INTELLIGENT ACTIVE FORCE CONTROL OF A HUMAN-LIKE ARM ACTUATED BY PNEUMATIC ARTIFICIAL MUSCLES

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DEDICATION

I would like to dedicate this thesis to:

My beloved parents, ***Mohammad Jahanabadi*** and ***Sedeigheh Agheb***, to my brothers ***Ali*** and ***Reza***, to my sister ***Atefeh*** for their tremendous support, encouragement and patience throughout my studies and indeed throughout my life.

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ABSTRACT

Robotic system driven by fluidic muscles is time-varying and exhibits high degree of nonlinearity due to the internal system behaviours and thus controlling it constitutes a major problem. This poses a great challenge to researchers to come up with suitable technique/s to control such system effectively. The research presents a simulation and experimental study of a force control method applied to a two-link planar 'human-like' robot arm that is actuated by fluidic muscles. Active force control (AFC) based scheme was particularly implemented to the system incorporating two types of intelligent techniques, namely, fuzzy logic (FL) and iterative learning (IL) to effectively and robustly control the arm driven by a pneumatic artificial muscle (PAM) system and subject to a number of operating and loading conditions. The PAM is actuated by two groups of fluidic muscles in bicep/tricep configuration. The simulation and the experimental study verify that proposed system performs excellently even in the presence of uncertainties, hysteresis behaviour of the actuator and inherent nonlinearity. Joint trajectory planning was applied to ensure that the arm tracks the given input commands accurately considering a number of different frequency settings. The simulated system was complemented and validated through an experimental study carried out on a developed rig via a convenient hardware-in-the-loop simulation (HILS) technique using suitable hardware and software interface. The obtained results both through simulation and experimental investigation clearly imply the viability of the proposed AFC-based system in controlling the PAM actuated robotic arm and they also demonstrate the system superiority over the PID controller alone counterpart.

ABSTRAK

Sistem robotik dipacu oleh otot bendalir yang berubah dengan masa dan menunjukkan darjah ketidaklelurusan yang tinggi disebabkan oleh kelakuan sistem dalaman; maka untuk mengawal sistem sedemikian merupakan satu masalah besar. Ini memberikan satu cabaran kepada para penyelidik untuk menghasilkan satu kaedah kawalan yang berkesan untuk menangani masalah tersebut. Penyelidikan yang dijalankan memaparkan suatu kajian simulasi dan eksperimen berkaitan dengan kaedah kawalan daya terhadap suatu lengan robot planar dua penghubung menyerupai lengan manusia yang dipacu oleh otot bendalir. Skema berlandaskan kawalan daya aktif (AFC) digunakan terhadap sistem dengan memuatkan dua jenis teknik pintar, iaitu logik kabur (FL) dan pembelajaran berlelaran (IL) bagi tujuan mengawal dengan lasak dan berkesan suatu lengan yang dipacu oleh satu sistem otot tiruan pneumatik (PAM) yang ditindakkan oleh beberapa keadaan bebanan dan pengoperasian. PAM digerakkan oleh dua kumpulan otot bendalir dalam konfigurasi bicep/tricep. Kajian simulasi dan eksperimen mengesahkan bahawa sistem yang dicadangkan memberikan prestasi yang amat baik walaupun beroperasi dalam keadaan wujudnya ketidaktentuan, kelakuan histerisis penggerak dan ketidaklelurusan dalaman. Perancangan trajektori sendi digunakan bagi memastikan lengan menjejaki dengan tepat arahan masukan yang dikenakan dengan mengambil kira beberapa nilai frekuensi yang berlainan. Sistem yang dikaji menerusi simulasi dapat ditentusahkan menerusi kajian eksperimen yang dijalankan terhadap suatu rig yang dihasilkan menggunakan kaedah simulasi perkakasan-di-dalam-gelung (HILS) melibatkan penggunaan pengantaramuka perisian dan perkaksan yang bersesuaian. Hasil keputusan kajian yang dijalankan baik menerusi simulasi mahupun eksperimen menunjukkan bahawa sistem berlandaskan AFC yang dicadangkan berupaya

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFC	Active force control
AFCAFL	Active force control and fuzzy logic
AFCAIL	Active force control and iterative learning
DOF	Degree of freedom
FL	Fuzzy logic
HILS	Hardware-in-the-loop simulation
IL	Iterative learning
PAM	Pneumatic artificial muscle
PID	Proportional-Integral-Derivative

LIST OF SYMBOLS

P	Absolute gas pressure
dV	Volume change
F	Actuator force
dl	Actuator length change
α	Wweave angle
b	Fibre length
l	Nominal length of PAM
D	Diameter of PAM
r	Radius
P	Internal pressure of PAM
ε	Contraction ratio
θ_1	Joint angle of link1
θ_2	Joint angle of link2
l_1	Length of link 1
l_2	Length of link 2
m_1	Mass of link1
θ_1	Joint angle of link1
θ_2	Joint angle of link2
m_1	Mass of link1
m_2	Mass of link2
l_{c1}	Distance to the center of mass of the link 1
l_{c2}	Distance to the center of mass of the link 2
$\boldsymbol{\tau}$	Actuated torque vector
$\mathbf{H}$	$N \times N$ inertia matrix manipulator

h	Coriolis and centripetal torque vector
G	Gravitational torque vector
τ_d	External disturbance torque vector
G	Open-loop gain
IN	Estimated inertia matrix
τ_d^*	Estimated disturbance torque
$\ddot{\theta}$	Actual acceleration
K_i	Multiplier constant
e	Track error
y_{k+1}	Next step value of the output
y_k	Current output value
e_k	Current positional error input
Φ	Proportional learning parameter
Γ	Derivative learning parameter
Ψ	Integral learning parameter
IN_{k+1}	Next step value of estimated inertia matrix
IN_k	Current estimated inertia matrix
TE_k	Current track error

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Engineering principles are commonly applied to mechanical or biomechanical systems to better understand the dynamics of the human arm. One such system is the robotic arm or manipulator which is normally and geometrically configured to resemble a human arm. A robust and stable performance of a robot arm is essential as it handles the capability of the arm to compensate for the disturbance effect, 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 and some kind of external disturbances. 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 robots control methods have been proposed such as proportional-integral-derivative (PID) control [1], computed-torque control [2], intelligent control [3], and active force control (AFC) [4]. It is a well-known fact that the conventional PID control is the most widely and practically used scheme in the industrial robots due to its good stability characteristic, simple controller structure, and reliability [1]. 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 weakness [5, 6]. Thus, a feedback control system should be ideally chosen so that it is able to overcome most if not all of the drawbacks and at the same time, it is practically viable and can be implemented in real-world applications. Considering these factors, the undertaken research project is an attempt to highlight the potentials of an AFC-based method applied to a two-link planar robot arm actuated by pneumatic artificial muscle (PAM) actuators.

1.2 Research Background and Contributions

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 [4]. The main feature of this type of control method is the potential of the AFC concept to dynamical systems including robot control. By implementing the 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 of effect in its control strategy.

Actuators are indispensable for all robots to provide forces, torques, and mechanical motions to move the joint, limb or body. Actuators are generally electric, pneumatic, or hydraulic. Today's mechanical systems have such criteria for actuators including high power density, high power to weight ratio, rapid response, accurate and repeatable control, low cost, cleanliness and high efficiency. An important area of robotics technology is concerned with the development of manipulators that can replace human beings in the execution of specific tasks. This makes such qualities such as lightweight, high power, and fast accurate response even more important for actuators. The pneumatic artificial muscle (PAM) actuator possesses many of these advantages, which therefore considered as an excellent candidate for robotic applications. However, the inherent nonlinearities, time-varying parameters, and high sensitivity to payload of the PAM make it a challenge for the accurate force and position control of manipulators in employing these actuators.

It is the central theme of the undertaken research project to investigate the implementation and the performance of a robot arm that is actuated and controlled by PAM through the AFC-based scheme. In the proposed research, an intelligent component is embedded into the AFC main loop to compute the appropriate inertia matrix of the arm. Both the theoretical and experimental aspects were highlighted in the study to validate and illustrate the practical viability of the proposed scheme.

The main research contributions can be summarised as follows:

1. The use of pneumatic artificial muscle (PAM) actuators to drive a two-link robot manipulator that resembles a human arm.
2. Direct application of the AFC technique to the robot arm through both simulation and experimental studies. The application of AFC to PAM actuated system is indeed new area of research.
3. Incorporation of intelligent methods using fuzzy logic (FL) and iterative learning (IL) algorithms to estimate the inertial parameters of the arms in the AFC loop for the given system.
4. Development of an experimental rig with Hardware-in-the-Loop-Simulation (HILS) to validate the proposed control scheme.

1.3 The Problem Statements

There are two main issues that need to be addressed and resolved in the project. The first is related to the AFC scheme while the second is concerned with the utilisation of the PAM actuator. Both are actually inter-related due to the fact that the PAM actuator is designed as the main actuating element in the proposed control schemes.

The AFC strategy is regarded very practical and effective if a number of criteria can be fulfilled as follows:

1. Accurate measurements of the actuator torques and body angular accelerations could be obtained.
2. A suitable inverse transfer function of the PAM actuator can be derived and implemented.
3. A good estimated inertia matrix in the AFC loop can be computed.

The first criterion could be realized easily either through theoretical investigation through simulation or experimental means using accurate sensors. The second part is complex as it involves the application of the non-linear PAM and the required function is derived based on the differential pressure of PAMs, ΔP. It is typical that the third criterion is considered the most critical since it involves directly the ever changing dynamics of a system and hence shall be described in greater detail here. The estimated inertia matrix of the robotic arm can be derived from the dynamic model as a function of joint angles which varies as the arm moves. Mathematically, the computation of this matrix becomes increasingly difficult with the corresponding increase in the number of degree-of-freedom (DOF) of the robot arm. It is thus clear that the utilization of the inertia matrix based on the perfect model of the robot arm with many DOF is quite impractical as far as the AFC scheme is concerned. For a single DOF case, the solution to the above scheme is rather straightforward and linear control theory is readily applicable. The proposed research work assumes a two-link arm (and hence a two DOF system) which is coupled and inherently non-linear - hence the computation of the estimated inertia matrix is becoming increasingly difficult. It is evident that different system dynamics produce correspondingly different operating environment related to the acquisition of the estimated inertial parameters of the arm. Intelligent methods were proposed in the study as the inertia matrix estimators of the arm driven by the highly non-linear PAM actuators.

The other aspect is the use of the PAM actuator in the design and development of the system. Research on the use of PAM actuator for controlling purpose is relatively new and still in its infancy stage. The main characteristics of the PAM actuator are the inherent non-linearities, time varying parameters and sensitivity in the loading of the PAM system that posed great difficulty and challenge in producing good coordinated motion control of a dynamic system including the proposed robot arm. This is further exacerbated by the fact that there are not many published works related to the area of study. On the whole, since the two-link planar mechanical arm itself is a very nonlinear system plus the use of PAM actuators, the proposed AFC–based scheme should be designed to be reliable, robust and effective to tackle the aforementioned problems.

1.4 Research Objective

The main objective of the research is to investigate the performance of the robotic arm actuated by fluidic muscle actuator through the application of AFC strategy. To achieve this, the following sub-objectives are considered:

- To carry out theoretical study involving the modelling, simulation and control of a two-link planar robot arm actuated by PAM.
- To validate the proposed AFC-based scheme through practical experimentations on a developed rig.

1.5 Research Scope

The scope of the undertaken research is as follows:

- A two DOF planar robot arm is investigated considering motion in a horizontal plane. Hence, gravitational effect can be totally ignored.
- Each joint of the arm is driven by a PAM actuator.
- The arm is assumed to operate at low speed and frequency due to the hysteresis of the PAM. The only disturbances considered in the study are due to the inherent non-linearity (including hysteresis) and other time varying parameters (pressure and contraction ratio) of the PAM actuator.
- Theoretical design and simulation of a robust motion control of the arm is based on AFC strategy. A class of PID control method is also employed for benchmarking.
- Two intelligent methods using FL and IL algorithms are utilised to compute the estimated inertial parameters of the system within the AFC loop.
- Design and development of an experimental PAM actuated two-link planar system for validation and comparison.

1.6 Research Methodology

The project is divided into five main stages. The stages are modelling and simulation, controller design, design and development of the rig, experimentation and performance analysis. Mechatronic system design approach involving the synergy of mechanical, electrical/electronics and computer (software) control would be the main feature of the research methodology. The more detailed description of the research methodology is described in the following sub sections.

1.6.1 Modelling and Simulation

As part of the mechatronic design process and prior to simulation, the system has to be sufficiently modelled to include rigorous manipulation of the governing mathematical equations representing the system dynamics and kinematics. The modelling will take into account realistic and valid assumptions related to the main dynamics of two-DOF robot arm, PAM actuator and disturbances based on the classic Newtonian mechanics. Other components such as the controllers (PID and AFC), reference inputs and the intelligent algorithms were mostly modelled based on typical procedures described in the literature. Simulation study shall include the evaluation of the system's performance and robustness against the highly nonlinear behaviour, hysteresis, and time-varying parameter of the actuators. Comparative study between the control strategies shall also be done to provide a useful platform in determining the best control method. The simulation works shall provide a good basis for designing and developing the experimental rig in later stages. MATLAB and Simulink software shall be the main design tool used for the simulation study. Later, the same simulation can be used through a HILS technique that integrates the hardware (sensors and actuators) and the software via MATLAB, Simulink and Real Time Windows (RTW) Target facility.

1.6.2 Controller Design

Two main control methods were employed in the study using PID and AFC methods. Both involve the use of simple control algorithms. In the former, the controller parameters were obtained using the heuristic method through One-Value-at-A-Time (OVAT) technique which is deemed sufficient. The robot PID control (with all the relevant models considered, i.e. the dynamics of the robot arm, PAM actuator, sensor, etc.) can be executed to observe the system performance.

Next the AFC technique is coupled directly to the PID controller. The AFC parameters were acquired through perfect modelling of the sensors (for the torque and acceleration measurements) and intelligent inertia matrix estimators via the FL and IL algorithms. The intelligent algorithms were deliberately selected so that their practical implementation in real-time is feasibly and readily applied to compute the required parameters continuously and on-line as the system actually operates. Their role in the proposed AFC-based scheme is indirect and supplementary in the sense that they do not directly interfere with the controller main algorithm but rather provide a method to complete the compensation strategy.

1.6.3 Design and Development of the Experimental Rig

The design and development of the proposed system is in-line with the *Mechatronics* approach. In this approach, all the main aspects or disciplines of the system are simultaneously or concurrently designed and integrated unlike the traditional approach which is typically more sequential and segregated in nature. This involves the integration of a number of classical engineering disciplines namely, the mechanical, electrical/electronics and computer-based control. A complete integration of the mentioned disciplines is thus very essential to realise a mechatronic product.

- **Mechanical:** Mechanical design initially involves the conceptual design of the physical two-link planar arm. A number of factors and suitable design criteria should be carefully considered in the design process. The design process will include conceptual and final design of the robot involving the development of suitable mechanisms, static and dynamic analysis of the structure of the system, selection of materials and others which are all referred to and should comply with the pre-determined design criterion. A finalized design will be subsequently chosen with the detailed production drawings ensued for fabrication purposes. Some of the mechanical aspects of the system such as the computation of the parameters for the length of pneumatic artificial muscle, dimensions of the system structure or parts can be obtained and/or manipulated from the simulation study. The design should also take into account the ease of the fabrication of the parts to be processed.

- **Electrical/Electronics:** The selection of the actuator system should be based on the force analysis of the system to ensure proper actuation of the system is achieved. Pneumatic artificial muscle-with high power-weight ratio, compliant nature and whereas their behavior is like muscle can be a suitable actuator to derive a robotic arm. A good knowledge and skill in electronics assembly is highly desirable at this stage. Again, the outcome from the simulation works help in determining for example the size (power, force, torque etc.) of the actuators to be used.

- **Computer-based Control:** The next stage will involve rigorous computer interfacing and control involving data acquisition process through the DAQ card and a PC for software control. Matlab and Simulink serve as the link between the mechanical and electrical/electronics components.

1.6.4 Experimentation

When the mechatronic system prototype is ready, experimental procedures will be drafted and testing will be done to validate the effectiveness and the robustness of the control strategy. Possible modification of the system can be carried out at this stage to enhance the system’s performance. Experimentation will be rigorously carried out to test the effectiveness of the proposed system. The tests will take into account various operating and loading conditions.

1.6.5 Performance Evaluation and Analysis

The systems performance will be critically evaluated and analyzed based on the trajectory tracking capability (accurate position control) of the schemes considering the effect of inherent non-linearities and disturbances in the system. The trajectory tracking errors produced by the respective control schemes shall be the basis for the study of the performance in executing the given tasks. This includes the results obtained from both the simulated and experimental rig developmental activities. The research outcomes should provide insights and information which would be useful for future development, improvement and expansion of the system. In addition to that, suggestion for further research works will also be outlined.

Figure 1.1 shows the flow chart of the proposed research methodology.

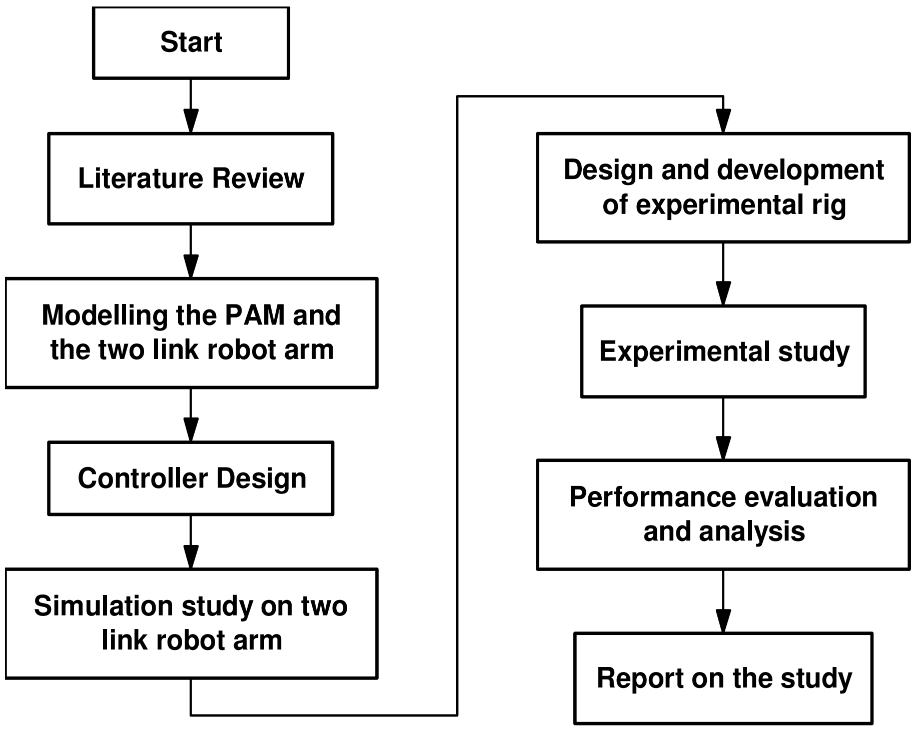

Figure 1.1: Implementation of the research project

1.7 Organization of Thesis

The thesis is organized into five chapters. In Chapter 2, the fundamental concepts, underlying theories and reviews of the main topics of research pertaining to modelling of the kinematics and dynamics of the robotic arm and its control, pneumatic artificial muscle, PID control, AFC, FL and IL algorithms are described. The modelling of the two link planar resembled as human-like arm and principles, characteristics and modelling of pneumatic artificial muscle are described as this provides the basis for the simulation of the control system. Next, the principles of the PID and the pure AFC method are discussed with special attention focused on the method to enhance the strategy using intelligent means, namely IL and FL methods. An inertia matrix estimation method using fuzzy logic for an AFC scheme is presented. The fuzzy logic mechanism computes the estimated inertia matrix (IN) automatically and continuously, while the robot arm is tracking the reference input that is followed by AFC incorporate with iterative learning (AFCIL). IL is embedded in the AFC strategy to estimate the estimated inertia matrix (IN) to control the performance of the robot arm.

Chapter 3 presents the simulation study of proposed controllers, AFCIL and AFCAFL based on some of the theoretical concepts and principles derived from previous chapter. Then, the comparative study of the proposed control schemes is described with a particular emphasis laid on the technique used to compute the estimated inertia matrix and the trajectory track performance of the proposed control schemes.

The experimental study is done in Chapter 4 to compliment the theoretical works. Mechatronics concept is applied here as it involves the rigorous integration of the mechanical, electronics and computer control disciplines.

Finally, Chapter 5 concludes the research project and the directions for the future works are outlined. Some of the additional materials pertaining to sketch of rig parts, mechatronics parts catalogue, publications and achievements related to the research are enclosed in the appendices.