MECHATRONIC DEVELOPMENT OF AN IN-PIPE MICROROBOT WITH INTELLIGENT ACTIVE FORCE CONTROL

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To my beloved Atena

And my beloved Mother and Father

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ABSTRACT

In this research, the development of an in-pipe microrobot system with intelligent active force control (AFC) capability was investigated and presented, including both simulation and experimental studies. Three actuated microrobot mechanisms driven by pneumatic, piezoelectric and voice-coil actuators were modelled and simulated in a constrained environment inside a pipe. The mechanisms were then embedded into the proposed AFC-based control strategy. The worm-like movement of these microrobots with the respective actuators were effectively modelled using the impact drive mechanism (IDM). A classic proportional-integral-derivative (PID) controller was first designed and applied to the microrobot system to follow a desired trajectory in the presence of disturbances, which may be created due to the frictional force or fluid viscosity inside a pipe. Later, an AFC-based controller was utilized to enhance the system dynamic performance by robustly rejecting the disturbances. To estimate the inertial mass of the AFC loop, artificial intelligence (AI) techniques, namely the variants of fuzzy logic (FL) and iterative learning algorithms (ILA) were explicitly employed. The dynamic response of the fully developed model of the in-pipe microrobot systems (with three different actuators) subject to various input excitations and disturbances was rigorously explored and numerically experimented. This involved the parametric study and sensitivity analysis to observe and to analyse the effects of a number of influential parameters that were deemed to have positive impact on the system performance. The simulation work was validated through an experimental investigation performed on a rig prototype that employed the voice-coil actuated mechanism to drive the selected AFC-based microrobot scheme, considering the given operating and loading conditions. Full mechatronic approach was adopted in the design of the rig by integrating the related sensors, actuator, mechanical parts and digital controller in a hardware-in-the-loop simulation (HILS) configuration. Parametric study was carried out to complement the simulation counterpart by taking into account the different settings and working environments. From the experimental results, the developed in-pipe microrobot system was proven to be effective and robust in its trajectory tracking, in spite of the existence of various excitation inputs and external disturbances. This implied that the produced experimental responses were in good agreement with those acquired via simulation. The outcomes of the study shall provide a strong foundation for furthering the design of specific in-pipe microrobot applications, such as visual inspection of the inner surface of pipes, fault-diagnostics, obstacle removal and other related tasks.

ABSTRAK

Pembangunan satu sistem robot mikro dalam paip dengan keupayaan kawalan daya aktif pintar (AFC) telah dikaji dan dipersembahkan dalam kajian simulasi dan eksperimen. Tiga jenis mekanisme penggerak robot mikro, iaitu penggerak pneumatic, piezoelektrik, dan voice-coil telah dimasukkan ke dalam strategi kawalan berasaskan-AFC, dan disimulasikan seterusnya dengan mempertimbangkan beberapa operasi dan keadaan beban di dalam persekitaran paip yang terhad. Robot mikro yang mempunyai pergerakan seperti cacing telah dimodelkan secara efektif dengan menggunakan mekanisme penggerak hentaman (IDM). Pengawal klasik berkadaran-kamiran-terbitan (PID) telah direka bentuk terlebih dahulu dan diaplikasikan kepada sistem robot mikro untuk menjejaki trajektori kehendak dengan kehadiran gangguan akibat daripada daya geseran atau kelikatan cecair dalam paip. Kemudian, pengawal berasaskan AFC digunakan untuk meningkatkan prestasi sistem dinamik berdasarkan kekukuhannya untuk menangkis gangguan. Dalam penganggaran jisim inersia bagi gelung AFC, teknik kepintaran buatan (AI) melalui variasi logik kabur (FL) dan algoritma lelaran pembelajaran (ILA) telah digunakan secara khusus. Respons dan gerak balas dinamik bagi model sistem robot mikro dalam-paip yang telah dibangunkan sepenuhnya (dengan tiga penggerak berbeza) dan tertakluk kepada pelbagai ujaan masukan dan gangguan telah dikaji dengan rapi melalui eksperimen numerical (simulasi). Ini melibatkan kajian parametric dan analisis sensitiviti untuk memerhati dan menganalisis kesan beberapa parameter berpengaruh yang dianggap mempunyai kesan positif terhadap prestasis sistem. Sebahagian proses simulasi disahkan melalui kajian eksperimen ke atas prototaip rig yang menggunakan mekanisme penggerak voice-coil untuk memacu robot mikro berasaskan skema AFC, dengan mengambil kira operasi dan beban keadaan yang telah diberikan. Pendekatan mekatronik yang sempurna telah diguna pakai dalam merekabentuk rig, di mana alat penderia, penggerak, bahagian mekanikal dan pengawal digital telah diintegrasikan bersama melalui konfigurasi simulasi perkakasan di dalam gelung (HILS). Kajian parametrik dijalankan untuk mengambil kira persekitaran dan penetapan yang berbeza berpandukan simulasi sebelum ini. Keputusan eksperimen jelas menunjukkan keberkesanan penjejakan trajektori sistem robot mikro dalam-paip yang telah dibangunkan, walaupun terdapatnya pelbagai ujaan masukan dan gangguan luar. Ini dengan jelas menunjukkan bahawa keputusan yang dihasilkan melalui eksperimen fizikal mempunyai banyak persamaan dengna hasil simulasi. Hasil kajian menyediakan satu asas yang kukuh untuk memajukan reka bentuk yang spesifik untuk aplikasi robot mikro dalam paip seperti pemeriksaan visual permukaan paip, diagnostik kegagalan, penyingkiran halangan dan lain-lain tugas yang berkaitan.

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LIST OF ABBREVIATIONS

ADC	-	Analogue to Digital Convertor
ADDA	-	Analogue to Digital-Digital to Analogue
AI	-	Artificial Intelligence
AFC	-	Active Force Control
AFCFL	-	Active Force Control with Fuzzy Logic
AFCILA	-	Active Force Control with Iterative Learning Algorithm
AFCILA-P	-	Active Force Control with Iterative Learning Algorithm and Proportional Control
AFCILA-PD	-	Active Force Control with Iterative Learning Algorithm and Proportional-Derivative Control
AFCILA-PI	-	Active Force Control with Iterative Learning Algorithm and Proportional-Integral Control
AFCILA-PID	-	Active Force Control with Iterative Learning Algorithm and Proportional- Integral-Derivative Control
BEMF	-	Back Electromotive Force
CV	-	Control Volume
DAC	-	Digital to Analogue Convertor
DAQ	-	Data Acquisition Card
DAS	-	Data Acquisition System
DC	-	Direct Current
DOF	-	Degrees of Freedom
FL	-	Fuzzy Logic
FLC	-	Fuzzy Logic Controller

FLE	-	Fuzzy Logic Estimator
FLT	-	Fuzzy Logic Toolbox
FS	-	Full Scale
GA	-	Genetic Algorithm
IAE	-	Integrated Absolute Error
IDM	-	Impact Drive Mechanism
IEPE	-	Integrated Electronic Piezoelectric
IL	-	Iterative Learning
ILA	-	Iterative Learning Algorithm
IPMC	-	Ionic polymer metal composite
ISE	-	Integrated Square Error
ITAE	-	Integrated of Time multiple Absolute Error
ITSE	-	Integrated of Time multiple Square Error
LCAM	-	Linear Current Amplifier Module
LS	-	Least Square
MF	-	Membership Function
MISO	-	Multi Input Single Output
NI	-	National Instruments
NN	-	Neural Network
P	-	Proportional
PC	-	Personal Computer
PD	-	Proportional Derivative
PI	-	Proportional Integral
PID	-	Proportional, Integral, And Derivative
PSO	-	Particle Swarm Optimization
SIDM	-	Smooth Impact Drive Mechanism

SMA	-	Shape Memory Alloy
TULA	-	Tiny Ultrasonic Linear Actuator

LIST OF SYMBOLS

A	-	Cross area of pipe
a_{act}	-	Actual acceleration
a_{ref}	-	Reference acceleration
C_1, C_2	-	Pneumatic capacitances
C_p	-	Damping coefficients of the piezoelectric actuator
d	-	Decay coefficient
e	-	Error
$\dot{e}$	-	Rate of change of error
e_k	-	Error signal for ILA
E	-	External supply
F	-	Applied force
F_a	-	Actuator force
F_d	-	Disturbing force
F^*_d	-	Estimated disturbance
F_f	-	Frictional force
F_N	-	Total normal force acting on the sliding surface
F_p	-	Piezoelectric force
F_{VCA}	-	Voice-coil actuator force
g	-	Acceleration of gravity=9.81 m/s^2
$G(s)$	-	Dynamic system transfer function
$G_a(s)$	-	Actuator transfer function
G_c	-	Transfer function of controller
G_s	-	Transfer function of sensor
I	-	Applied current
K_1, K_2, K_3	-	Spring stiffness
K_F	-	Back electromotive force constant
K_c	-	Critical gain

K_D - Derivative gain

K_F - Force sensitivity

K_I - Integral gain

k_p - Stiffness coefficient of the piezoelectric actuator

K_P - Proportional gain

$k(t)$ - Number of iteration

L - Inductance of the coil

m - Mass

$\dot{m}$ - Mass rate

m_1 - Mass of the main body

m_2 - Mass of the small body

m_{act} - Actual mass

m_{VCA} - Mass of voice-coil actuator

N - Perpendicular force

P_1 - Input pressure

P_2 - Output pressure

Q - Disturbances

R - Bladder constant

T - Temperature

T_c - Oscillation period

u - Fluid velocity

u_k - Input signal for ILA

u_{k+1} - New input signal for ILA

μ - Friction coefficient

μ_s - Static frictional coefficients

μ_k - Kinetic frictional coefficients

v - Velocity of the cylinder

V - Applied voltage

x_1 - Displacement of the main body

x_2 - Displacement of the small body

x_{act} - Actual displacement

$x_{actuator}$ - Displacement of actuator

x_d - Desired displacement

x_{ref} - Reference displacement

X_{VCA} - Displacement of voice-coil actuator

$\dot{x}_p$ - Reference velocity

y - Desired output for ILA

y_k - Output signal for ILA

α - Acceleration

Ψ - Integral learning parameter

Φ - Proportional learning parameter

Γ - Derivative learning parameter

ρ - Density

τ - Shear stress

ϑ - Dynamic viscosity

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CHAPTER 1

INTRODUCTION

1.1. Research Background

Nowadays, microrobots are widely used in a number of engineering applications since robots of this type may be able to operate in unstructured environments thanks to their enhanced adaptability to operate effectively, even under hostile conditions such as radioactivity, electromagnetic field and high temperature gradients. For industrial applications, microrobots and micromechanisms have found more applications like equipping with appropriate instrument or micro tools which make them more beneficial. On the other hand, the application of interest is the operation of microrobot in unreachable or hazardous pipes that can perform a number of tasks such as in-pipe inspection, fault diagnostics, condition monitoring and obstacle removal. Detection or maintenance inside pipes is a very common application for in-pipe microrobots. This type of application is often related to difficulties such as unreachability (size restriction) or hazardous environments (poisonous gas). The establishment of microrobots for in-pipe applications is based on navigation, maintenance, obstacle removal, or fault detection abilities. Inside pipes there are also different constraints that the mechanism should adapt to like different pipe diameter or different inner surface.

1.2. Problem Statements

In this decade, microrobots are widely used in a number of engineering applications such as high-precision manipulation system, intelligent micro-transportation system, support surgical operation, and others. One of the major applications of these types of robots is in-pipe application, in which microrobots are able to operate in unstructured environments because of their enhanced adaptability to operate effectively, even under hostile conditions such as radioactivity, electromagnetic field and high temperature gradients. Mechatronic development of in-pipe application microrobot systems embedded with intelligent active force control strategy is presented and investigated in this research.

The proposed microrobots are driven by pneumatic, piezoelectric and voice-coil actuators which are modelled and simulated with AFC-based control strategy. The intelligent active force control strategy is applied to the proposed microrobot systems and the performance of the controller in rejection of disturbance is investigated. Based on the advantages and benefits of the proposed actuators, voice-coil actuated microrobot is selected for experimental study. An experimental rig was set up including the integration of the related sensors, actuator, mechanical parts and digital controller via a hardware-in-the-loop simulation configuration. Outcomes of the study provide a strong foundation for furthering the design of specific in-pipe microrobot applications such as visual inspection of the inner surface of pipes, fault-diagnostics, surface machining, obstacle removal and other related tasks. Finally, a comparative study among the proposed intelligent control schemes and some design features (spring compression, mass material, inner pipe surface, inclined surface and etc) was carried out.

1.3. Research Objectives

This research focuses on the mechatronic design and development of a novel intelligent AFC scheme for the proposed in-pipe application microrobot mechanisms. Hence, three main objectives of thesis are as follows:

- To present three different microrobot mechanisms driven by pneumatic, piezoelectric, and voice-coil actuators

- To model, simulate, and control the proposed system using intelligent AFC method

- To validate the overall proposed system through experimentation and evaluation performed on a developed physical test for voice-coil actuated microrobot

To achieve these objectives, the following sub-objectives are considered:

- To derive and develop the mathematical model of the microrobot systems to study the kinematic and dynamic behaviour of the system

- To implement a robust and effective feedback control scheme for the proposed microrobot systems through a comprehensive simulation study

- To reduce the effect of disturbance through the intelligent AFC method (AFCILA and AFCFL)

- To design and develop an experimental rig employing mechatronic approach for voice-coil actuated microrobot

- To evaluate the performance of the controller through simulation and experimental study for voice-coil microrobot

1.4. Scope of Research

The scope of this research comprises the following:

- Propose three microrobot mechanisms for in-pipe application driven by pneumatic, piezoelectric, and voice-coil actuators
- Derive the kinematic and dynamic equations of microrobot mechanisms based on the type of mechanism, actuator, and movement.
- Design suitable feedback controllers based on the PID and AFC strategies for simulation study
- Apply intelligent techniques (FL and ILA) to AFC strategy for robust movement for the time that the system is under disturbance
- Carry out a comparative study of the proposed control schemes
- Employ a Voice-coil actuated microrobot mechanism for the experimental rig
- Perform experimental validation of the intelligent AFC algorithm on the developed voice-coil actuated microrobot
- Investigate the performance of the control systems under different case studies and input excitations
- Equip the microrobot with a laser pointer for specified application and a wireless high definition video scope inspection camera

- Consider the effects of different conditions (friction, disturbance, pipe surface, microrobot material, and etc) on microrobot movement

1.5. Research Significance and Contribution

This research focuses on the mechatronic design of a new control system to control movement effectively and suppress unwanted disturbances of in-pipe application microrobots driven by pneumatic, piezoelectric and voice-coil actuators. Voice-coil actuated microrobot is selected for mechatronic approach and there is no background with voice-coil actuators for this kind of motion and application. By assuming some conditions inside the pipe, the derived kinematic and dynamic equations are unique. Intelligent AFC as a robust strategy was shown to be a powerful disturbance rejecter is applied as main control scheme of the system. External force as disturbance effect is applied to the microrobot and effectiveness of intelligent AFC to perform robust movement is examined. There is no published research in which AFCILA or AFCFL is applied to this type of in-pipe application microrobot. This research attempts to present an in-depth investigation of intelligent AFC controller incorporated to voice-coil actuated microrobot and show how the controller rejects the unwanted disturbances effectively and controls the movement of robot precisely by experimental and simulation studies.

A brief outline of the main contributions of this research is given in this subsection as follows:

- A comprehensive kinematic/dynamic model that justifies the dynamic characteristics of microrobot mechanisms which are driven by pneumatic, piezoelectric, and voice-coil actuators

- A novel in-pipe application microrobot driven by voice-coil actuator

- A novel AFC algorithm to control system behaviour in order to reject unwanted disturbance while moving inside the pipe

- Intelligent algorithms applied to the main controller of system (AFC) to find the parameters of the controller by programming the related codes inside LabVIEW software

1.6. Research Methodology

The project is divided into five main stages i.e.; literature review, modeling and simulation, design and development of the experimental rig, experimentation and performance evaluation, and analysis. *Mechatronic* approach involving the synergy of mechanical, electrical/electronic and computer control would be the main feature of the research methodology. More detailed description of the research methodology is as follows:

1.6.1 Literature Review

In-pipe application microrobot mechanisms and their application, available actuators and mechanisms are first reviewed based on previous studies. PID and AFC controllers are also introduced and reviewed in the second section. Finally, intelligent algorithms like FL and ILA which are used to determine specifications of controllers intelligently are reviewed.

1.6.2 Modelling and Simulation

Prior to the performance evaluation of the proposed model of the system, the modelling and simulation phase include the mathematical equations, representing the system's dynamics and kinematics is presented. The modelling will take into account realistic and valid assumptions related to the physical systems. Three suitable and practical microrobot mechanisms driven by pneumatic, piezoelectric and voice-coil actuators are introduced based on real physical system. A number of intelligent methods such as Fuzzy Logic (FL) and Iterative Learning Algorithm (ILA) will be studied and later implemented with the AFC strategy to control the system robustly. Simulation works shall include the evaluation of the system's performance and robustness against the disturbance. Differences in the design parameters, environmental situations, simulation, and learning algorithms shall also be taken into account. Comparative study between the control strategies shall also be done to provide a useful platform in determining the best control method. The simulation works serve as a basis for designing and developing the experimental rig in later stages. MATLAB and Simulink software's shall be the main tool for the simulation study.

1.6.3 Design and Development of Experimental Rig

The design and development of the experimental rig is based on *Mechatronics* approach. In this approach, all main important aspects of mechanism and environmental situation are considered. 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 very essential to realize a mechatronic product.

- **Mechanical**

Mechanical design initially involves the conceptual design of in-pipe application microrobot driven by voice-coil actuator. A number of factors and suitable design criteria should be carefully considered in the design process. The design process will involve the development of suitable mechanisms, dynamic analysis of the structure of the system, selection of materials and others which should all comply with the pre-determined design criterion. A finalized design for voice-coil actuated microrobot will be subsequently chosen with the detailed production drawings ensured for fabrication purposes. Some of the mechanical aspects of the system such as the computation of the parameters for the actuator, mass and shape of masses, 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 and sensors should be based on the advantages comparison to ensure proper actuation of the system is achieved. Voice-coil actuator is suitable to be used in the system with some powerful specifications related to other actuators and its novelty. Voice-coil actuator should be driven by a set of suitable power supply and related amplifier. A good knowledge and skill in electronics assembly is highly desirable at this stage. Again, the outcome of the simulation works help in determining for example the size (power, force, friction etc.) of the actuators to be used.

- **Computer-Based Control**

The next stage is involve rigorous computer interfacing and control involving data acquisition process through the use of *analogue to digital, digital to analogue* (ADDA) card and a PC/Laptop for software control. All the sensors and actuator shall be connected to a PC-based data acquisition system (DAS). All the important elements are later integrated and fully tested prior to the experimentations. Matlab, Simulink, and LabVIEW serve as the link between the mechanical, electrical, and electronics components.

- **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. An experimental rig prototype shall be designed and developed using full mechatronic approach involving the integration mechanical engineering, electrical, electronic and computer control elements for voice-coil actuated microrobot. The design of the rig shall be largely based on the parameters and results obtained from the theoretical and simulation study carried out earlier since the main aim of developing the rig is in fact to complement simulation counterpart. Experimentation will be rigorously carried out to test the effectiveness of the proposed control scheme. The tests will take into account various operating and loading conditions like applied voltage, applied frequency, different masses, pipe surface, etc. Finally, the outcomes of the research are summed up.

1.6.4 Performance Evaluation and Analysis

The system performance will be critically evaluated and analyzed based on the capability of the control schemes. An experimental rig is setup and tested to validate the AFCILA scheme. A comparative study of the proposed schemes in terms of their performance and differences shall also be presented in the research. The research outcomes should provide the information which would be useful for future development, improvement and expansion of the system. In addition to that, suggestions for the further research works will also be outlined.

The flowchart presented in Figure 1.1 describes the research methodology considered in this thesis.

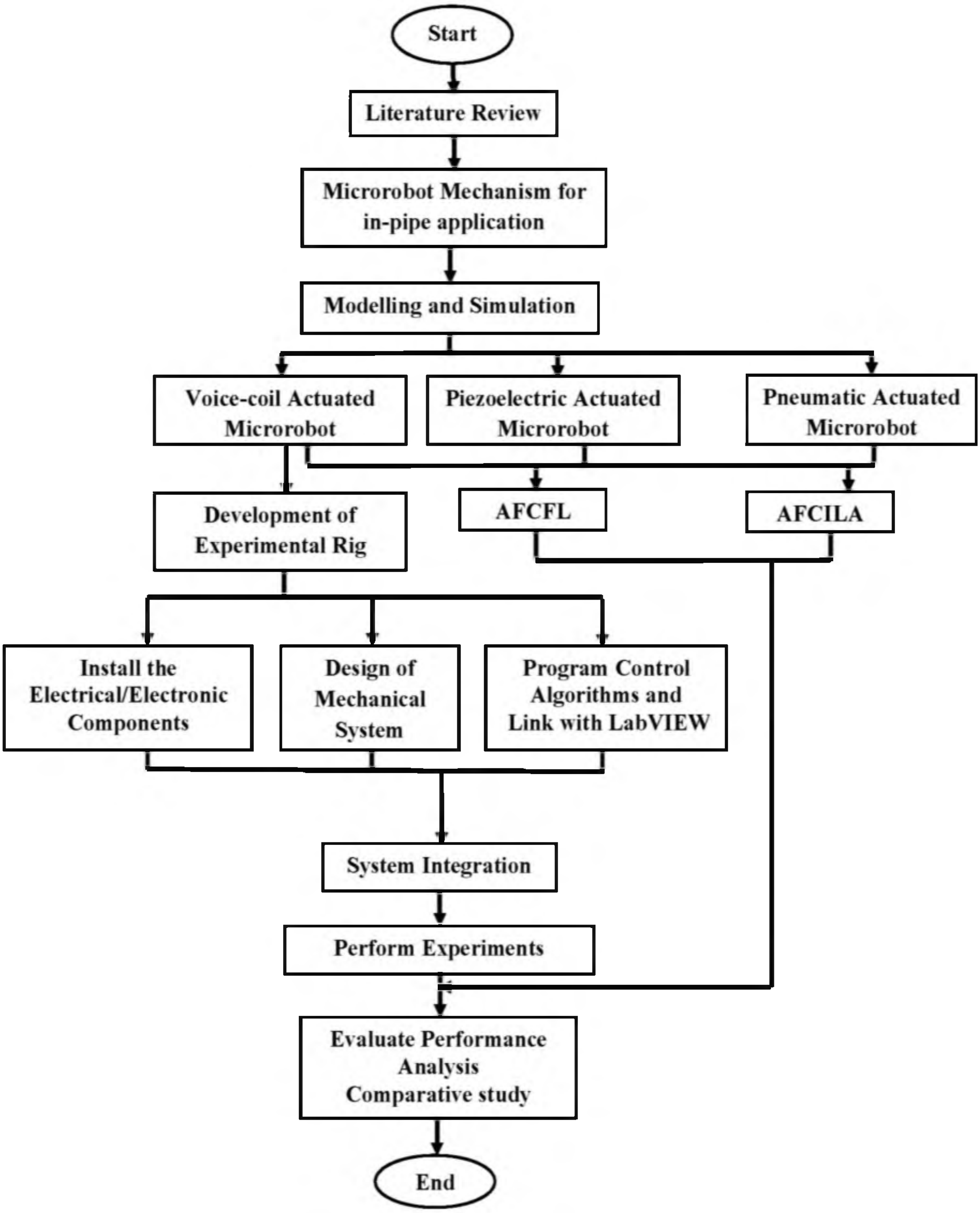

Figure 1.1 Flow chart of research procedure

1.7. Organization of Thesis

This thesis is organized into eight chapters. A brief outline of the contents of the thesis is as follows:

Chapter 1 presents an introduction to the research problem. It involves the background and significance of the research as well as the problem statement and contributions. The logical flow and structure of the thesis are also outlined in this chapter.

Chapter 2 is devoted to literature study that has been carried out related to subjects concerning this thesis. Firstly, the types and classifications of microrobots and their actuators are studied. Secondly, Impact Drive Mechanism (IDM) and its application on microrobots are reviewed and discussed. Thirdly, the applications of PID and AFC strategy are described. Finally, intelligent techniques including ILA and FL are described and reviewed due to their application in next chapters.

Chapter 3 focuses on introducing principle of three proposed mechanisms driven by pneumatic, piezoelectric, and voice-coil actuators. Mathematical formulations of proposed microrobots are done. Kinematic/dynamic relations of microrobots are derived to model the systems and find transfer functions.

Chapter 4 presents the application and principles of the PID and AFC methods. FL and ILA which are employed as intelligent methods to estimate the value of mass required in AFC loop are introduced. The optimum learning parameter as well as appropriate stopping criteria for the mentioned ILA is proposed based on the simulation. The microrobot mechanisms are studied when the simulated model is excited by disturbing signals and the performance of AFCFL and AFCILA in suppressing the unwanted disturbance is investigated. First, different types of signals are input to system. After that, of the system after applying disturbance is considered.

Chapter 5 focuses on mechatronic design and evaluation of the experimental rig. An in-pipe application microrobot actuated by voice-coil is developed and fabricated. The control action is applied to the voice-coil actuator through a data acquisition system which has been connected to a PC equipped with LabVIEW software. The control algorithm is coded using the LabVIEW graphical programming. Performance of the intelligent control system is evaluated through experimental measurements. Different case-studies are prepared by altering the design parameters (mass material, spring stiffness, friction, etc.) which are then compared together and their effects on the output response are studied.

Chapter 6 describes the comparative study among the proposed control schemes presented in the previous chapters. The effectiveness and imperfections of the each technique is described and compared with each other.

Chapter 7 sums up the research project and the directions for the future research works are outlined.

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