control torques have the same situation. In
Figure 4.10: The velocity comparison of tracking a elliptic trajectory by using the proposed controller (a) and the conventional method (b).

Figure 4.11: The torques of tracking a elliptic trajectory by using the proposed controller (a) and the conventional method (b).
contrast, proposed controller generates the stable and regular control signals, which can reach the desired state in a short time and staying on it. Although the speed jump problem and chattering problem are not clearly happened in this case, the compared performance still approves that proposed method is more effective than conventional approach.

4.5 Summary

In this chapter, an integrated bioinspired backstepping and sliding mode controller is proposed to improve the underactuated surface vehicle tracking strategy. First, some fundamental knowledge of the USV kinematic and dynamic model is presented. Then, a backstepping based approach is designed to generate a virtual velocity based on kinematic algorithm. In this part of the controller, the bioinspired model is utilized to optimize the large initial tracking errors that frequently cause speed jump problems in the traditional backstepping application. Due to the advanced features of the bioinspired method, the smooth velocity signals are bounded in a reasonable interval, which are also delivered to the sliding mode control as inputs. In addition, the sliding mode control part is applied to generate the control torques of the USV. Considering the existence of the chattering problem, the bioinspired model is obtained to optimize the significant parameters of the control torques. Thus, the chattering problem is efficiently avoided. The main idea in designing the proposed controller was to fully consider both the kinematic and dynamic models for real application preparation. These common problems that occur in both the conventional backstepping systems and sliding mode systems are solved successfully by integrating the bioinspired intelligent system.
Chapter 5

Conclusions and Future Work

This thesis focuses primarily on investigating the tracking control of underactuated surface vessels. Due to a variety of complex situations involved in tracking control systems, the development of new intelligent control methods is required in order to solve various challenges. In traditional systems, the simple design of controllers is not an effective means to confront many problems in real applications. The conventional design of a manual trial and error process is inefficient for feasible control strategies. Due to the demands of increasingly modern technology, it is a challenge to develop multiple flexible control systems. However, due to the efforts of researchers worldwide, many intelligent control techniques have been developed and improved in recent years. In order to develop a new strategy that combines the significant advantages of each control method, there is a trend toward improving the existing approaches to be increasingly effective. Several specific issues of the complex control systems are solved by integrating various control methods, which is an important measure for optimizing the capabilities of the control systems.

5.1 Conclusions

Two intelligent controllers are introduced in this thesis: an integrated type-2 fuzzy sliding mode control and a hybrid bioinspired backstepping sliding mode tracking control. Both kinematic and dynamic models are considered and analyzed in detail for
the proposed control methods. By considering the influence of system uncertainties, type-2 fuzzy logic control is applied to deal with uncertain parameters, which is more effective than type-1 fuzzy control. Due to the characteristics of IT2FLC, which has a wide extension of the type-2 fuzzy set, the control system performs better when dealing with system noisy inputs and uncertain components. Meanwhile, it also has the capability of dealing with discontinuous signals to help sliding mode control in the avoidance of the amplitude phenomenon. The controller can select the optimized parameters by using this intelligent technique. Further, the integration of the IT2LFC and SMC result in better system performance for handling disturbances, due to the insensitivity and robustness of the SMC itself.

In order to further examine the tracking control of USV, another effective approach, the backstepping algorithm, is developed. In this case, an important technique, bioinspired shunting model, is utilized to combine with the backstepping algorithm and SMC. The conventional problems for backstepping are solved by the existence of the optimization function of the bioinspired model. By considering the existence of the chattering problem in sliding mode, another bioinspired model is applied to generate continuous signals. The smooth velocity inputs are transmitted into SMC, which produces suitable control torques for the USV. Finally, the limitations of the two effective control methods are successfully avoided, and the model utilize the advantages associated with this tracking control.

5.2 Future Work

Trajectory tracking control is a fundamental topic in intelligent control. The proposed work in this thesis only considers theoretical issues; many challenges and possibilities have not been investigated. Therefore, several suggestions for future work are presented here.

- The underactuated surface vessel is considered as three degrees of freedom in this research. Therefore, six coordinates of surge, sway, yaw, heave, roll and pitch can be fully considered for the realistic application in the ocean current.
• Path planning would be a possible extension of this research.

• Torque control has only been conducted using control laws, which is insufficient for real application. In nonlinear control systems, torque control would be examined via a serious consideration of the entire model of the surface vessels.

• The proposed methods would be implemented in real unmanned surface vessels.
References


Chen, X. T. and W. W. Tan (2010). A type-2 fuzzy logic controller for dynamic posi-


