AN IMPLEMENTATION OF A KNOWLEDGE-BASED SYSTEM METHOD TO AN ACTIVE FORCE CONTROL ROBOTIC SCHEME

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ABSTRACT

This thesis presents a method to improve the response of a robotic control system in order to obtain a more robust system performance using an active force control with a knowledge-based system method called the Active Force Control and Knowledge-Based System (AFCKBS). The focus of the study is the implementation of a mechanism to refine the trajectory error generated by an Active Force Control (AFC) scheme applied to a two-link robotic planar arm. This is accomplished by utilizing features of the signal patterns produced by the input and output functions. Based on the previous research that employed a number of robotic control schemes, knowledge of the trajectory track error pattern was obtained when a specific trajectory tracking command was forced to the system. The correlation between the generated track error pattern and the input function of the robot scheme provides the essential knowledge to be utilized via the proposed technique. A simulation and experimental study was performed and the result obtained was consequently analyzed and compared to show the performance enhancement in the proposed method.

ABSTRAK

Tesis ini membincangkan suatu kaedah untuk memperbaiki sambutan daripada sistem kawalan robot untuk memperolehi prestasi sistem yang lebih lasak menggunakan kawalan daya aktif dan satu kaedah berasaskan pengetahuan yang dipanggil *Active Force Control and Knowledge-Based System* (AFCKBS). Penumpuan utama daripada penyelidikan ini ialah tentang penerapan suatu mekanisme untuk membaiki ralat trajektori yang dihasilkan oleh skema *Active Force Control* (AFC) dan diuji pada sebuah lengan planar robot dua sendi. Hal ini dapat dilakukan dengan mengambilkira ciri-ciri khas yang terdapat pada isyarat paten yang dihasilkan oleh fungsi masukan dan luaran. Berdasarkan kepada kajian yang dibuat terhadap beberapa jenis skema kawalan robot sebelum ini, pengetahuan tentang ralat jejak trajektori dapat diperolehi apabila suatu arahan penjejakan trajektori diberikan kepada sistem. Korelasi bentuk isyarat ralat trajektori terhasil dan juga fungsi masukan daripada skema robot menyajikan suatu pengetahuan yang diperlukan serta boleh diterapkan melalui teknik yang dicadangkan. Suatu kajian melibatkan kedua-dua penyelakuan dan ujikaji sebenar telah dilakukan dan hasil kajian dapat dihurai serta dibandingkan secara saksama untuk menunjukkan pembaikan dan peningkatan prestasi menggunakan kaedah yang dicadangkan.

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LIST OF SYMBOLS

SYMBOL	**SUBJECT**
α	Angular acceleration of the link (arm)
θ	Joint angle of the robot arm
θ_1	Joint angle of the robot arm, link-1
θ_2	Joint angle of the robot arm, link-2
θ_{d1}	Joint velocity of the robot arm, link-1
θ_{d2}	Joint velocity of the robot arm, link-2
θ_{bar}	Desired joint angle
θ_d	Joint velocity of the robot arm
θ_{dbar}	Desired joint velocity
θ_{dd}	Joint acceleration of the robot arm
θ_{ddbar}	Desired joint acceleration
θ_{ddref}	Joint acceleration command vector
A	Magnitude of the force applied at the end of second link
ADC	Analog to Digital Converter
AFC	Active Force Control
AFCANN	Active Force Control And Neural Network
AFCAIL	Active Force Control And Iterative Learning
AFCEKBS	Active Force Control with Extended KBS
AFCKBS	Active Force Control with KBS
ATE	Average Track Error
C	A command vector

cf	Confidence factor
CTE	Cumulative Track Error
DAC	Digital to Analog Converter
$EKBS_v$	Extended KBS value applied in the **IN**
F_h	Harmonic force applied at the end of second link
F_k	Spring force applied at the end of second link
F_m	Like F_o plus a change in the mass of payload at the end effector
F_o	No visible external disturbance
g	Acceleration due to gravity (m/s^2)
$G(s)$	A function in La place domain representing the feedforward gain inthe **AFC** loop
$G_c(s)$	A function in La place domain representing the controller gain
$H(s)$	A function in La place domain representing the compensated gain in the AFC loop
h	Vector of the coriolis and centrifugal torques
h_c	Harmonic frequency coefficient of disturbance
h_f	Harmonic Factor in AFCEKBS parameters
I_a	Compensated current vector
I_c	Command or reference current vector
IN	Estimated inertia matrix
$\mathbf{IN}_{KBS}$	Estimated inertia matrix of AFCKBS scheme
$\mathbf{IN}_{EKBS}$	Estimated inertia matrix of AFCEKBS scheme
I_t	Motor torque current vector
k	Spring stiffness
KA	Knowledge Acquisition
K_d	Derivative gain
K_p	Proportional gain
K_{tn}	Motor torque constant
KBS	Knowledge-Based System
KBS_v	KBS value applied in the **IN**

K_{gain}	Gain of KBS value applied in AFCKBS and AFCEKBS
l	Length of the link
l_c	Length of the link from the joint to the center of gravity of link
m	Mass of the link
mot	Mass of the motor
Q	General disturbance torque vector
Q^*	General estimated disturbance torque
RMAC	Resolved Motion Acceleration Control
s	Extension or compression of the spring
T	General torque vector
T_i	Torque output of IN estimator
t	Time
TE	Track Error
TTE	Trajectory Track Error
$TTEs$	Trajectory Track Errors
T_q	Actuator torque
$tstop$	Simulation terminating time
V_{cut}	Tangential end point velocity of link
$W(s)$	A decoupling transfer function in La place domain
x	Actual position of the end effector in Cartesian space
X	Output displacement vector
x_{bar}	Desired position of the end effector in Cartesian space
x_{dbar}	Desired velocity of the end effector in Cartesian space
x_{ddbar}	Desired acceleration of the end effector in Cartesian space
x_{ddref}	Linear acceleration command vector
$X_{desired}$	Desired displacement vector

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CHAPTER I

INTRODUCTION

1.1 General Introduction

A robust and stable performance of a robot arm is essential as it deals with the capability of the arm to compensate for the disturbance effects, uncertainties, parametric and non-parametric changes, which are prevalent in the system particularly when the arm is executing tasks involving the interaction of the robot's end-effector with the environment. Often, manufacturing processes which are executed by industrial robots such as deburring, contour tracking, profile cutting, grinding and burnishing, demand a certain degree of accuracy, stability and robustness to produce high quality finishes or end-products. Thus, the coordinated motion and force control of a robot arm is an important subject area of research, which can directly contribute to the accomplishment of such objective. A very desirable and effective robot control system is one in which the issue of robustness is well accounted for. Many robot control methods have been proposed such as Proportional-Integral-Derivative (PID) control (Seraji, 1998), adaptive control as in Slotine and Li (1987) and Craig *et al.* (1987), hybrid force/position control as in Raibert and Craig (1981) and Kawamura *et al.* (1985), computed-torque control (Fu *et al.*, 1987), intelligent control (Jung and Hsia, 1995) and active force control (AFC) (Hewit and Burdess, 1986).

It is a well-known fact that the conventional PID control is the most widely and practically used scheme in industrial robots due to its good stability characteristic, simple controller structure, and reliability (Seraji, 1998). It provides a medium to high performance when it comes to robot's operation at relatively low speed with little or no disturbance effects. On the contrary, the performance suffers severe setbacks when adverse conditions prevail. A number of researches have been conducted to seriously address the issue and determine ways to counter the weaknesses (Arimoto *et al.*, 1984, 1986).

Almost all the robot control methods contained the classical elements (of the PID control), which contribute to the better overall performance of the system. One such robot control method, which is of particular interest, is the active force control strategy first proposed by *Hewit* in the late seventies (Hewit and Burdess, 1981). The main feature of this type of control method is the potential application of the AFC concept to dynamical systems including robot control. By implementing AFC to the system, the effects due to any known or unknown disturbances (internal or external), parametric changes and varied operating conditions can be significantly compensated or eliminated. The AFC method involves a direct measurement of the acceleration and force quantities plus the appropriate estimation of the inertia matrix to effect its control strategy.

The research study is aimed at investigating the AFC strategy with an intelligent mechanism using a Knowledge-Based-System (KBS) method applied to the control of rigid robotic arm. Both the theoretical and experimental aspects were highlighted in the study to illustrate the practical viability of the proposed scheme.

1.2 Research Background

The active force control strategy is one of the potential and practical force control methods, which can be implemented in encountering the robot force control problem. The advantage of the AFC method is that it has the ability to compensate the unpredictable external (and internal) forces effectively and reliably without rigorous mathematical computations. The capability of AFC method greatly depends on how efficient the estimated inertia matrix of the robot arm being computed.

Various methods have been developed by researchers to estimate the inertia matrix such as by using crude approximation method (Active Force Control with Crude Approximation - AFCCA), reference of a look-up table and intelligent methods such as neural network (Active Force Control And Neural Network - AFCANN) and iterative learning (Active Force Control And Iterative Learning - AFCAIL) algorithms (Musa, 1998). A new novel intelligent technique of computing the estimated inertia matrix using a knowledge-based system (KBS) is proposed and investigated in this thesis.

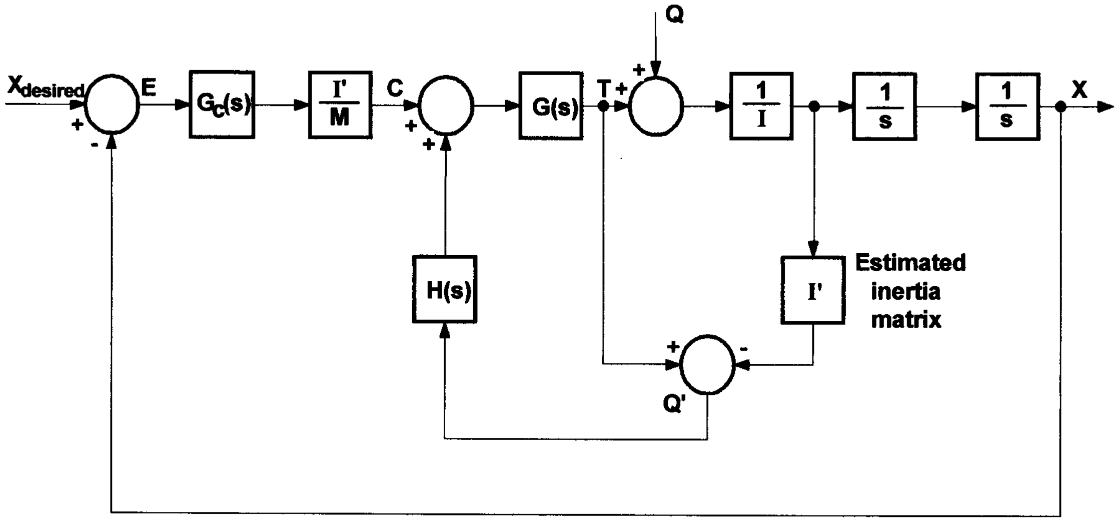

Figure 1.1: A representation of an AFC scheme

A representation of an AFC scheme is shown in Figure 1.1. With reference to the figure and considering a continuous robot arm operation with known and or unknown disturbances, the acquisition of the estimated inertia matrix (**I'**) in AFC scheme should be obtained appropriately and in real-time due to the non-linear characteristics of the robot and its environment. It is therefore necessary to propose and implement an intelligent control mechanism such as a KBS method. A set of inference mechanisms is formulated such that the proposed control scheme could compute the inertia matrix of the robot arm continuously and on-line. This is done while the arm is performing its task under various loading and operating conditions. In this way, the robustness of the scheme can also be investigated and analyzed.

1.3 Research Objectives

The objectives of the research are:

- to investigate theoretically the feasibility of applying the concept of KBS method to the control of a robot arm with AFC strategy in the form of a detailed simulation study.
- to evaluate the system's performance in terms of its robustness and effectiveness.
- to integrate the hardware and software in the form of an experimental robot arm with the implementation of the on-line KBS algorithm to estimate the real-time inertia matrix of a robot arm in the active force control feedforward loop.

1.4 Research Scope, Methodology and Strategy

The scope of the project encompasses both the theoretical and experimental aspects of the proposed robot control strategy. The study focuses on the implementation of an intelligent mechanism, particularly the knowledge-based method in conjunction with a number of selected AFC schemes (AFCCA, AFCANN and AFCAIL); this is applied to a robotic system comprising a rigid two-link planar manipulator that is assumed to operate horizontally, i.e., without any reference to any gravitational torques. The theoretical framework involves the study of the various underlying principles related to the AFC methods, dynamics of the system, and knowledge-based technique. This is transformed into a rigorous modeling and simulation study of the integrated schemes assuming a number of prescribed conditions and limitations. The performance of the proposed system is evaluated and consequently compared to the classical PD control counterpart for the purpose of benchmarking. A design and development of the hardware (to complement the theoretical part) in the form of an experimental two-link planar robotic arm was envisaged using mechatronics approach; integrating robot arm with the sensors, actuators via a PC-based controller.

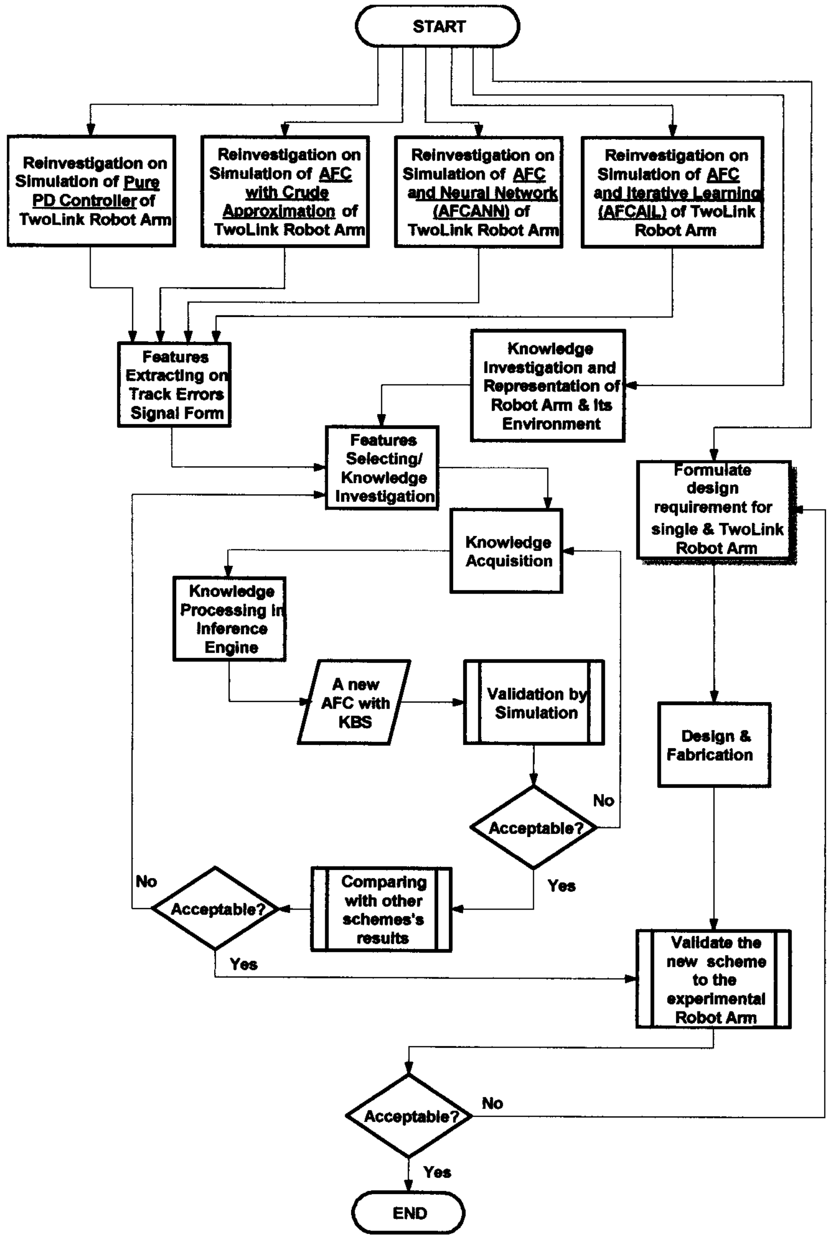

Figure 1.2: Research strategy in a flowchart

The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.2. The research methodology pertaining to the project can be briefly described as follows:

- Review literatures on areas of robot, force control and intelligent control.
- Study the AFC mechanism and related works applied to the control of robot arm. Simulate some of the AFC strategies as proposed in the literatures.
- Identify the problems of the existing AFC strategies and other related issues.

- Design the inference mechanisms for the KBS method. A suitable database should also be gathered for the decision making process.
- Test the robustness of the scheme by introducing a number of disturbances. Analyze the results and compare the system performance with other methods.
- Design and fully develop a laboratory scale two degrees-of-freedom (d.o.f) rigid robot arm to verify the proposed method. This includes the development of the KBS hardware and software (C program), electronic interfacing devices, motors, sensors and mechanical robot arm.
- Perform a series of experiments on the arms. Analyze the results, discuss and compare them to those obtained theoretically.

1.5 Expected Results

The proposed study is expected to produce:

- a new approximation method that could make decision to compute continuously and on-line the appropriate inertia matrix of the robot arm in order to improve the AFC strategy.
- results that show the effectiveness and robustness of the proposed scheme.
- a laboratory scale two d.o.f rigid robot arm to verify the proposed method. This includes the development of the system hardware (electronic interfacing devices, motors, sensors and mechanical robot arm) and software (a graphical and real-time monitoring plus online control in C program).

1.6 Organization of Thesis

The thesis is organized into eight chapters. In Chapter II, the fundamental concepts, underlying theories and reviews of the main topics of research pertaining to robot arm control, AFC, expert system and knowledge-based system are described.

The basic principles of 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 methods. For KBS, the inference mechanism is discussed plus the knowledge investigation and validation, knowledge representation, knowledge acquisition and knowledge processing as well as the KBS procedures. A review on the use of the expert system and/or knowledge-based system methods to robot control is also included.

Chapter III describes the knowledge investigation procedure performed on the AFC robot control schemes. A number of selected AFC schemes (AFCCA, AFCANN and AFCAIL) were revisited in view of trying to obtain features of the trajectory track error signals to be investigated. The knowledge investigation procedure is the first and foremost phase of the KBS method and thus investigated. The results of the investigation would lead to the acquisition of the essential knowledge to be implemented into the proposed AFC scheme with the KBS feature. Chapter IV presents a simulation study of the new novel proposed scheme – AFC with KBS (AFCKBS), based on the knowledge investigation described in Chapter 3. The detailed procedures after the knowledge investigation phase as described earlier were highlighted in this chapter. These procedures are knowledge validation, representation, acquisition and processing. A simple *Bayesian* approach to perform the knowledge validation process is also given.

Chapter V elaborates an extended KBS method based on AFCKBS described in Chapter IV. The strategy is called AFCEKBS, an acronym for *AFC* with *E*xtended *KBS*. It implies an extended rule is employed in the system. A simulation study with the same parameters used in the previous scheme was performed. Chapter VI provides a comparative study of the AFCKBS and AFCEKBS methods. 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 VII describes the design and development of the experimental robot arm (a two-link planar manipulator) with graphical and real-time monitor control-programming feature. Some important design parameters are also given and discussed. This chapter also provides a programming and experimental procedure based on the AFCKBS scheme (described in Chapter III).

Finally, Chapter VIII concludes the research project. The directions and recommendations for future research works are also outlined. Some of the executable programs designed for the experimental robot arms and list of publications related to the study are enclosed in the appendices.