FUZZY MODEL-REFERENCE ADAPTIVE CONTROL METHOD FOR AN UNDERWATER ROBOTIC MANIPULATOR

by

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Thesis submitted in fulfillment of the requirements for the degree of Master of Science

January 2010

ACKNOWLEDGEMENT

In the name of Allah, the most Beneficent, the most Merciful

All praise and glory goes to Almighty Allah (Subhanahu Wa Ta'ala) who gave me courage and patience to carry out this work. Peace and blessing of Allah be upon His last prophet Muhammad (Sallallahu Alaihi Wassalam).

My deepest appreciation and gratitude goes to my thesis supervisor Assoc. Prof. Dr. Mohd Rizal Arshad for his guidance and numerous moment of attention he gave throughout this research work. His valuable suggestions made this work interesting and knowledgeable for me. I extend my deepest gratitude to my co-supervisor, En. Muhammad Nasiruddin Mahyuddin for his guidance and encouragement during my study.

I would like to thank to all friends especially those in Underwater Robotics Research Group (URRG) for their favor, encouragement and cooperation.

And last but not least, I would like to thank to my parents, brothers and sister for their support and prayers.

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Notations and symbols

$V(x)$	Lyapunov Function
e_{m}	model following error
θ	updated parameter of fuzzy controller
u_f	signal of fuzzy controller
u_{s_i}	additional control term
$q_i, \dot{q}_i$	measured joint position
x_i^T	state vector
φ_i	unknown bounded external disturbances
x_{m_i}	state vector of the *i*th reference model
r_i	bounded reference input
x_j	fuzzy input vector
V_p^i	fuzzy sets of inputs
$\mu_k^i(x_j)$	grade of membership of x_j
σ_i	proportional term in PI Adjustment Mechanism
$\emptyset_i$	integral term in PI Adjustment Mechanism
γ_{ij}	tuning constants of update gain
ω_i	modeling error
d_i	uncertainties term

Abbreviations

URM	Underwater Robotic Manipulator
ROV	Remotely Operated Vehicle
AUV	Autonomous Underwater Vehicle
URV	Underwater Robotic Vehicle
UVMS	Underwater Vehicle-Manipulator System
FLC	Fuzzy Logic Control
MRAC	Model-Reference Adaptive Control
FMRAC	Fuzzy Model-Reference Adaptive Control
DOF	Degree of Freedom
EOM	Equation of Motion
LE	Langrange-Euler
NE	Newton-Euler
QL	Quasi-Langrange
LTI	Linear Time-Invariant
SISO	Single-Input/Single-Output
MIMO	Multi-Input/Multi-Output
MISO	Multi-Input/Single Output
PI	Proportional-Integral
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
SMC	Sliding Mode Control
TS	Takagi-Sugeno

DH	Denavit-Hartenberg
AI	Artificial Intelligent
IAE	Integral Absolute Error

KAEDAH KAWALAN BOLEH SUAI MODEL RUJUKAN SAMAR UNTUK APLIKASI PENGENDALI ROBOTIK DALAM AIR

ABSTRAK

Pengendali robotik dalam air (URM) adalah berbeza jika dibandingkan dengan pengendali robotik biasa atau yg berada di permukaan. Dinamiknya mempunyai ketidakpastian yang besar bergantung kepada daya apungan, daya yang dihasilkan oleh jisim tambahan/momen luas kedua dan daya geseran. Tambahan lagi, ia juga dipengaruhi oleh gangguan luaran yang penting seperti arus dan ombak. Oleh itu, adalah sukar untuk membina hukum kawalan dan memastikan prestasi sistem kawalan. Untuk menyelesaikan masalah ini, model dinamik yang tepat bagi URM haruslah dibina, tetapi ianya sukar untuk direalisasikan dan memerlukan daya usaha yang tinggi. Oleh itu, sistem kawalan yang berprestasi tinggi diperlukan untuk mengatasi masalah tersebut. Di dalam tesis ini, kaedah Kawalan Bolehsuai Model Rujukan Samar (FMRAC) dicadangkan untuk mengawal pergerakan URM. Pengawal Takagi-Sugeno Samar digunakan dan diubah secara terus untuk mencapai prestasi menjejaki model rujukan. Parameter pengawal samar diubah menggunakan hukum berkadar terus-kamiran (PI), yang mana dapat menghasilkan perubahan parameter yang lebih cepat dan secara tidak langsung akan menyebabkan penyusutan kesalahan kepada sifar berlaku dengan lebih cepat. Teori kestabilan *Lyapunov* digunakan untuk menyiasat kestabilan sistem. Prestasi FMRAC dinilai dengan kajian simulasi ke atas pengendali dalam air yang mempunyai dua darjah kebebasan. Prestasi pengawal dianalisis dari segi jejakan servo pada setiap sambungan pengendali. Keputusan simulasi menunjukkan prestasi jejakan servo oleh skema kawalan yang dicadangkan telah terbukti baik dan memuaskan walaupun dikenakan dengan input dan parameter yang bervariasi, dan gangguan.

FUZZY MODEL REFERENCE-ADAPTIVE CONTROL METHOD FOR AN UNDERWATER ROBOTIC MANIPULATOR

ABSTRACT

The underwater robotic manipulators (URMs) are different with the ordinary or land-based robotic manipulators. Its dynamics have large uncertainties owing to the buoyancy, force induced by the added mass/moment of inertia and the drag force. Moreover, they are also affected by the crucial external disturbances such as currents and waves. Therefore, it is difficult to construct a control law and not easy to guarantee control performance. To solve this problem, an exact dynamic model for the URMs should be established, but it is quite unrealistic and requires great efforts. Thus, a high performance controller is needed to overcome the problems. In this thesis, fuzzy model-reference adaptive control (FMRAC) method is proposed for the motion control of the URM. A Takagi Sugeno fuzzy controller is used and directly tuned to achieve the reference model tracking performance. The fuzzy controller parameters are updated using a proportional-integral (PI) law, which can provide a faster parameter update and automatically produce a faster convergence of error to zero. Lyapunov stability theory is used to investigate the system stability. The FMRAC performance is evaluated by a simulation study on a 2-dof underwater planar manipulator. The performance of the controller is analyzed in terms of servo tracking at each of the manipulator joint. The simulation results demonstrate that the servo tracking performance of the proposed controller scheme is proven to be good and satisfactory, even though the system is subjected to input variations, parameter variation, and disturbances.

CHAPTER 1
INTRODUCTION

1.1 Research Motivation

Generally, a control system is a device in which a sensed quantity is used to modify the behavior of a physical system through computation and actuation. Conceptually, a feedback-loop in control system will have the basic loop of sensing, computation, and actuation. The feedback-loop operates based upon the deviation between the measured and reference signal. The key issues in designing a control system are ensuring that the dynamics of the closed-loop system (system to be controlled plus the controller) are stable (bounded disturbances give bounded error) and at the same time the dynamics achieve the desired performance (good disturbance rejection, small tracking error, and fast adaptation to changes in operating point, etc). Figure 1.1 depicts the basic concept of feedback-loop in control system.

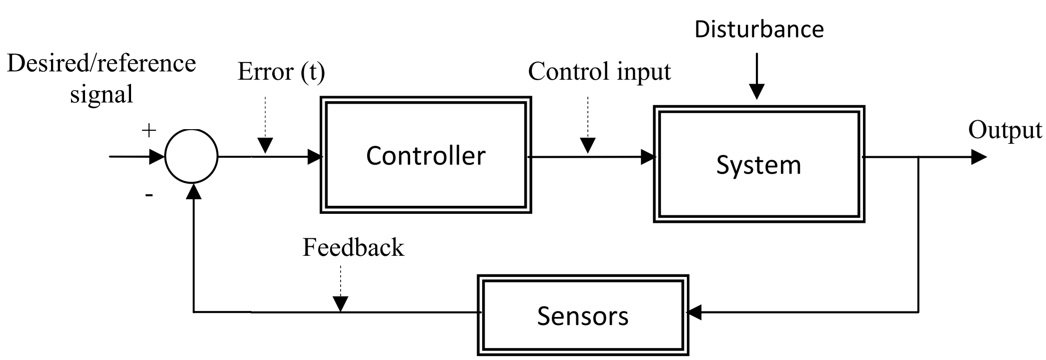

Figure 1.1: General block diagram of a feedback control

It is well-known that the real physical systems, especially in engineering field are usually uncertain or vague. Moreover in an underwater environment, which make it difficult to accurately model the system. Uncertain means that the exact dynamics or outputs of a real physical system cannot be predicted by mathematical model even if the input to the system is known. Uncertainty arises from two sources which are unknown or unpredictable inputs (e.g., disturbance, noise) and unknown or unpredictable dynamics (K. Zhou et al., 1996). Control system particularly designed to manage uncertainties is called *robust control system.* The influence of uncertainties on the closed-loop behavior of a particular application can be reduced if an appropriate design method is chosen for the robust control system.

Robotic manipulators in nature are strongly nonlinear uncertain systems with human-like behavior. This is due to the presence of coulomb friction, backlash, payload variation, unknown disturbances, dynamic coupling between different links, time-varying, and etc. Two main classes of robotic manipulators are serial and parallel manipulators in which the serial type will be used in this project. The serial robotic manipulator consists of link that connected in series which form an open loop. Robotic manipulators are developed either to replace or to enhance the human work such as in manufacturing or manipulation of heavy or hazardous materials. The motion control problem of a robotic manipulator is to determine the generalized torques/forces (developed by the joint actuators) required to cause the end-effector to execute a commanded motion. This thesis will concern about the robotic manipulator used for underwater applications.

For the past decades, most of the research works on Underwater Robotic Manipulators (URMs) have focused on the study of its dynamics and modeling, mechanical development and control strategies (I. Ishitsuka & K. Ishii, 2007; T. W. McLain & S. M.

Rock, 1996; T. J. Tarn & S. P. Yang, 1997; K. N. Leabourne & S. M. Rock, 1998). These manipulators are used for various unmanned/manned underwater missions such as pipeline inspection, coral reefs exploration and ship hull inspection, to name a few. From the survey that has been made by J. Yuh (2000), many remotely-operated vehicles (ROVs) are equipped with one or two manipulators; meanwhile, most autonomous underwater vehicles (AUVs) do not have any or are limited to a survey-type application. J. Yuh has claimed that the commercially available URMs such as Predator, Titan III S, and the Arm-66 are designed with grippers as the end-effector.

The control of URMs for high performance in terms of speed and accuracy are more challenging as compared to the ordinary one. The URMs are different with the ordinary or land-based robotic manipulators where its dynamics have large uncertainties owing to the buoyancy, force induced by the added mass/moment of inertia and the drag force. Moreover, they are also affected by the crucial external disturbances such as currents and waves. The parameters due to the added mass/moment of inertia and the drag forces, and other disturbances are quite complex such that it is difficult to construct a control law and not easy to guarantee control performance. In order to solve this problem, an exact dynamic model for the URMs should be established, but it is quite unrealistic and requires great efforts. Many control strategies have been introduced to overcome those problems for coordinating the URMs such as described in Chapter 2. That is also the purpose of this thesis, where a robust control scheme will be proposed for the URMs.

1.2 Scope of Research

The research study started with robotics fundamentals specifically on robotic arm/manipulator. The studies cover the kinematic analysis, dynamic analysis (Equation of motion), Denavit-Hartenberg Convention, and its control system. The main focus is on the mathematical derivation of the dynamic model.

This thesis highlighted the modeling of a 2-DOF underwater planar robotic manipulator with concerns on the uncertain dynamic terms and also the external disturbance terms. Specifically, the ordinary dynamic model is included with added mass/moment of inertia, buoyancy force, drag force, and coulomb and viscous friction of the motors as well. For the analysis, payload variation and current/wave forces are taken into account. Therefore, a derivation of mathematical model for each term is conducted.

A robust control scheme which is intelligent and adaptive is proposed in this thesis to control the joints motion to follow a desired trajectory. The proposed controller has integrated the Takagi-Sugeno Fuzzy Logic Control (FLC) and Model-Reference Adaptive Control (MRAC) methods, thus, the studies on both methods are required.

At the same time, it is important for the controller to ensure the system remains stable even though the external disturbances and input variations occur. Lyapunov stability theorem is found to be an appropriate method to investigate the system stability. Thus, this research also will cover on this theorem.

1.3 Objective

Based on the facts that the high-performance URMs are highly nonlinear uncertain systems, the following objectives are set for this thesis.

1. To develop a nonlinear robust motion control strategy with good tracking error and capability against the uncertainties exist in an underwater environment.
2. To develop a control strategy with adaptive capability using computational-intelligent methodologies to cope with the changes in URM parameters.
3. To develop a control strategy with on-line learning capability to account for disturbances.

1.4 Thesis Overview

In Chapter 1, the research background is presented to introduce the control system, URM and the issues that encouraging this research to be undergone. The definition of uncertainty is briefly mentioned. The related subjects covered by this research are stated one by one. Besides, the research objectives are also given in this chapter.

In Chapter 2, a literature review of the subjects related to the URMs and its control methodology is presented. Some available URMs manufactured by different companies are stated. The mechanical parts and modeling of URMs are also reviewed and discussed. Some topics on control theories are explained briefly. The current control strategies for the URMs are reviewed. Subsequently, the advantages and widely used of FLC and MRAC methods for the nonlinear systems are also reviewed and discussed in this chapter.

In Chapter 3, the theoretical background essential for understanding some issues in developing a dynamic model of a robotic manipulator and a brief explanation on the hydrodynamics and hydrostatics forces exist in underwater world are introduced. The fundamentals of FLC and MRAC methods are presented independently. Lyapunov stability theorem is also introduced.

In Chapter 4, the addition of hydro effects into the dynamic model of 2-DOF planar robotic manipulator is shown mathematically. Architecture of the systematic FMRAC modeling is presented. The proposed controller is proven numerically to achieve the model following and by using the Lyapunov stability theorem, the system stability is ensured.

In Chapter 5, the analyses of the dynamic model and the proposed controller are given via simulation approach using Matlab™ Simulink. A detailed discussion on the results obtained is provided.

In chapter 6, the conclusions and recommendations for future work are presented.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter, a literature review of the selected subjects related to the underwater robotic manipulators (URMs) and its motion control are presented. A review is done briefly on the commercial URMs produced by some companies, on the mechanical design and its dynamic modeling. Some fundamental topics on the control theory are reviewed. Previously, there are some control strategies for the URM are studied and proposed by the researchers. A review has been done to the existing control strategies to identify their advantages and disadvantages. The control methods which have a potential for developing a robust nonlinear control for the URMs are reviewed and discussed in this chapter as well.

2.2 Underwater Robotic Manipulator

Ocean covers about two-thirds of the earth and worth to explore due to its mineral resources, energy and so on. Recent decades, research and development of underwater world are progressing gradually. However, the dangerous condition such as the water pressure, invisibility and non-oxygen give a problem to human being to access directly. Therefore, the underwater robots are developed to do the operations instead of human being. This robot is also known as an underwater robotic vehicle (URV). There are two types of URV which is the remotely-operated vehicle (ROV) and autonomous underwater vehicle (AUV). Nowadays, the URMs are usually mounted on these URVs to enhance its capabilities.

2.2.1 The Commercial Underwater Robotic Manipulator

J. Yuh (2000) has stated a few names of commercial URMs such as *Predator* ™ and *Titan III S* ™. These manipulators have 6 degree of freedom (DOF) with gripper as the end-effector. *Predator* ™ URM as shown in Figure 2.1 was developed by Kraft Telerobotics, Inc (Krafttelerobotics, 2008). Figure 2.1 illustrates the mechanical design of master and slave of *Predator* ™. Kraft is a company who has manufactured the manipulator system for over 25 years especially for undersea applications. Today, Kraft's manipulators are used in deep ocean environment in support of offshore oil and gas industry. These manipulators have also been used for the construction activities and underwater drilling by major international underwater contractors.

Figure 2.1: Master and slave of *Predator* ™ (Krafttelerobotics, 2008)

Titan III ™ currently has been upgraded to the fourth-generation, *Titan IV* ™. *Titan* ™ URM is a product of Schilling Robotics Systems (Schilling Robotics, 2008). The first product of *Titan* ™ system was *Titan 7F* ™ in 1987. *Titan IV* ™ is widely regarded as the world's premier servo-hydraulic remote manipulator system. It has the dexterity and accuracy necessary to perform the fine movements needed for complex tasks. These *Titan*™ systems are extensively used on ROVs. Figure 2.2 shows the pictures of master and slave of *Titan IV*™.

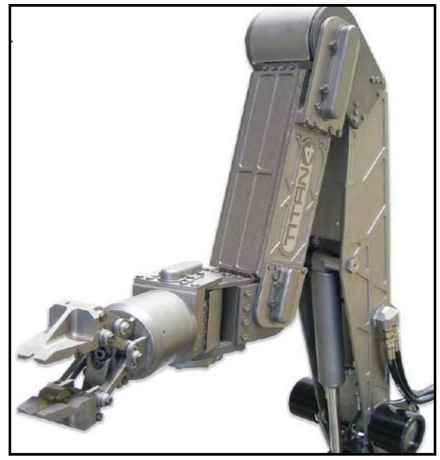

Figure 2.2: Master and slave of *Titan IV*™ (Schilling Robotics, 2008)

2.2.2 Mechanical Design and Dynamic Modeling

Proper selection of materials for the underwater environment cannot be neglected. When selecting materials, some factors such as corrosion, swelling, and organisms attack should be considered. For the links architecture, aluminum is mostly used because of its strength-to-weight ratio and low cost. All the electronics parts need to be packaged in housing for water proof. The importance of effective motor selection also cannot be overstated.

The equation of motion (EOM) or dynamic model describes the dynamic response of the manipulator to input actuator torques. The EOM is useful for computation of torque and forces required for execution of a certain work, which is important information for the design of links, joints, drives and actuators. The manipulator EOM can be developed by applying methods such as Lagrange-Euler (LE) which is “energy based” and Newton Euler (NE) which based on “force balance” (R. K. Mittal & I. J. Nagrath, 2004). These two methods are the most commonly used modeling methods. These methods are very useful for developing the dynamic model of a fixed land-based manipulator which is well understood (T. J. Tarn et al., 1996). Recursive NE formulation is advance in term of an order computational complexity, $O(n)$ where the multiplication and addition operations are only proportional to n. n refers to the Degree of Freedom (DOF) of the manipulator. Meanwhile, the LE formulation has a complexity of order $O(n^4)$. The drawback of recursive formulation is that it is not amenable to a simple physical interpretation (R. K. Mittal & I. J. Nagrath, 2004). However, the authors of this book claimed that the recursive formulation is much more efficient in terms of computational effort, especially when the number of DOF increases. It ideally suited for computer implementation.

Nowadays, there are two other methods used for deriving the dynamic model of URM; i.e., Kane’s method and Quasi-Langrange (QL) method. Kane’s method is sort of a combination of LE and NE methods. For instance, Kane’s method was used by T. J. Tarn et al. (1996), and T. J. Tarn and S.P. Yang (1997) to derive the dynamic model of URM. T. J. Tarn et al. claimed that Kane’s method is more direct in eliminating the link interaction forces associated with the NE method, and eliminating the need to develop an energy function (Langrangian) associated with the LE method. Besides, this method provides straight forward approach for incorporating external forces into the model. QL method is always used in developing dynamic model of underwater vehicle-manipulator system (UVMS). This method is attractive because it is similar to the widely used standard Lagrange formulation but it generates the EOM in the body attached, non-inertial reference frame (G. Xu et al., 2007; Y. Cui & N. Sarkar, 2000; Y. Cui et al., 1999).

2.3 Control Theories

Before entering into the main discussions, an introduction to the control theories is reviewed in this section. The revision is focused on the history and the revolution of control methods.

2.3.1 Classical versus Modern Control

There are two main approaches of control theory which are classical control and modern control. Classical control (between the 1930's and the 1950's) is expressed in the frequency domain and the s-plane using the methods of Nyquist, Bode, Nichols and Evans. It is primarily applicable to linear time-invariant (LTI) systems and very useful for single-input/single-output (SISO) system because the frequency response, and, poles and zeros of a transfer function can be determined accurately. However, this technique is difficult to implement for multi-input/multi-output (MIMO) system. Hence, the quantitative feedback theory is introduced by Horowitz to overcome many of the limitations (Neculai Andrei, 2005). The classical control techniques can be used to the nonlinear systems by linearizing the system at the equilibrium point, thus the system behavior is approximately linear. This method is useful in some circumstances but still limited especially when the dynamical changes. This limitation has led to the development of modern control approaches.

Modern control design (after the 1950's) is, fundamentally, a time-domain technique and was, firstly, established for linear systems. It is not only applicable to LTI systems, but also, to time-varying system and useful when dealing with nonlinear systems. The system's dynamical interconnections are described by vectors and matrices also known as state-space. The advantage of this modern control is that the state-space model can represent a MIMO system as a SISO system. In modern control, the open-loop properties of controllability and observability are investigated to answer some questions on the performance of the closed-loop system. These controllability and observability was introduced by Kalman in 1960, and are very fundamental to modern control approaches (D. N. Burges & A. Graham, 1980).

2.3.2 Linear and Nonlinear Control

There are two basic methods in control system; linear and nonlinear methods. The linear control system is very useful because the dynamical performance of all elements can be described by linear differential equations (Z. Vukic at al., 2003). Practically, there is no linear systems exist, since all physical systems are nonlinear. However, majority of control strategies are designed assuming that the system has linear behavior. Linear control can also be applied to nonlinear system by linearizing the system (feedback linearization). But, there are some control situations where the linear control system fails to meet the requirements. For instance, when the systems with large parameter variations or when the state of the system is far from the linearization point. The parameter variations and nonlinearities can degrade the performance and cause the system to be instable. Well-known linear control methods used in a wide range of applications are, Proportional-Integral (PI) control, Proportional-Derivative (PD) control and

Proportional-Integral-Derivative (PID) control. The existence of at least one nonlinearity in automatic control systems will make the system behaves in a nonlinear fashion. Typically, the processes involved in the industries like robotics and aerospace industries will have strong nonlinear dynamics. Up to now, many nonlinear controls have been developed and each one has its own advantages and disadvantages. Figure 2.3 shows some of the established linear and nonlinear control methods used in the literatures. Considering the linear and nonlinear control methods, the nonlinear ones are more general. This is because they can be successfully applied to linear systems but a linear controller might be insufficient for control of a nonlinear system (Z. G. Meysar, 2007).

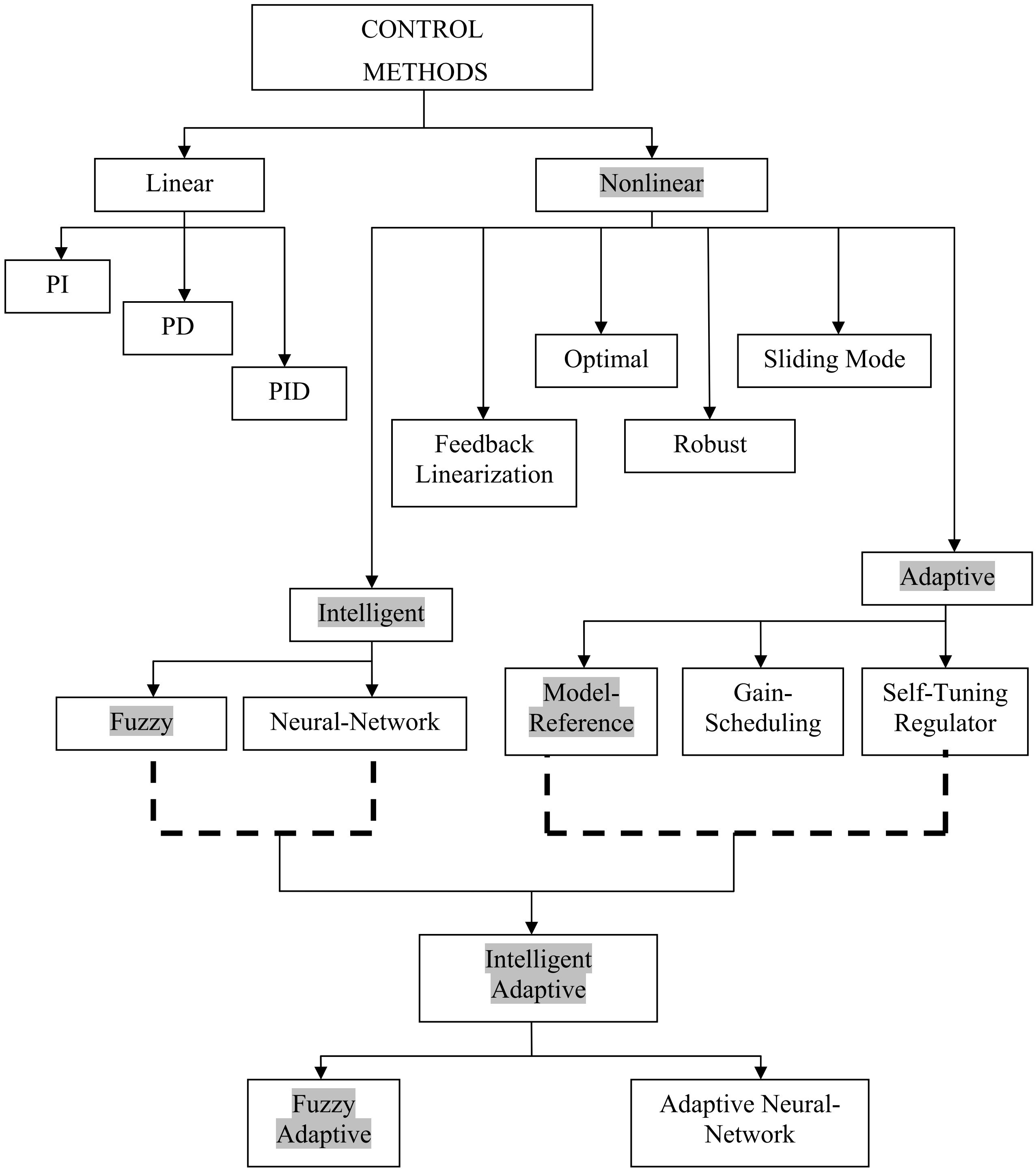

Figure 2.3: Control methods for linear and nonlinear systems

2.4 The Underwater Robotic Manipulator Control Methods

Although the URM starts to be commercialized since past decades, not much information on their control strategies is published as compared to the land-based manipulator system. *Nonlinear feedback control* is proposed by T. J. Tarn and S. P. Yang (1997) for motion and trajectory tracking control of underwater robotic vehicle (URV) and its three manipulators. This type of control method requires a detailed mathematical model in order to get a good performance of the system. URV system with manipulators is a complex system which is very challenging to get the exact model. The EOM of the system is derived using Kane's method. However, the external disturbance like current and wave are not included in the model. The URM will be heavily affected by accelerated waves as it operates in the shallow water region (M. Lee & H. S. Choi, 2000). The controller probably will provide poor performance if such disturbances occur during its motion.

Sliding mode control (SMC) is one of the control methods used in developing control strategy for the URM. SMC is claimed to have robust performances such as insensitivity to variations parameter and can reject disturbances. In SMC approaches, the precision model is not necessary, and the simplified linear model is accepted. Two important tasks in designing SMC system are, choosing switching function and solving the control law. M. Lee and H. S. Coi (2000) have proposed the combination of *SMC* and *neural network* to produce a high performance controller to overcome the uncertainties exist in URM. The Neural Network may however suffer from inability to handle linguistics information, manage imprecise or vague information, combine numeric data with linguistic or logical data, and reach global minimum even by complex back-propagation learning. Neural Network also needs a trial-and-errors method to determine the number of layers and nodes (neurons). Despite successful results, lack of systematic approach to design and analysis of Neural Network is an issue.

The main disadvantage of using SMC is its chattering problem. The chattering effect will influence, particularly, the performance of tasks that require high accuracy, such as underwater maintenance jobs. Chattering can be caused by time delay in the actual system. G. Xu et al. (2007) have solved this problem by improving the ordinary control law to an exponential approaching law. When high gain is used in the SMC, a high performance of control system will be obtained, but consequently, it will also produce high frequency chattering. Thus, fuzzy logic control is used to tune the gain of the control system, in order to get the best performance but lowest high frequency chattering (G. Xu et al., 2007). However, these control methods obviously do not consider the system stability which is a very important issue.

2.5 Model-Reference Adaptive Control

As shown in Figure 2.3, there are three main methods of adaptive control which is self-tuning regulator, gain-scheduling control and model-reference adaptive control. Among those three methods, MRAC is the most widely studied in the adaptive literature. MRAC is introduced by H. P. Whitaker et al. (1958) to solve the autopilot control system. The sensitivity method and the MIT rule were used to design the adjustment or adaptive laws for estimating the unknown parameters of the MRAC scheme. By 1966, P. Parks (1966) have improved the MIT rule-based adaptive law to the Lyapunov design approach. The motivation for the use of the MRAC comes from the fact that a relatively simple control algorithm can provide the desired behavior of the controlled system specified by the reference model without estimation of the system parameters. It is convenient if the precise knowledge about the system parameters is not available or they cannot be identified. Since the control algorithm is not based on the state variables measurement, but rather on the output measurement i.e. the output error, the estimation of the state variables is also not needed. The motivation for the use of this control technique comes also from the fact that in practical and industrial applications simpler control laws usually give best results. This was also confirmed by examples referenced by H. Kaufman et al. (1998) showing some practical and industrial applications of this method.

M. H. Toodeshki and J. Askari (2008) designed MRAC for a class of nonlinear MIMO systems which has parametric uncertainties. Simulation results show that stability, tracking and perfect performance are satisfied well in the presence of parametric uncertainties. In addition, disturbance rejection and robust stability of the system to nonparametric uncertainty also are proven. Basic MRAC scheme is modified by augmenting the integral term of the control law in order to provide the robustness of the control system with respect to the stability (T. N. Trajkov et al., 2008). This approach provides preserving the boundness of the system states and adaptive gains, with small tracking error over large ranges of non-ideal conditions and uncertainties. From the discussion, MRAC seems to have a potential to be implemented for the underwater manipulator where the issues of stability, uncertainties and disturbance also need to be considered.

2.6 Takagi-Sugeno Fuzzy Control

The mathematical modeling of fuzzy concept was first presented by Professor Lotfi Zadeh in 1965 to describe mathematically, class of objects that do not have precisely defined criteria of membership. Then, Takagi-Sugeno (TS) fuzzy model was proposed by Takagi, Sugeno and Kang in 1985-1986 to develop a systematic approach for generating fuzzy rules from a given input-output data set in the application of multilayer incinerator (T. Takagi & M. Sugeno, 1985; M. Sugeno & G. T.Kang, 1986). Since then, researchers started implementing their model in wide range of applications. TS fuzzy system is frequently used in adaptive control area.

J. T. Spooner and K. M. Passino (1996) introduced a stable direct and indirect adaptive controller that uses TS fuzzy systems for a class of continuous-time nonlinear plant with poorly understood dynamics. The direct adaptive scheme uses linguistic knowledge of the inverse dynamics of the plant to accelerate the adaptation. Again, J. T. Spooner et al. (1997) introduced an indirect adaptive control scheme for a class of discrete-time nonlinear system based on functional approximation approach which modifies TS fuzzy control system. H. J. Kang et al. (1998) proposed an approach to the indirect adaptive fuzzy algorithm that uses TS fuzzy model to identify the unknown nonlinear SISO system. S. Barada and H. Singh (1998) published their approach to generate optimal adaptive fuzzy-neural models for I/O data which combine structure and parameter identification of TS fuzzy models. They compared the measured state with the state of the estimation model and implemented in robot manipulator.

V. Gazi and K. M. Passino (2000) presented a direct adaptive control scheme for a class of continuous time non-linear systems where strictly dynamic TS fuzzy systems used as on-line function approximator and gradient method for adaptation. C.W. Park et al. (2001) presented an adaptive fuzzy control scheme via parallel distributed compensation for MIMO plant of TS model type and implemented to track a flexible-link robot manipulator. P. S. Yoon et al. (2001) presented a control method for general nonlinear systems using TS fuzzy models and developed an adaptation law to adjust the parameters of the fuzzy systems. G. Noureddine et al. (2001) proposed an adaptive scheme that uses TS fuzzy controller which allows the inclusion of a priori information in terms of qualitative knowledge about the plant. C. L. Lin (2002) developed an adaptive fuzzy gain-scheduled missile autopilot that uses TS fuzzy system to represent the fuzzy relationship between the scheduling variables and controller parameters with an adaptation law that uses scheduling parameter variation information. F. Zheng et al. (2003) studied the issue of designing robust adaptive stabilizing controllers for nonlinear systems in TS fuzzy model with both parameter uncertainties and external disturbances. The above discussion motivate the use of TS fuzzy model as being a powerful tool to model the nonlinear systems and in addition using MRAC to achieve adaptation to plant output.

2.7 Fuzzy Adaptive Control Strategies

T. K. John Koo (1995) proposed a model reference adaptive fuzzy control (MRFAC). The scheme is designed for manipulator control to incorporate with nonlinear and time-varying dynamic behavior of the system. The MRAFC scheme is developed to perform the adaptive feedback linearization such as to asymptotically cancel the nonlinearity in the system and place system poles in the desired locations as specified in the reference model. The fuzzy controller is expressed in an explicit form so-called generalized multilinear fuzzy logic controller (GMFLC). T. K. Yin and C. S. George Lee (1995) have developed a FMRAC to deal a plant with unknown parameters which are relying on known variables. Fuzzy basis function expansion (FBFE) is used to represent the unknown parameters and the identification problem is changed from the identifying the original unknown parameters to the identifying the coefficients of the FBFE. By using this FBFE, the unknown parameters can be estimated more precisely. The adaptation scheme of the proposed FMRAC is based on the tracking error and prediction error. Hence, it is claimed to provide more adaptation power than the traditional adaptive control. Y. W. Cho et al. (1999) presented a direct MRAFC scheme to provide asymptotic tracking of a reference signal for the robot manipulator system with uncertain or slow time-varying parameters. The TS fuzzy model is used to describe the continuous-time nonlinear system. The boundness of all signals in the closed-loop system is guaranteed by the developed control law and adaptive, therefore, can ensure the stability.

T. John Koo (2001) proposed some improvement for the previous MRAFC. The stability of the system can be assured and the performance also enhanced in terms of its robustness and parameter convergence. Again, GMFLC is applied and the author said that if a large sufficient number of fuzzy rules are used, the GMFLC is capable to approximate the nonlinear functions to any degree of accuracy. The feasibility of the proposed scheme is demonstrated by implementing to the inverted pendulum. N. Golea et al. (2002) have designed a FMRAC scheme for continuous-time multiple-input-multiple-output (MIMO) nonlinear systems. TS fuzzy adaptive system is used that allows for the inclusion of priori information in terms of qualitative knowledge about the plant operating points or analytical regulators (e.g., state feedback) for those operating points. Different with other schemes, the update law of this FMRAC is designed based on proportional-integral (PI) technique to obtain a fast parameters adaptation. This control scheme is developed for a two-link robot manipulator and the performance is compared with robust adaptive control. They are tested to cope with the external disturbances and parameter variations of the plant. The results proved that FMRAC is better than robust adaptive control. W. S. Yu and C. L. Hwang (2006) have used the idea proposed by N. Golea et al. (2002) to develop the FMRAC scheme but it is expanded by considering the time-delay issue. It is evaluated to the parallel robot manipulator to validate the ability. From the literature studies, it is obviously showed that the Lyapunov stability theorem is a famous and reliable method to ensure the stability of nonlinear systems.

2.8 Joint Space Control and Operational Space Control

Generally, the end-effector motion is usually carried out in the operational space, whereas control action (joint troques/forces) is performed in the joint space. Thus, this fact led to the consideration of two kinds of motion control methods that is, *joint space control* and *operational space control*. According to J. J. Craig (2005), currently, the joint space control method is widely used in industrial robotic manipulators. The direct measurement of operational space variables is more expensive than the measurement of joint space variables; i.e. an infrared tracking system for operational space measurement with a shaft encoder for joint space measurement (Z. G. Meysar, 2007). Therefore, only joint space will be reviewed and discuss throughout this thesis.

2.9 Summary

The development of URM is not a new research area. Some robotics companies have manufactured and commercialized this underwater manipulator for varied applications since the past decades. However, research into URM control strategy is still premature as compared to the land-based manipulator. Fuzzy control system can be applied to many systems without knowing the mathematical model and to approximate any continuous nonlinear function. TS fuzzy system is a powerful tool to model the nonlinear systems. MRAC is one of the most feasible methods to be implemented with fuzzy control systems, since the stability robustness of the system can be analyzed via Lyapunov stability theorem. Besides, MRAC is proven to have an ability to tolerate the uncertainties and disturbances.

CHAPTER 3
THEORETICAL BACKGROUND

3.1 Introduction

A manipulator consists of a chain of rigid bodies called, links which is connected to each other by joints. The joints will allow linear or revolute motion between connected links where each joint has one Degree of Freedom (DOF). The end-effector of the manipulator is required to follow a planned trajectory to carry out the tasks in the workspace. Hence, the position control of each link and joint are needed. In this case, a mathematical model of the manipulator is required in order to program the tool and joint-link motions. In designing a robotics manipulator, kinematics and dynamics play an important role and will be discussed in this chapter. In the kinematics analysis, it is necessary to identify the joint-link parameters for each link with respect to the frame assigned by Denavit-Hartenberg (DH) Convention. The DH Convention will be presented in this chapter as well. This chapter will also have the derivation steps of EOM using Langrange-Euler and a discussion about the additional hydro static-dynamic forces exerted onto the underwater robotics manipulator. As mentioned before, FMRAC applies the basic concept of MRAC method and incorporated with the TS-fuzzy control method. This chapter will also explain on the theory of both control methods independently. The Lyapunov stability theorem that is a reliable method to assure the system stability will be discussed too.

3.2 Manipulator Modeling

This section will discuss on the theory background of DH Convention, kinematic modeling, and dynamic modeling. Since an underwater manipulator will be applied throughout this thesis, the hydro effects exist when it moves in an underwater environment also will be discussed in this section.

3.2.1 Denavit-Hartenberg Convention

DH Convention was introduced by Denavit and Hartenberg in 1955 (R. K. Mittal et al, 2003). DH Convention is a procedure for assigning right-handed orthonormal coordinate frames to the links. Through the assigned frames, four important joint-link parameters can be identified. These parameters are useful in the kinematics analysis. The parameters so-called Denavit-Hartenberg (DH) parameters are defined as link length, a_i, link twist, α_i, joint distance, d_i and joint angle, θ_i. Figure 3.1 shows an example of how DH Convention interprets the connected links.

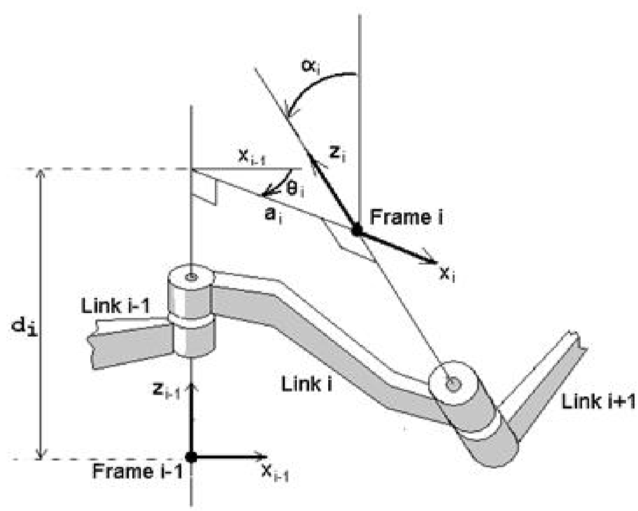

Figure 3.1: DH Convention for assigning frames to links and identifying joint-link parameters