INTELLIGENT ACTIVE FORCE CONTROL FOR MOBILE MANIPULATOR

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A thesis submitted in fulfilment of the
requirement for the award of the degree of
Doctor of Philosophy

Faculty of Mechanical Engineering
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FEBRUARY 2006

ABSTRACT

This thesis presents a resolved acceleration control (RAC) and intelligent schemes of active force control (AFC) as approaches for the robust motion control of a mobile manipulator (MM) comprising a differentially driven wheeled mobile platform with a two-link planar arm mounted on top of the platform. The study emphasizes on the integrated kinematic and dynamic control strategy in which the RAC is used to manipulate the kinematic component while the intelligent schemes are implemented to compensate the dynamic effects including the bounded known/unknown disturbances and uncertainties. The proposed intelligent schemes are based on iterative learning control (ILC) and knowledge-based fuzzy (KBF) strategies. The effectiveness and robustness of the proposed schemes are investigated through a rigorous simulation study and later complemented with experimental results obtained through a number of experiments performed on a fully developed working prototype in a laboratory environment. A number of disturbances in the form of applied constant, vibratory and impact forces are deliberately introduced into the system to evaluate the system performances. The investigation clearly demonstrates the extreme robustness feature of the proposed control schemes compared to other systems considered in the study.

ABSTRAK

Tesis ini membincangkan suatu kaedah kawalan pelerai pecutan (RAC) dan kawalan pintar daya aktif (AFC) yang lasak terhadap sebuah robot pengolah mudah gerak (MM) melibatkan sebuah pelantar beroda yang dipacu pacu secara pembezaan dan mudah alih bersama dengan sebuah pengolah lengan planar dua-sendi yang dipasang di atas pelantar. Kajian ini mengutamakan gabungan strategi kawalan kinematik dan dinamik yang mana RAC digunakan untuk mengolah komponen kinematik manakala skema AFC diterapkan untuk memampas kesan dinamik termasuk gangguan dan keadaan tak menentu. Skema pintar yang dicadangkan adalah berasaskan strategi kawalan pembelajaran berlelaran (ILC) dan kaedah logik kabur berasaskan pengetahuan. Kebolehan dan kelasakan skema yang dicadangkan dikaji dan diuji melalui kaedah simulasi dan seterusnya ditentusahkan melalui hasil eksperimen yang dibuat menggunakan sebuah prototaip robot pengolah mudah gerak yang dibina di dalam makmal. Sejumlah gangguan berupa daya malar, getaran dan dedenyut dikenakan kepada sistem robot untuk meneroka kebolehan dan keberkesanan sistem. Hasil simulasi dan eksperimen menunjukkan kelasakan dan keberkesanan skema kawalan yang dicadangkan berbanding dengan sistem lain.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
AFC	Active Force Control
AI	Artificial Intelligence
D	Derivative
DAC	Digital to Analog Converter
DDMR	Differentially Driven Mobile Robot
FS	Fuzzy System
I	Integral
IL	Iterative Learning
ILAFC	Iterative Learning Active Force Control
ILC	Iterative Learning Control
ILPI	Iterative Learning Proportional Integral
ILPIAFC	Iterative Learning Proportional Integral Active Force Control
KBF	Knowledge Based Fuzzy
KBFAFC	Knowledge Based Fuzzy Active Force Control
KBS	Knowledge Based System
MF	Membership of Function
MM	Mobile Manipulator
MMAFCON	Mobile Manipulator Active Force Control Online
P	Proportional
PC	Personal Computer
PD	Proportional Derivative
PI	Proportional Integral
PIAFC	Proportional Integral Active Force Control
PIC	Programmable Interface Controller

RAC	Resolved Acceleration Control
RACAFC	Resolved Acceleration Control - Active Force Control
RACILAFC	Resolved Acceleration Control - Iterative Learning Active Force Control
RACILPIAFC	Resolved Acceleration Control - Iterative Learning Proportional Integral Active Force Control
RACKBFAFC	Resolved Acceleration Control - Knowledge Based Fuzzy Active Force Control
RACPIAFC	Resolved Acceleration Control - Proportional Integral Active Force Control
RMAC	Resolved Motion Acceleration Control
RMRC	Resolved Motion Rate Control
TTE	Trajectory Tracking Error

LIST OF SYMBOLS

SYMBOL	SUBJECT
α	Proportional constant of ILPIAFC scheme
$A(q)$	Constraint matrix
$B(q)$	Input transformation matrix
β	Integral constant of ILPIAFC scheme
b	Half width of the robot
$C(q,\dot{q})$	Centripetal and Coriolis matrix
d	the distance of point G to F of mobile manipulator
$F(q,\dot{q})$	Friction and gravitational vector
g	Acceleration due to gravity (m/s^2)
$G(s)$	A function in La place domain representing the feedforward gain in the AFC loop
$G_c(s)$	A function in La place domain representing the controller gain
$H(s)$	A function in Laplace domain representing the compensated gain in the AFC loop
h	Vector of the Coriolis and centrifugal torques
I	Inertia
I'	Estimated inertia
I_m	Motor current
I'_m	Measured motor current
$\boldsymbol{I_c}$	Applied motor current
IN, **IN**	Inertia matrix
IN'	Estimated inertia matrix

IN_F	Fixed *IN*
IN_I	Integral *IN*
IN_{IF}	Fixed integral *IN*
$\mathbf{IN}_{\mathrm{IL}}$	Estimated inertia matrix from learning process
IN_{init}	Initial *IN*
IN_{IV}	Varied integral *IN*
IN_{KBF}	Knowledge-based fuzzy *IN*
IN_P	Proportional *IN*
IN_{PF}	Fixed proportional *IN*
IN_{PV}	Varied proportional *IN*
IN_{RACAFC}	Fixed (crude) *IN* of RACAFC scheme
J	Jacobian
K_p	Proportional constant
K_d	Derivative constant
$K_{pRACAFC}$	Proportional constant for RACAFC scheme
$K_{dRACAFC}$	Derivative constant for RACAFC scheme
K_{tn}	Motor constant
$\lambda \in \Re^r$	Lagrange multiplier
Γ	Derivative constant for ILAFC scheme
$M(q)$	Symmetric and positive definite inertia matrix
m	Mass
Φ	Proportional constant for ILAFC scheme
Q	Bounded (known/unknown) disturbance
Q'	Measured disturbance
Q^*	Estimated disturbance
Q_c	Constant torque disturbance
Q_{ca}	Q_c of $[0.2\ 0.2\ 0.5\ {-0.5}]^T$ Nm
Q_{cb}	Q_c of $[2\ 2\ 5\ {-5}]^T$ Nm
Q_{cc}	Q_c of $[20\ 20\ 20\ {-20}]^T$ Nm
Q_{cd}	Q_c of $[30\ 30\ 30\ {-30}]^T$ Nm
Q_{gain}	Scaling factor for impact and vibration
Q_{imp}	Impact disturbance
Q_{vib}	Vibration disturbance

$q \in \Re^{p}$	p generalized coordinate
r	radius of wheel
$S(q)$	Transformation matrix
θ	Angular position
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
$\ddot{\theta}'$	Measured angular acceleration
θ_{ref}	Reference angular position
$\dot{\theta}_{ref}$	Reference angular velocity
$\ddot{\theta}_{ref}$	Reference angular acceleration
θ_{act}	Actual angular position
$\dot{\theta}_{act}$	Actual angular velocity
$\ddot{\theta}_{act}$	Actual angular acceleration
τ	Torque
T_q	Applied torque
φ	Heading angle of platform

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Mobile manipulator is basically a conventional robotic arm mounted on a moving base. It is analogous to a human being with respect to the body and arm sections. He or she must control these parts integrally when performing a dynamic task to achieve the desired performance. As an example, a welder carrying out a welding operation needs to carry out the task by coordinating (control) simultaneously and continuously both the arm and body movements so that a favourable effect could be obtained from executing such task. It is indeed more challenging when human operators are replaced by robots or automated machines. Comprehensive analytical studies on the kinematics, dynamics and control aspects of the physical system should be carefully carried out in order to come up with an alternative system that produces results comparable with those of human operators.

The main subject of this thesis is the control of a mobile manipulator. As can be found in common industrial plants, robotic manipulators are conventionally bolted onto the floor, implying that the tasks involving a ground-fixed manipulator must be carefully configured within a limited volume of the workspace so that they (the tasks) can be executed in an efficient way. It is a well-known fact that the configuration is even more restrictive when a dextrous manipulation is required because the manipulator workspace is only a small part of the whole workspace.

Thus, attaching the manipulator onto a mobile platform offers the distinct advantages of dextrous manipulation and considerably larger workspace than the fixed-platform.

In recent years, there has been a great deal of interest in research on mobile manipulator (Yamamoto and Yun, 1996; Lin and Goldenberg, 2001; Umeda and Yakoh, 2002; and Tanner *et al*., 2003). The study of mobile manipulator is mostly concentrated on the following main question: how to move, navigate or manoeuvre the system efficiently from one location to another in a structured or unstructured environment. The study normally focuses on two aspects, i.e., the kinematics and the dynamics of the system. Each has a different domain of analytical study with different goal setting, but the final or ultimate goal should be clearly defined in terms of the robot's capability to operate effectively within the specified workspace and environment with an additional feature – robustness, as a key factor in the development of the robotic system. The kinematic analysis is particularly useful to describe the robot's workspace and motion path planning tasks including obstacles avoidance, collision free moving capability and manoeuvrability, while the dynamic analysis deals with robustness in actual implementations.

Intelligent Active Force Control (AFC) combined with a resolved acceleration control (RAC) applied to the motion control of a mobile manipulator is the central theme of the proposed study. The work on AFC that was initiated by Hewit and Burdess (1981) can be regarded as one of the potentially robust force control schemes. A main feature of AFC is that the scheme is theoretically viable and can be practically implemented to the control of dynamical systems including robots (Hewit and Burdess, 1986, Hewit and Morris, 1996, Mailah, 1998). The AFC method involves a direct measurement of the acceleration and force quantities plus the appropriate estimation of the inertia (or mass) matrix to trigger its control strategy. The RAC part that was initially proposed by Luh *et al.* (1980) is a powerful acceleration mode control method that is still considered as one of the best control options due to its simplicity in real-time implementation. In the study, the RAC was designed as the basic kinematic controller while the AFC was applied as the dynamic counterpart.

1.2 Research Background

The study of motion control of mobile manipulators spans several different research domains and that it usually focuses on the kinematic and/or dynamic analyses. Research on kinematic analysis and dynamic analysis as two separate subjects have been extensively studied, but a study on integrating both the kinematics and dynamics is fairly new and relatively little research has been done.

In terms of its movement, a mobile manipulator can be classified as either holonomic or nonholonomic. The former can be simply described as one that can move in all directions without restriction. In classical mechanics, a nonholonomic system can be described as a rigid disk rolling on a horizontal plane without slippage (Goldstein, 1980) which in the control perspective is equivalent to a wheeled mobile robot driven by two wheels differentially. Theoretically, if a mechanical system exhibits certain symmetry properties, it is well known that there exist conserved quantities. If these conserved quantities are not integrable, then a class of nonholonomic systems is thereby obtained (Kolmanovsky, 1995). The kinematic control of mobile manipulators which the moving base subjects to these constraints had been widely investigated in the last decade, such as using Jacobian Transpose Control (Hootsmans *et al*., 1992), adaptive stabilization (Colbaugh, 1998), genetic algorithm (Sakka and Chocron, 2001), repeatability analysis of Jacobian inverse kinematics (Tchon, 2002), readhesion control using external sensors (Umeda and Yakoh, 2002), and cooperative mobile manipulators (Tanner *et al*., 2003). From the literatures reviewed, the kinematic control problem on mobile manipulators had been well established.

On the contrary, research that deals with both integrating kinematic and dynamic control is fairly new, especially on issue related to real-time implementation that directly involves computational costs and feasibility in hardware design. In this case, only a limited number of works can be found in the last decade, such as dynamics interaction (Yamamoto and Yun, 1996), and neural networks-based robust control (Lin and Goldenberg, 2001).

It is therefore proposed that the performed study dwells on the kinematic and dynamic control through the effective integration of RAC and AFC which is thought to be the main contribution of the thesis. The RAC deals with the kinematics while the AFC deals with the dynamics of the system. The RAC scheme is a powerful acceleration mode control method that could improve the performance of the existing conventional servo control as reported in a number of studies (Muir and Neuman, 1990; Kircanski and Kircanski, 1998; and Campa *et al*., 2001). However, basically RAC is equivalent to a proportional-derivative control that cannot be classified as a robust control without additional robust control schemes. The AFC method has been rigorously studied by a number of researchers particularly in areas related to robotic control applications (Hewit and Burdess, 1981; Uchiyama, 1989; Hewit and Marouf, 1996; Mailah, 1998; and Kwek *et al*., 2003). The AFC strategy is one of the practical force control methods that can be implemented in encountering the robot force control problems. The advantage of AFC method is that it has the ability to compensate the unpredictable external (and internal) forces effectively and reliably without rigorous mathematical computation. The capability of AFC method lies on how efficient the real-time inertia matrix of the robot could be estimated. Thus, the estimation technique of the inertia matrix is central to the implementation of the AFC strategy. More specifically, in the case of mobile manipulators, the AFC implementation has not been found in the literatures so that there exists possible research propositions that ought to be investigated and resolved particularly on the implementation of the AFC to the nonholonomic mobile manipulator system and the appropriate acquisition and estimation of the inertia matrix as duly described in the thesis.

1.3 Problem Statements and Formulation

In the study the RAC was developed as the integrated simplified mobile platform coordinate and heading angle, (x_v, y_v, φ) control and the *XY Cartesian* planar manipulator's tip position coordinate, (x_m, y_m) control. By using this RAC-based x, y, and heading angle control instead of the velocity and heading angle control as suggested by Umeda and Yakoh (2002), the proposed control scheme would have a more flexible position, velocity and acceleration control. This flexibility is gained by the use of simultaneous input reference position, velocity and acceleration parameters. To tackle the robot's dynamic problem particularly those involving disturbances and uncertainties, the AFC schemes were incorporated into the control scheme. In general, the total control scheme was RACAFC.

An extension of an AFC by using an integral control to the existing pure (crude) AFC was proposed and investigated. Based on classical feedback control theories, by considering the fixed inertia matrix estimator as a proportional (P) term in the acceleration control mode, an integral (I) term can then be incorporated to the proportional control as a steady-state error refinement. The scheme was RACPIAFC.

As one of the proposed intelligent mechanisms, an iterative learning-based AFC was also designed, namely RACILAFC. The iterative learning method that was first introduced by Arimoto (1984) has been extensively developed by researchers in the case of robotics (Liang and Looze, 1993; Moon *et al*., 1997; and Norrlof, 2002). The iterative learning method is known as one of the effective adaptation methods that can iteratively seek the optimum value of the control parameters. As an extension, a combination of the RACPIAFC and RACILAFC was also proposed, namely RACILPIAFC. In this case, the iterative learning procedure was used to optimise the proportional and integral parameters of the PIAFC.

A hybrid method namely Knowledge-Based Fuzzy (KBF) AFC was also proposed in the study. The concept of this scheme is to estimate the inertia matrix of the system using fuzzy logic (FL) system. The inference mechanism is based on a prior knowledge investigation of the system operations. For uncertain dynamic problems, it is usual to combine FL with online learning algorithms, such as Adaptive Network-based Fuzzy Inference System (Jang, 1993; Mar and Lin, 2001; and Hassanzadeh *et al*., 2002). An example of knowledge-based fuzzy method applied to a feedback control can be found in Rhee *et al*. (1990). The KBF concept has mostly been found in system identification and data retrieval system, such as dynamic voltage security (Tso *et al*., 1996), classification and rule generation (Mitra *et al*., 1997), heuristic learning-based KBF (Ouchi and Tazaki, 1998), and automatic model-based image segmentation system (Nanayakkara and Samarabandu, 2003). In this study, the KBFAFC was proposed as an alternative robust motion control of the mobile manipulator.

From the proposed schemes mentioned above, the problem formulation of the study can be summarised as follows:

1. In a continuous mobile manipulator motion with a continuous trajectory tracking the kinematic control should be integrated with the dynamic control effectively to perform the proper robust motion control. In this case, the combination of RAC and AFC scheme would satisfy the robustness requirements of the motion control.

2. In a continuous mobile manipulator operation with known/unknown disturbances the multiplication of the inertia matrix in the AFC scheme should be estimated correctly and in real-time due to the non-linear characteristics of the robot and its environment.

3. It is therefore necessary to implement the proper estimation techniques namely PIAFC, ILAFC, ILPIAFC, and KBFAFC.

4. An experimental investigation is then important to validate the feasibility for real implementation.

1.4 Research Objectives

The objectives of the research are as follows:

1. To investigate theoretically the feasibility of implementing the concept of proportional-integral (PI), IL, and KBF methods to the RACAFC

scheme applied to the mobile manipulator in the form of a detailed simulation study.

2. To evaluate the systems' performance in terms of its robustness and effectiveness.

3. To integrate the hardware and software in the form of an experimental mobile manipulator with the implementation of the proposed schemes.

1.5 Research Scope, Strategy and Methodology

The scope of the project encompasses both theoretical and experimental aspects of the proposed mobile manipulator control strategies. The study focused on the implementation of the RACPIAFC, RACILAFC, RACILPIAFC, and RACKBFAFC in conjunction with the RACAFC scheme. These were applied to a mobile manipulator system comprising a nonholonomic differentially-driven wheeled mobile platform with a rigid two-link planar manipulator mounted on top of the platform that was assumed to operate horizontally. The theoretical framework involves the study of various underlying principles related to the AFC methods, kinematics and dynamics of the system, proportional-integral and iterative learning control, and knowledge-based fuzzy technique. This was transformed into a rigorous modelling and simulation study of the integrated schemes assuming a number of prescribed conditions and limitations. The performances of the proposed systems were evaluated and consequently compared to RAC and/or RACAFC counterparts for the purpose of benchmarking. The design and development of the hardware in the form of an experimental mobile manipulator was envisaged using mechatronics approach; integrating mobile manipulator with sensors and actuators via a PC-based controller. In addition, a simple embedded controller system based on Microchip IC PIC16F877 was implemented and introduced as a prototype to exhibit the practical implementation of the RACAFC scheme in the form of an autonomous mobile manipulator.

The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.1.

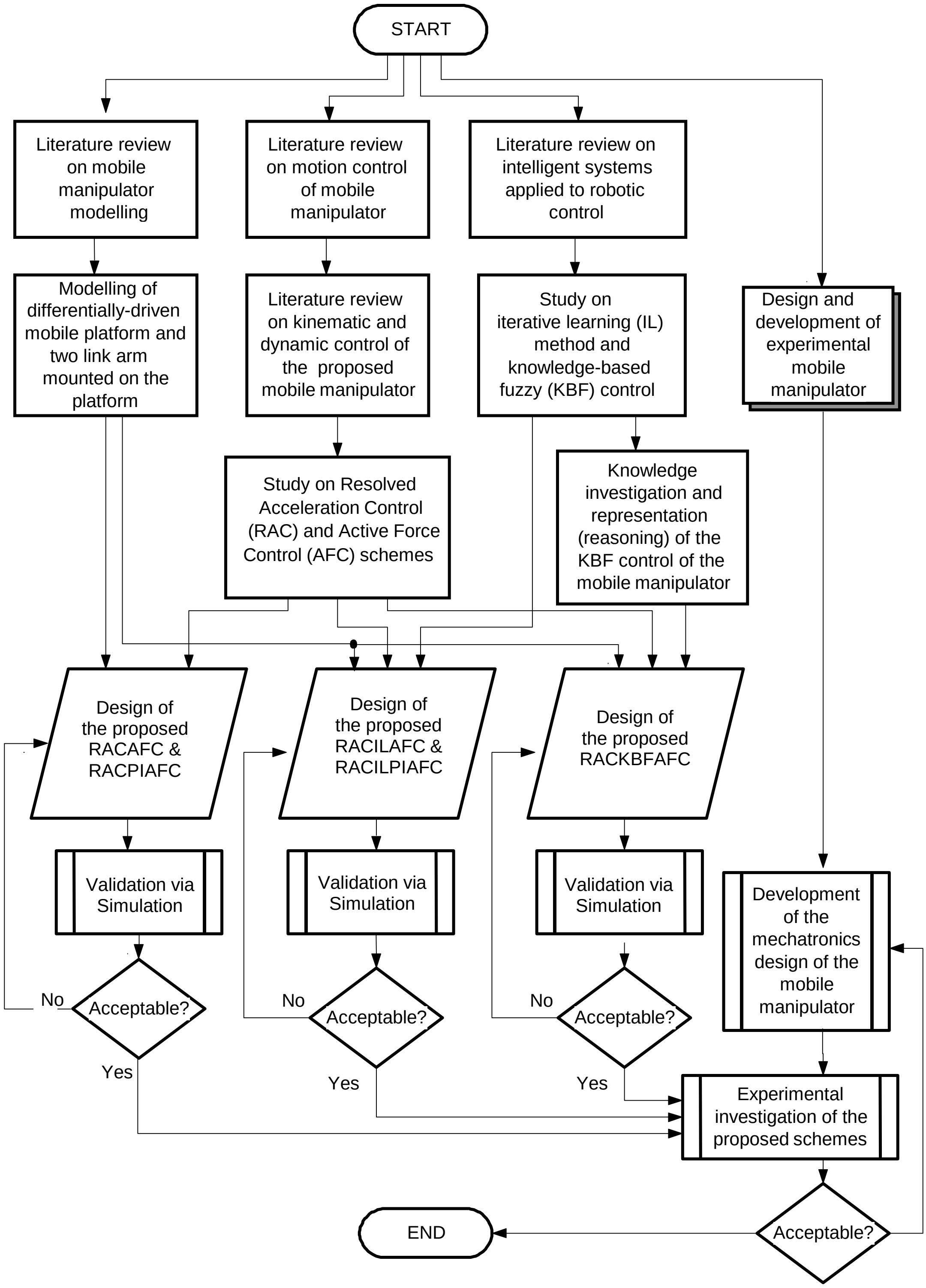

Figure 1.1: The research strategy in a flowchart.

From Figure 1.1, the research methodology pertaining to the project can be briefly described as follows:

1. Review literatures on areas of mobile manipulator robot, force control and intelligent control.

2. Study the AFC mechanism and related works applied to the control of mobile manipulator.

3. Identify the problems of the existing AFC strategies and other related issues involving concepts of proportional-integral, iterative learning, and knowledge-based fuzzy control.

4. Design and simulate the proposed basic RACAFC applied to the mobile manipulator.

5. Design and simulate the proposed extended RACAFC scheme in the form of RACPIAFC, RACILAFC, and RACILPIAFC.

6. Test and evaluate the robustness of the schemes by introducing disturbances. Investigate the knowledge generated from these simulation studies.

7. Design and fully develop a laboratory scale mobile manipulator to verify the proposed methods. This includes the development of the hardware and software (C program), electronic interfacing devices, motors, sensors and mechanical mobile manipulator robot.

8. Perform an initial experimental investigation for the RAC and or RACAFC and investigate the knowledge from this experiment.

9. Design the fuzzy reasoning and inference mechanisms for the KBF method. A suitable database from the simulation and experimental study should be gathered for the decision making process.

10. Design the complete RACKBFAFC based on the previous knowledge investigation.

11. Simulate the proposed RACKBFAFC. Test and evaluate the robustness of the scheme by introducing disturbances.

12. Analyze the results and compare the system performances among the proposed methods.

13. Perform a series of experiments, analyze the results, discuss and compare them to those obtained theoretically.

1.6 Research Contributions

The main research contributions from this study are as follows:

1. New approximation methods that could make decision to compute continuously and on-line the appropriate inertia matrix of the mobile manipulator in order to improve the AFC strategy in the form of PIAFC, ILPIAFC, and KBFAFC.

2. New robust motion control schemes of the mobile manipulator in the form of the RACAFC, RACPIAFC, RACILAFC, RACILPIAFC, and RACKBFAFC.

3. A PC-based controlled laboratory-scaled mobile manipulator comprising a differentially-driven (wheeled) mobile robot/platform and a two-link planar manipulator mounted on top of the platform with a vertical gripper at the tip end position. This includes the development of the system hardware (electronic interfacing devices, motors, sensors and mechanical mobile manipulator) and software (a graphical real-time monitor & mobile manipulator online control in C program).

4. An autonomous mobile manipulator based on an embedded controller system.

1.7 Organization of Thesis

The thesis is organized into nine chapters. In Chapter 2, the fundamental concepts, underlying theories and reviews of the main topics of research pertaining to kinematic and dynamic control of mobile manipulator, RAC, AFC, iterative learning control and knowledge-based fuzzy are described. The basic principles of the well known RAC and the pure AFC method is first discussed with special attention focused on the method to enhance the strategy using intelligent means such as the use of neural network, fuzzy logic, and KBS (knowledge-based system) methods. The KBS inference mechanism, i.e. knowledge investigation and validation, knowledge representation, knowledge acquisition and knowledge processing are discussed as well as the KBS procedures. A preliminary discussion on the use of knowledge-based method to a fuzzy system is also addressed.

Chapter 3 describes a simulation study of the new proposed scheme of Resolved Acceleration Control combined with Active Force Control (RACAFC) which employs a crude approximation on the inertia matrix estimation. This proposed scheme is considered as the basic robust motion control using AFC applied to the mobile manipulator that deals with the kinematics and dynamics as well. Based on this the new AFC based on a proportional-integral approach and the intelligent control using iterative learning and knowledge-based fuzzy could be developed and realized as presented in Chapters 3, 4 and 5. The tuning procedures of the inertia matrix estimator of the mobile platform are rigorously discussed in this chapter as well as for the manipulator. Some disturbances introduced to test the robustness of the proposed scheme are also described.

Chapter 4 presents a simulation study of the proposed extended version of the RACPIAFC (Resolved Acceleration Control and Proportional-Integral Active Force Control). This chapter provides a discussion on the advantages of using proportional and integral term to the existing AFC. Some results on the operation with disturbances are discussed by comparing the performances with pure AFC.

Chapter 5 discusses the next two proposed schemes, i.e., RACILAFC and RACILPIAFC. The first scheme incorporates a pure PD-type iterative learning control (ILC) to the AFC based on the tracking error. The second is a combination of the RACILAFC and RACPIAFC. The chapter provides alternative intelligent procedures applied to AFC, i.e. iterative learning, proportional-integral control, and the combination of both. A simulation study with the same parameters used in the previous scheme was performed.

Chapter 6 presents a simulation study of the main proposed scheme, i.e., Resolved Acceleration Control and Knowledge-Based Fuzzy Active Force Control (RACKBFAFC). The complete procedure to realize the knowledge-based fuzzy including the procedures of knowledge investigation, validation, representation, acquisition and processing is discussed. The procedure to investigate the knowledge is highlighted. As the most important part of knowledge based fuzzy, i.e., how the knowledge can be used as the reasoning mechanism to design the proper fuzzy output function is then described. This chapter also presents the complete results of the simulation study subjected to several conditions of the kinematic and dynamic aspects including some disturbances effect.

Chapter 7 discusses a comparative study of the RACAFC, RACPIAFC, RACILAFC, RACILPIAFC, and RACKBFAFC. The comparison is mainly focused on the generated track errors signal patterns, the computed estimated inertia matrix and the applied starting current and torques due to a number of varied external disturbances.

Chapter 8 describes the design and development of the experimental mobile manipulator (a differentially driven mobile robot/platform with a two-link planar robot arm mounted on the top of the platform) with graphical and real-time monitor control-programming feature. This chapter also provides a programming and experimental procedure based on the RAC and RACAFC schemes.

Finally, Chapter 9 concludes the research project. The directions and recommendations for future research works are also outlined. A list of publications related to the study and some of the specifications and datasheet of components used for developing the experimental mobile manipulator are enclosed in the appendices.

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