

Linear Actuators for Locomotion of Microrobots

by

Haiwei Lu

M.Eng., B.Eng. (Elec.)

**Submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy**



University of Technology, Sydney

June 2007

CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Name of Candidate: **Haiwei Lu**

Signature of Candidate:

Production Note:

Signature removed prior to publication.

03/10/2007

To my mother, my wife, and my daughter

ABSTRACT

The successful development of the miniaturisation techniques for electronic components and devices has paved the way for the miniaturisation in other technological fields. In the past two decades, the research achievements in micromechatronics have spurred fast development of micro machines and micro robotic systems. Miniature or micro actuators are the critical components to make these machines more dexterous, compact and cost effective.

The main purpose of this dissertation is to develop micro actuators suitable for the locomotion of an in-pipe or endoscopic microrobot. The content of the thesis covers the selection of the actuation principle, robotic system design, actuator design and prototype construction, performance analysis, and design, analysis, and implementation of the appropriate drive control system.

Among different types of actuation principles, piezoelectric and electromagnetic actuators are the two major candidates for the micro robotic systems. In order to find a suitable actuation principle for the desired robotic application, a comparative study was conducted on the scaling effects, attainable energy density, and dynamic performances of both types of actuators. Through the study, it was concluded that the electromagnetic actuator is more suitable for the endoscopic microrobot.

Linear actuators are the common design used for the locomotion of microrobots due to many advantages compared to their rotational counterparts. Through a thorough review and comparison of the electromagnetic linear actuator topologies, a moving-coil tubular linear actuator was chosen as the first design due to its simplest structure. Via the magnetic circuit analysis and numerical magnetic field solutions, the actuator was designed for optimum force capability, and the electromagnetic force and the machine parameters of the actuator were predicted. According to the results obtained from the magnetic field analysis, the dynamic model of the actuation system with a driving

control scheme was established and used in the actuation performance analysis of the robotic system.

Based on the experience achieved through the first design, a new moving-magnet tubular linear actuator was designed. The methodology developed in the design and analysis of the moving-coil linear actuator was adopted for the moving-magnet actuator design. However, the optimal design is more complicated due to the multi-pole and multi-phase structure of the moving-magnet actuator. The electromagnetic force of the actuator was analysed under the condition of different excitation methods. An enhanced parameter computation method is proposed for predicting the actuator parameters. Based on the results of magnetic field analysis, a comprehensive dynamic model of the actuator was developed. Through the coupled field-circuit analysis, this model can predict accurately the dynamic performance of the actuator. The characteristics analysis shows that the performance of the moving-magnet actuator is much better than that of the moving-coil actuator.

Two prototypes of the moving-magnet tubular linear actuator with different dimensions were constructed to verify the performance and the scaling theory. Various precision machining techniques were employed during the fabrication. The performances and parameters of the two different prototypes were measured and the results agree substantially with the theory.

The brushless DC drive method was chosen for the driving control of the proposed linear actuator because of the compact circuit topology and simple implementation, which are two essential factors for micro applications. A sensorless control scheme based on the back EMF was developed as physical position sensors are not permitted in such a micro system. The control scheme was then applied to the locomotion control of the proposed microrobot. The system simulation shows that the control performances of both the actuator and microrobot are satisfactory.

A dSPACE prototyping system based driving control hardware was designed and implemented to experimentally verify the control design. The experimental results agree substantially with the theoretical work.

ACKNOWLEDGMENTS

I am gratefully indebted to my supervisor, Prof. Jianguo Zhu, for his inspiring guidance and encouragement throughout the development of this thesis. His valuable comments and suggestions definitely improved the quality of entire research work.

I wish to express my gratitude to my co-supervisor, A/Prof. Quang Ha for his helpful advice and support.

I also wish to express sincere thanks to Dr. Youguang Guo, Dr. Zhiwei Lin, Mr. Ram Chamdru, Miss Ying Yan, Dr. Peter A. Watterson, Dr. Greg Hunter, and other colleagues in the Centre for Electric Machines and Power Electronics (CEMPE), UTS, for their fruitful discussions, advices and assistances.

Many thanks are due to the staff in the faculty's workshop, i.e. Mr. Ron Smith and Mr. Richard Moore, for their elaborate mechanical work in the manufacturing of the prototypes. Without their professional job, the project would not be successful.

I feel very grateful to Mr. Jiang Chen of the CEMPE Laboratory for his assistance in preparing equipments and experimental setup for the parameter and performance tests. Thanks also go to Mr. Russell Nicholson for his support and advice.

Acknowledgements go to Mr. David Baer, Manager of the Laser Micromachining Solutions (LMS) in Macquarie University, Sydney, for providing the laser cutting services in manufacturing the prototype components.

Special gratitude goes to Mr. Adam Goldsmith and Dr. Shuli Jiao in CHK GridSense Pty. Ltd. for their understanding and support during my thesis work.

Thanks also go to the Department of Education, Training and Youth Affairs, Australia, for providing an International Postgraduate Research Scholarship (IPRS), which allowed me to carry out four years of PhD study.

Last but not the least, my heartfelt gratitude goes to my beloved wife, Wei Li, for her patience, sacrifices, and great support during this work, to my mother and sister in China for their consistent love and encouragement, and to my lovely daughter, Yonghan (Renée) Lu, who brings a lot of happiness into my life, and therefore I would like to dedicate this work to them.

TABLE OF CONTENTS

DECLARATION	i
ABSTRACT	iii
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vii
LIST OF SYMBOLS	xv
LIST OF ACRONYMS	xx
LIST OF FIGURES	xxii
LIST OF TABLES	xxxiv
Chapter 1 INTRODUCTION	1
1.1 Background	1
1.2 Thesis Overview	4
Chapter 2 LITERATURE SURVEY	8
2.1 Introduction	8
2.2 Microrobots	9
2.2.1 Introduction to robotics	9
2.2.2 Micromechatronics	10
2.2.3 Micro machines and micro robots	12
2.2.4 Applications of micro robots	18
2.2.5 The state-of-the-art	20
2.2.5.1 Walking/jumping microrobots	21
2.2.5.2 In-pipe microrobots	32
2.2.5.3 Swimming microrobots	41
2.2.5.4 Medical microrobots	44

2.3 Actuators for Microrobots	54
2.3.1 Hydraulic/Pneumatic actuators	55
2.3.2 Electromagnetic actuators	59
2.3.3 Piezoelectric actuators	68
2.3.4 Shape memory alloy actuators	75
2.3.5 Electrostatic actuators	78
2.3.6 Electrostrictive and magnetostrictive actuators	82
2.4 Conclusion	84

Chapter 3 PIEZOELECTRIC AND ELECTROMAGNETIC ACTUATORS

– A COMPARATIVE STUDY	86
3.1 Introduction	86
3.2 Scaling Effect	87
3.2.1 Scaling of piezoelectric actuators	88
3.2.2 Scaling of electromagnetic actuators	92
3.2.2.1 Actuator with electromagnet	93
3.2.2.2 Actuator with permanent magnet	98
3.3 Power Density Limitations	102
3.4 Analytical Performance Analysis - A Case Study	104
3.4.1 Structures of the actuators for comparison	105
3.4.2 Analytical study of the piezoelectric actuator	106
3.4.2.1 Equivalent circuit model for a T-effect transducer	106
3.4.2.2 Dynamic performance of the actuator	108
3.4.2.2.1 Actuator with no load	108
3.4.2.2.2 Actuator with external load	110
3.4.2.2.3 Attainable force and displacement	112
3.4.3 Analytical study of the PM type electromagnetic actuator	113
3.4.3.1 Thickness of the permanent magnet	114
3.4.3.2 Dynamic performance of the actuator	114
3.4.4 Quantitative comparison with specified dimensions	117

3.4.4.1 Electromagnetic actuator	117
3.4.4.2 Piezoelectric actuator	117
3.4.5 Piezoelectric actuator vs. Electromagnetic actuator	118
3.5 Actuator for an In-pipe/Endoscopic Microrobot	119
3.6 Conclusion	122

Chapter 4 DESIGN METHODOLOGY AND THE FIRST ATTEMPT:

A MOVING-COIL LINEAR ACTUATOR	123
4.1 Introduction	123
4.2 Linear Electromagnetic Actuator – A Brief Overview	124
4.2.1 General concept of linear electromagnetic machines	124
4.2.2 Types of linear electromagnetic machines	125
4.2.2.1 AC linear machines	125
4.2.2.2 DC linear machines	128
4.2.3 PM Linear machines	130
4.2.3.1 Moving-magnet machines	130
4.2.3.2 Moving-armature machines	131
4.2.3.3 Moving-coil machines	131
4.2.3.4 Comparison of PM linear machines	132
4.3 General Design Methodology of the Electric Machines	133
4.3.1 Basic procedure of machine design	134
4.3.2 Advanced design and analysis techniques	136
4.3.2.1 Numerical electromagnetic field analysis	136
4.3.2.2 Combined field-circuit simulation	137
4.4 Design of a Moving-coil Linear Actuator	138
4.4.1 Structure, materials and dimensions	139
4.4.2 Determination of the magnet thickness	142
4.4.2.1 2D FE model of the actuator	143
4.4.2.2 The electromagnetic field solutions	145
4.4.2.3 Linear 2D FE magnetic field analysis	146

4.4.2.4 Non-linear 2D FE magnetic field analysis	148
4.4.3 3D magnetic field analysis of the actuator	149
4.5 Calculation of Machine Parameters	152
4.5.1 Calculation of coil resistance	152
4.5.2 Calculation of coil inductance	153
4.6 System Modelling and Performance Analysis	156
4.6.1 Dynamic modelling of the moving-coil linear actuator	156
4.6.2 Kinetic modelling of the robotic system	157
4.6.3 Dynamic model of the microrobot	159
4.6.4 Locomotion control of the microrobot	159
4.6.5 Locomotive performance analysis	160
4.6.5.1 Masses of the microrobot	160
4.6.5.2 Elastic constant of the equivalent spring	162
4.6.5.3 Simulated locomotive performance	162
4.7 Conclusion and Discussion	165
 Chapter 5 DESIGN AND ANALYSIS OF THE MOVING-MAGNET TUBULAR LINEAR ACTUATOR	 167
5.1 Introduction	167
5.2 General Structure of Moving-magnet Tubular Linear Actuators	168
5.3 Design Considerations of PM Tubular Linear Actuators	169
5.3.1 Number of poles	170
5.3.2 Surface mounted and interior mounted magnets	171
5.3.3 Slot and slotless magnetic core	173
5.4 Design of the PM Tubular Linear Actuator	174
5.4.1 Basic structure	174
5.4.2 Major dimensions	177
5.4.3 Optimal design by magnetic circuit method	179
5.4.3.1 Equivalent magnetic circuit model	179
5.4.3.2 Electromagnetic force per pole	180

5.4.3.3 Maximum flux design	181
5.4.3.4 Maximum force design	183
5.4.4 Design summary	185
5.5 Characteristic Analysis of the Actuator	186
5.5.1 2D FE modal for the actuator	186
5.5.2 Flux density distribution	187
5.5.3 Electromagnetic force of the actuator	190
5.5.3.1 Sinusoidal excitation	190
5.5.3.2 2-phase DC excitation	192
5.5.4 Summary of the characteristic analysis	194
5.6 Calculation of the Machine Parameters	194
5.6.1 Calculation of phase resistance	194
5.6.2 Calculation of phase inductances	195
5.6.2.1 Apparent inductance vs. Differential inductance	195
5.6.2.2 Inductances in dynamic machine model	197
5.6.2.3 Calculation of differential inductances	197
5.6.2.3.1 Energy and current perturbation	197
5.6.2.3.2 Numerical solution for E/C perturbation	199
5.6.2.4 Inductances of the PM TLA	203
5.7 Dynamic Modelling of the Actuator	207
5.7.1 Flux linkages of the phase windings	207
5.7.1.1 Flux linkage and back EMF of an enclosed coil pair	207
5.7.1.2 Flux linkages of the actuator	209
5.7.2 Electrical equations of the actuator	211
5.7.3 Electromagnetic force of the actuator	214
5.7.4 Dynamic model of the actuator	215
5.7.5 Application of the dynamic model	216
5.8 Conclusion	219
Chapter 6 PROTOTYPE FABRICATION AND EVALUATION	221

6.1 Introduction	221
6.2 Construction of the Prototypes	222
6.2.1 Basics of laser cutting technology	222
6.2.2 Fabrication of stators	223
6.2.3 Fabrication of pole pieces	226
6.2.4 Construction of the translators	228
6.2.5 Assembly of the prototypes	229
6.2.6 Design of the test bench	230
6.3 Prototype-based Characteristic Analysis – A Reassessment	231
6.3.1 Considerations in magnetic modelling of the prototype	232
6.3.1.1 The pole pieces	232
6.3.1.2 The stator core	235
6.3.2 Predicted characteristics of the prototypes	235
6.4 Measurement of the Actuation Force	238
6.4.1 Measurement setup	238
6.4.2 Experimental results	239
6.5 Measurement of the Phase Inductances	240
6.5.1 Measurement setup	240
6.5.2 Experimental results	242
6.6 Conclusion	247
 Chapter 7 CONTROL OF THE LINEAR ACTUATOR	 248
7.1 Introduction	248
7.2 Operation of Brushless DC Machines and Its Sensorless Control	249
7.3 Dynamic Machine Model for Electronic Converters	254
7.3.1 Universal model for electronic converters	255
7.3.2 Dynamic model for the brushless DC drive	256
7.3.3 Implementation of the actuator model in SIMULINK	258
7.4 Drive Control of the PM TLA	265
7.4.1 Sensorless control of the actuator	265

7.4.2 Start up strategy and the detection of first commutation position	268
7.4.3 Flow chart of the sensorless control scheme	270
7.5 Performance Simulation of the Control Scheme	271
7.5.1 System model in SIMULINK	271
7.5.2 Actuation performance without load	272
7.5.3 Actuation performance with load	276
7.6 Implementation of the Actuator Control System	279
7.6.1 Introduction to dSPACE DS1104 prototyping system	279
7.6.2 Hardware of the control system	280
7.6.2.1 Hardware configuration	280
7.6.2.2 Implementation of the gate driver	281
7.6.2.3 Three-phase full bridge converter	284
7.6.2.4 Design of 3-channel signal amplifier	284
7.6.3 dSpace RTI Implementation	286
7.7 Experimental Results	288
7.7.1 Experimental setup	288
7.7.2 Measurement of the back EMF	289
7.7.3 Motion test of the actuator	290
7.8 Conclusion	293
 Chapter 8 LOCOMOTION CONTROL OF THE MICROROBOT	 295
8.1 Introduction	295
8.2 Improvement on the Locomotion Mechanism	296
8.3 Dynamic Modelling of the Robotic System	299
8.3.1 Kinetic equations of the microrobot	299
8.3.2 Collision between stator and translator	302
8.3.3 SIMULINK model of the microrobot	303
8.4 Locomotion Control of the Microrobot	304
8.4.1 Locomotion control method	304
8.4.2 Simulation of the locomotive performance	306

8.5 Experiment on the locomotion control	310
8.6 Conclusion	313
Chapter 9 CONCLUSIONS AND FURTHER WORK	314
9.1 Conclusion	314
9.2 Future work	317
References	318
Appendix A. CURRENT DENSITY ESTIMATION	A-1
Appendix B. CENTRAL DIVIDED DIFFERENCE	A-2
Appendix C. SCHEMATIC DIAGRAM OF THE DRIVING CIRCUIT	A-3
Appendix D. LIST OF PUBLICATIONS	A-4

LIST OF SYMBOLS¹

\vec{A}	Magnetic vector potential (Wb/m)
A	Area (m ²)
A_c	Cross sectional area of a conductor (m ²)
A_{cl}	Area enclosed by a coil (m ²)
A_g	Cross sectional area of an air gap (m ²)
A_p	Contact area (m ²)
A_s	Surface area of a conductor (m ²)
\vec{B}	Magnetic flux density vector
B_g	Flux density in an air gap (T)
B_{gr}	Radial component of flux density in an air gap (T)
B_m	Magnetising flux density in a phase winding (T)
B_r	Radial component of flux density (T)
C_d	Clamped capacitance (SI)
D_i	First-rank tensor electrical displacement (C/m ²)
d_{ikl}, d_{in}, d_{mk}	Third-rank and second-rank tensor piezoelectric constant (m/V)
E	Electrical field strength (V/m)
E_k	First-rank tensor electric field strength (V/m)
E_m, e_m	Back electromotive force caused by permanent magnets (V)
\hat{E}_m	Complex notation of E_m
e_s	Back electromotive force caused by machine saliencies (V)
F	Force (N)
\hat{F}	Complex notation of force
F_{em}	Electromagnetic force (N)
F_{emm}	Electromagnetic force generated by permanent magnets (N)
F_{emp}	Electromagnetic force under one pole (N)
F_{ems}	Electromagnetic force generated by machine saliencies (N)

¹ Symbols which are not listed here are defined where they appear.

F_f	Frictional force (N)
F_{load}	Load force (N)
F_{mm}	Magnetomotive fore (A·t)
F_N	Normal force (N)
F_{sp}	Elastic force of a spring (N)
g	Length of an air gap (m)
\vec{H}	Magnetic field strength vector
H_c	Coercive force of a permanent magnet (A/m)
h_c	Height of a coil (m)
h_d	Thickness of friction layer in an ultrasonic motor (m)
h_m	Height of a permanent magnet (m)
h_p	Penetration of stator into friction layer in an ultrasonic motor (m)
h_s	Thickness of a piezoelectric segment (m)
I, i	Current (A)
\hat{I}	Complex notation of current $\hat{I} = Ie^{j\omega t}$
I_0	<i>rms</i> value of phase current (A)
I_1	Conductor current (A)
I_m	Field excitation current (A)
I_{rated}	Rated winding current (A)
\vec{J}	Current density vector
J	Current density (A/m ²)
J_s	Effective current density (A/m ²)
K_e	Back electromotive force coefficient (V·s/m)
K_f	Force coefficient (N/A)
K_{sp}	Elastic constant (N/m)
k_d	Deformation coefficient of friction layer in an ultrasonic motor
k_{ff}	Fill factor
k_m	Magnetic occupation ratio
k_p	Coefficient of restitution
k_T	Thermal conductivity (W/m·K)
k_v	Wave number of a plane wave
L	Inductance (H)

L_a	Self inductance of a coil (H)
L_1	Self inductance of a conductor (H)
L_{1m}	Mutual inductance between a conductor and an excitation coil (H)
L_m	Self inductance of an excitation coil (H)
L_{jk}^{app}	Apparent inductance between windings j and k (H)
L_{jk}^{diff}	Differential inductance between windings j and k (H)
\vec{l}	Length vector
l_c	Length of a conductor, or mean circumference of a coil (m)
\vec{M}	Magnetisation vector (A/m)
m_a	Mass of a moving coil or translator (kg)
m_s	Mass of a stator (kg)
N_t	Number of turns of a coil (turns)
p	Pressure (N/m ²)
Q	Heat flow (W)
R	Resistance (Ω)
R_a	Winding Resistance (Ω)
R_{coil}	Coil resistance (Ω)
R_{ph}	Phase resistance (Ω)
r_c	Radius of a conductor or mean radius of a coil (m)
r_r	Effective radius of rotor ring in an ultrasonic motor (m)
S_{ij}, S_m	Second-rank and first-rank tensor mechanical strain
S_{ijkl}, S_{mn}	Fourth-rank and second-rank tensor elastic compliance coefficient (m ² /N)
S_{ijkl}^E, S_{mn}^E	Elastic compliance coefficient at constant electric field (m ² /N)
T	Temperature (K)
T_{kl}, T_n	Second-rank and first-rank tensor mechanical stress (N/m ²)
U, u	Voltage (V)
\hat{U}	Complex notation of voltage $\hat{U} = Ue^{j\omega t}$
U_0	<i>rms</i> value of phase voltage (V)
u_{a0}, u_{b0}, u_{c0}	Phase terminal voltages (V)
u_n	Neutral voltage (V)
V	Volume (m ³)

v_a, v_m	Velocity of a moving coil and a translator, respectively (m/s)
v_r	Rotor velocity (m/s)
v_s	Stator velocity (m/s)
W_E	Electrical field energy (J)
$[W_E]$	Electrical field energy density (J/m ³)
W_M, W'_M	Magnetic field energy and co-energy (J)
$[W_M], [W'_M]$	Magnetic field energy density and co-energy density (J/m ³)
x, y, z	Cartesian coordinates
\hat{x}	Complex notation of x
\dot{x}	dx/dt
$\hat{\dot{x}}$	Complex notation of \dot{x}
Y	Young's Modulus
Z, Z_0	Elastic impedances of a piezoelectric actuator
ϵ	Electrical permittivity (F/m)
ϵ_r	Relative electrical permittivity
ϵ_0	Electrical permittivity of free air (F/m)
$\epsilon_{ik}^T, \epsilon_{ik}^S$	Electrical permittivity at constant stress and strain, respectively (F/m)
θ	Angle between a stationary and a moving windings
λ_j	Flux linkage of the j -th winding (Wb)
λ_m	Magnetising flux linkage (Wb)
λ_{jk}	k -th component of λ_j (Wb)
μ	Magnetic permeability (T·m/A)
μ_0	Magnetic permeability of free space (T·m/A)
μ_f	Coefficient of friction
μ_m	Permeability of a permanent magnet (T·m/A)
μ_r	Relative magnetic permeability
v_{ph}	Phase velocity of a plane wave
ξ	Characteristic size of an object
ρ	Resistivity ($\Omega \cdot m$)
ρ_e	Resistance per meter (Ω/m)
ρ_m	Mass density of a piezoelectric material (kg/m ³)
Γ	Torque (N·m)

τ	Pole pitch (m)
τ_c	Thickness of a pole-piece (m)
τ_m	Thickness of a permanent magnet (m)
Φ	Electromechanical coupling factor
ϕ	Magnetic flux (Wb)
ϕ_g	Magnetic flux in an air gap (Wb)
ϕ_p	Magnetic flux per pole (Wb)
ω	Angular frequency or speed (rad/s)
\mathcal{F}	Magnetic scalar potential (SI)
\mathfrak{R}	Reluctance (SI)
\mathfrak{R}_g	Reluctance of an air gap (SI)
\mathfrak{R}_m	Reluctance of a permanent magnet (SI)

LIST OF ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AC	Alternating Current
CAD	Computer Aided Design
DC	Direct Current
DOF	Degree of Freedom
DSP	Digital Signal Processors
ECDM	Electro-Chemical Discharge Machining
EDM	Electrical Discharge Machining
EMF	Electromotive Force
FE	Finite Element
FEM	Finite Element Method
FMA	Flexible Micro Actuator
GMM	Giant Magnetostrictive Material
GUI	Graphical User Interface
IDM	Impact Drive Mechanism
LIGA	<i>German:</i> Lithographisch Galvanoformingung und Abformung
LIM	Linear Induction Machines
LRM	Linear Reluctance Machine
LSM	Linear Synchronous Machine
MIS	Minimally Invasive Surgery
MMF	Magnetomotive Force
NdFeB	Neodymium Iron Boron
PM	Permanent Magnet
PWM	Pulse Width Modulation
PZT	Lead Zirconate Titanate
RTI	Real-Time Interface
SMA	Shape Memory Alloy
SME	Shape Memory Effect

SmCo	Samarium-Cobalt
SPWM	Sinusoidal PWM
TLA	Tubular Linear Actuator
ULSI	Ultra Large Scale Integration
ZCP	Zero-Crossing Point

LIST OF FIGURES

Fig.2-1	Scheme of Mechatronics	12
Fig.2-2	The range of size of mechanical systems displayed in logarithmic scale	13
Fig.2-3	Unified micro machine	15
Fig.2-4	Classes of micro robot with respect to linear dimensions	15
Fig.2-5	An examples of minirobot	16
Fig.2-6	A flying microrobot by the University of California, Berkeley	16
Fig.2-7	Conceived nanorobot with Ion mobility based on molecular electronics	17
Fig.2-8	Functional classification of micro robots	17
Fig.2-9	Applications of micro robots	19
Fig.2-10	Inspection of water pipe	19
Fig.2-11	Micro moving robot developed by H. Aoyama <i>et al.</i>	21
Fig.2-12	Structure of the four stack-type desktop microrobot	22
Fig.2-13	Microrobot with permanent magnet linear actuation mechanism	22
Fig.2-14	Crawling microrobot - Abalone	23
Fig.2-15	Y-shaped Microrobots proposed by A. Torii <i>et al.</i>	23
Fig.2-16	Moving principle of the Y-shaped microrobot	24
Fig.2-17	The NanoWalk microrobots developed in MIT	25
Fig.2-18	Microrobot MINIMAN by S. Fahlbusch	25
Fig.2-19	Bristle-based micro mobile robots	26
Fig.2-20	Operation principle of the bristle-based micro mobile robot	26
Fig.2-21	Micro Line Trace Robot by H. Ishihara <i>et al.</i>	27
Fig.2-22	An autonomous microrobot based on bristle structure and piezoelectric device	28
Fig.2-23	Prototype of the bristle-type microrobot using centrifugal forces	28
Fig.2-24	Conceptual view of the microrobot using centrifugal forces	29

Fig.2-25	TOSUMO-KUN microrobot proposed by Y. Hasegawa	30
Fig.2-26	Prototype and structure of the Pillicino microrobot	30
Fig.2-27	Working principle of the wobble micro motor	31
Fig.2-28	Conceptual design of the cricket microrobot	32
Fig.2-29	Schematic structure of an in-pipe microrobot using GMM	33
Fig.2-30	Screw principle microrobot by I. Hayashi <i>et al.</i>	34
Fig.2-31	Configuration of a wheel-driving micro inspection robot	34
Fig.2-32	Driving principle of the micro inspection robot	34
Fig.2-33	The vermiculation of an earthworm	35
Fig.2-34	An in-pipe microrobot based on FMA structure	36
Fig.2-35	In-pipe inspection microrobot by T. Idogaki <i>et al.</i>	36
Fig.2-36	Locomotive principle of the in-pipe inspection microrobot	37
Fig.2-37	In-pipe wireless microrobot by H.Nishikawa <i>et al.</i>	37
Fig.2-38	An inchworm type in-pipe microrobot using linear electromagnetic mechanism	38
Fig.2-39	Pneumatic in-pipe microrobot by C. Anthierens	39
Fig.2-40	Structure of the IntraTube microrobot	39
Fig.2-41	A flexible in-pipe microrobot using locomotion module	40
Fig.2-42	An inchworm type in-pipe microrobot based on SMA actuator	41
Fig.2-43	The clamping mechanism and locomotive principle	41
Fig.2-44	A fin-type swimming microrobot	42
Fig.2-45	A spiral-type swimming microrobot	42
Fig.2-46(a)	A swimming microrobot with a steering mechanism	43
Fig.2-46(b)	Principle of the steering mechanism	43
Fig.2-47(a)	Schematic structure of a spiral type swimming microrobot	43
Fig.2-47(b)	Prototype of the spiral-type swimming microrobot for running in gel	43
Fig.2-48	A screw type swimming microrobot with guide-wheel	44
Fig.2-49	Basic concept of medical microrobot MEDIWORM	45

Fig.2-50	Proposed intelligent microcapsule MiRO	45
Fig.2-51	Robotic endoscope by J. Burdick <i>et al.</i>	46
Fig.2-52	An artificial inchworm for medical treatment	47
Fig.2-53	Endoscopic microrobot by K. V. Asari <i>et al.</i>	48
Fig.2-54	Robotic endoscope developed by M. C. Carrozza <i>et al.</i> (a) Clamping mechanism, (b) prototype	48
Fig.2-55	Schematic of a self-propelling endoscope	49
Fig.2-56(a)	Pneumatic locomotion actuator	49
Fig.2-56(b)	Prototype with flexible supporter	49
Fig.2-57	A robotic endoscope actuated by impact drive mechanism	50
Fig.2-58	Millipedes locomotion mechanism by M. Utsugi	51
Fig.2-59	EndoCrawler proposed by W. S. Ng	51
Fig.2-60	An autonomous medical microrobot with legged locomotion	52
Fig.2-61	Concept of wireless endoscope by F. Gong <i>et al.</i>	53
Fig.2-62(a)	M2A developed by Given Imaging Ltd.	53
Fig.2-62(b)	NORIKA3 developed by RF Lab	53
Fig.2-63	Drawing of a double action hydraulic actuator	55
Fig.2-64	Cutaway view of a basic pneumatic actuator	56
Fig.2-65(a)	Flexible micro actuator developed by K. Suzumori	58
Fig.2-65(b)	Movement of a 1mm diameter FMA	58
Fig.2-66	Pneumatic wobble motor (a) Prototype, (b) Schematic structure	58
Fig.2-67	Micro hydraulic active catheter	59
Fig.2-68	Basic structure of a solenoid actuator	60
Fig.2-69	Schematic of a DC motor	61
Fig.2-70	Basic principle of an AC motor	62
Fig.2-71(a)	Smoovy micro motor produced by RMB	64
Fig.2-71(b)	1.9mm brushless DC motor produced by Minimotors	64
Fig.2-72	A 1cm ³ microrobot using 3mm smoovy micro motor	65
Fig.2-73	Actuation structure of the Mckibben artificial muscles in cricket	65

	microrobot	
Fig.2-74	A planar type PM synchronous micro motor	66
Fig.2-75	Schematic of the electromagnetic wobble micro motor	67
Fig.2-76	Theoretical mechanical performance of the wobble micro motor	67
Fig.2-77	Structure of a threaded wobble micro motor	67
Fig.2-78	A silicon-based electromagnetic micro motor	68
Fig.2-79	Piezoelectric effect	69
Fig.2-80	A microrobot with piezoelectric bimorph actuators	70
Fig.2-81	IDM mechanism using piezoelectric actuator	71
Fig.2-82(a)	First design of the linear Cybernetic Actuator	72
Fig.2-82(b)	Prototype of the linear Cybernetic Actuator	72
Fig.2-83	Second design of the linear Cybernetic Actuator	73
Fig.2-84	A universal joint with 2-DOF driven by Cybernetic Actuator	73
Fig.2-85	Operation of an inchworm actuator	74
Fig.2-86	Scheme and principle of a planar travelling wave type ultrasonic motor	74
Fig.2-87	A tubular piezoelectric ultrasonic micro motor	75
Fig.2-88	Active endoscope using SMA actuator developed by K. Ikuta	77
Fig.2-89	SMA actuator developed by B. Kim <i>et al.</i>	78
Fig.2-90	Basic principle of electrostatic actuators	79
Fig.2-91	Side-driven rotary electrostatic micro actuators	81
Fig.2-92	Surface driven electrostatic actuator developed by X. Gao <i>et al.</i>	81
Fig.2-93	A bidirectional inchworm electrostatic actuator for microrobot	82
Fig.2-94	Schematic structure of a GMM linear actuator	84
Fig.2-95	Operation principle of the GMM linear actuator	84
Fig.3-1	Piezoelectric actuator coordinator systems	89
Fig.3-2	Interaction between the stator and rotor via friction layer	91
Fig.3-3	Electromagnetic force on a conductor in magnetic field	93

Fig.3-4	A conductor with surface area A_s and cross sectional area A_c	95
Fig.3-5	A conductor of radius r_c and length l_c	97
Fig.3-6	An electromagnetic linear actuator	105
Fig.3-7	A piezoelectric linear actuator	106
Fig.3-8	Piezoelectric transducer of T-effect	107
Fig.3-9	Mason's equivalent circuit model of piezoelectric transducer	108
Fig.3-10	Equivalent circuit of the piezoelectric actuator with no load	109
Fig.3-11	Simplified equivalent circuit of the piezoelectric actuator with no load	110
Fig.3-12	A piezoelectric actuator with external load	111
Fig.3-13	Equivalent circuit of the piezoelectric actuator with external load	112
Fig.3-14	Dimensions of the linear electromagnetic actuator	113
Fig.3-15	Movement of the electromagnetic actuator under sinusoidal excitation	115
Fig.3-16	Equivalent circuit of the electromagnetic actuator	116
Fig.3-17	Schematic of the proposed micro mobile robot	121
Fig.4-1	Imaginary process of unrolling a conventional induction machine to obtain a linear induction machine	126
Fig.4-2	(a) A single sided machine, and (b) a double sided machine	126
Fig.4-3	A salient-pole linear synchronous machine	127
Fig.4-4	Linear reluctance machines	128
Fig.4-5	A multi-pole-piece DC linear machine	129
Fig.4-6	A two-pole DC linear machine with cylindrical field unit	129
Fig.4-7	A moving-magnet linear machine	131
Fig.4-8	A moving-armature linear machine	132
Fig.4-9	A moving-coil linear motor	132
Fig.4-10	Proposed moving-coil linear actuator	139
Fig.4-11	Micro moving robot using the moving-coil linear actuator	140
Fig.4-12	Typical DC hysteresis loop and average B/H curve of 2605SA1	141

Fig.4-13	Dimensions of the moving-coil linear actuator	142
Fig.4-14	2D FE model of the moving-coil linear actuator	143
Fig.4-15	Round wire in a square region	144
Fig.4-16	Linear 2D FE analysis results (a) flux contour, (b) flux density distribution	147
Fig.4-17	Flux density distribution obtained from non-linear 2D FE analysis	148
Fig.4-18	3D model of the actuator for FE analysis	150
Fig.4-19	3D flux density vectors of the moving-coil linear actuator	151
Fig.4-20	Radial flux densities B_{gr} within the moving coil	151
Fig.4-21	Electromagnetic force of the moving-coil linear actuator	152
Fig.4-22	Flux linkage of the moving coil generated by the current in the coil	153
Fig.4-23	Flux density vectors generated by the coil current	155
Fig.4-24	Calculated inductances under different moving coil positions	155
Fig.4-25	Mechanical model of the proposed microrobot	158
Fig.4-26	Forces in the system	158
Fig.4-27	Locomotion principle of the microrobot	161
Fig.4-28	Excitation voltage for the actuator	161
Fig.4-29	Actuation force of the actuator	163
Fig.4-30	Displacements of the microrobot	163
Fig.4-31	Velocities of the microrobot	163
Fig.4-32	Strain of the equivalent spring during the locomotion voltage	164
Fig.4-33	The displacement of the robot when the mass of the main body is 2g	164
Fig.4-34	Strain of the equivalent spring during the locomotion when the mass of the main body is 2g	165
Fig.5-1	From a rotary brushless PM machine to a moving-magnet tubular linear actuator	168
Fig.5-2	An example of moving-magnet TLA	169
Fig.5-3	Multi-pole configuration studied by Bruno Lequensne	171

Fig.5-4	Different topologies for PM TLA	172
Fig.5-5	Improved interior mounted topology	173
Fig.5-6	Proposed slotless interior mounted PM TLA	175
Fig.5-7	3D view of moving magnet assembly (translator)	175
Fig.5-8	Flux density distribution (a) Surface mounted, (b) Interior mounted	176
Fig.5-9	Stator windings of the PM TLA	177
Fig.5-10	3D configuration of the PM TLA	177
Fig.5-11	Major dimensions of the PM TLA	178
Fig.5-12	Magnetic circuit model of the PM TLA	179
Fig.5-13	Equivalent magnetic circuit for the analytical analysis	180
Fig.5-14	Flux and flux density per pole obtained by analytical and numerical methods	182
Fig.5-15	Variation of force vs. k_m obtained by analytical analysis	184
Fig.5-16	Comparison of F_{em} vs. k_m obtained by numerical and analytical solutions	185
Fig.5-17	2D FE model of the PM TLA	186
Fig.5-18	Finite element mesh for the actuator model	187
Fig.5-19	Flux contour distribution in the actuator: (a) right hand side, (b) middle	188
Fig.5-20	Flux densities in phase coils (a) phase A , (b) phase B , (c) phase C	189
Fig.5-21	The electromagnetic force under sinusoidal excitation	191
Fig.5-22	Conventional 120° energisation	192
Fig.5-23	The electromagnetic force generated by brushless DC drive method	193
Fig.5-24	An electrical device with N windings	196
Fig.5-25	Magnetic energy and co-energy for a single coil	198
Fig.5-26	Numerical solution for E/C perturbation	200
Fig.5-27	Linear system with the permeability equal to the differential permeability at operational point P of the non-linear system	201
Fig.5-28	Flowchart of 2D differential inductances computation	204

Fig.5-29	Calculated phase inductances of the PM TLA	205
Fig.5-30	Calculated inductances without considering the saturation effect	206
Fig.5-31	Principle of the variation of self inductances	206
Fig.5-32	Flux linkage of an enclosed cylindrical coil pair	208
Fig.5-33	Axes and centre positions of the coil pairs in stator winding	210
Fig.5-34	Phase currents of the actuator	217
Fig.5-35	Output force of the actuator	217
Fig.5-36	Translator velocity and position during the operation	218
Fig.5-37	EMFs caused by the machine saliencies	218
Fig.5-38	Force caused by the machine saliencies	219
Fig.5-39	Translator velocity and position during the operation	219
Fig.6-1	Operating principle of laser cutting	222
Fig.6-2	The laser cutting equipment used for the fabrication of designed actuator	223
Fig.6-3	Fabrication of the stator core	224
Fig.6-4	The completed large sized stator core	225
Fig.6-5	Fabrication of the small sized stator core	225
Fig.6-6	Phase coils for the prototypes	226
Fig.6-7	Assembled stator for the small prototype	226
Fig.6-8	Pole piece sheet cut by over powered laser beam	227
Fig.6-9	Pole piece sheets obtained by the proper setting of the laser power	228
Fig.6-10	The constructed pole pieces for the small sized prototype	228
Fig.6-11	Translator shafts for the prototypes	229
Fig.6-12	Assembly of the translator for large sized prototype	229
Fig.6-13	Assembly of the translator for small sized prototype	229
Fig.6-14	Assembly process of the large prototype	230
Fig.6-15(a)	Completed large sized prototype	231
Fig.6-15(b)	Completed small sized prototype	231

Fig.6-16	Schematic diagram of the test bench	231
Fig.6-17	Practical implementation of the test bench	232
Fig.6-18	Modelling of lamination effect by introducing concentrated air gap	233
Fig.6-19	Introduction of the computational permeability for the magnet	234
Fig.6-20	Predicted force of the large sized prototype	235
Fig.6-21	Predicted self inductances of the large sized prototype	236
Fig.6-22	Predicted mutual inductances of the large sized prototype	236
Fig.6-23	Predicted force of the small sized prototype	236
Fig.6-24	Predicted self inductances of the small sized prototype	237
Fig.6-25	Predicted mutual inductances of the small sized prototype	237
Fig.6-26	Experimental setup for force measurement	238
Fig.6-27	Output force of the large sized prototype	239
Fig.6-28	Output force of the small sized prototype	240
Fig.6-29	Experimental setup for the inductances measurement	241
Fig.6-30	Electrical circuit for the inductances measurement	241
Fig.6-31	Measured self inductance of the large sized prototype	243
Fig.6-32	Measured mutual inductances of the large sized prototype	244
Fig.6-33	Measured self inductances of the small sized prototype	245
Fig.6-34	Measured mutual inductances of the small sized prototype	246
Fig.7-1	Schematic of brushless DC machine	249
Fig.7-2	Three phase bridge inverter	250
Fig.7-3	Hall position sensors	250
Fig.7-4	Comparison of three phase and two phase conduction mode	251
Fig.7-5	Hall sensor signals, back EMFs, phase currents and output torque	252
Fig.7-6	Winding energizing sequence with respect to the hall sensor	253
Fig.7-7	S-Function structure within SIMULINK	260
Fig.7-8	Flow chart of output function	261

Fig.7-9	Flow chart of derivative function	261
Fig.7-10	Electrical block of the SIMULINK model for the actuator	261
Fig.7-11	Mechanical block of the SIMULINK model for the actuator	262
Fig.7-12	Complete SIMULINK model for the actuator	262
Fig.7-13	Actuator model with electronic converter	263
Fig.7-14	Force of the actuator when driven by SPWM voltage	264
Fig.7-15	Operation of the actuator when driven by SPWM voltage	264
Fig.7-16	The magnetising flux density in each phase	266
Fig.7-17	Implementation of ZCP detection method	266
Fig.7-18	Function of the ZCP filter signal	267
Fig.7-19	Back EMF and magnetising flux density	269
Fig.7-20	Flow chart of the sensorless control scheme	270
Fig.7-21	SIMULINK model of the sensorless control system of the PM TLA	271
Fig.7-22	Excitation voltages applied to the PM TLA	273
Fig.7-23	Phase currents in each phase of the PM TLA with no load	273
Fig.7-24	Control signals for sensorless drive of the PM TLA	274
Fig.7-25	Actuation force of the PM TLA with no load	275
Fig.7-26	Actual and estimated translator velocities	275
Fig.7-27	Actual and estimated translator positions	275
Fig.7-28	Phase currents in each phase of the PM TLA with maximum load	276
Fig.7-29	Actuation force of the PM TLA with maximum load	277
Fig.7-30	Actual and estimated translator velocities	277
Fig.7-31	Actual and estimated translator positions	277
Fig.7-32	Input electrical power during the operation	278
Fig.7-33	Output mechanical power of the PM TLA	278
Fig.7-34	Basic structure of the dSPACE prototyping system	280
Fig.7-35	Block diagram of the actuator control system	281
Fig.7-36	Implementation of gate drive circuit	282

Fig.7-37	Implementation of electronic power converter	284
Fig.7-38	Detection of the phase voltage	285
Fig.7-39	One channel of the signal amplifier for detection of the phase voltage	286
Fig.7-40	Implementation of the SIMULINK model with RTI for the sensorless control	287
Fig.7-41	Block diagram of the experimental system	288
Fig.7-42	Control panel within ControlDesk for the experiment	288
Fig.7-43	Measured back EMFs of the small sized prototype	289
Fig.7-44	Control signals generated by sensorless algorithm	291
Fig.7-45	Measured phase voltages of the small sized prototype	291
Fig.7-46	Estimated translator velocity during the operation	291
Fig.7-47	Estimated translator position during the operation	292
Fig.7-48	Motion of the small sized PM TLA prototype	292
Fig.7-49	Measured phase voltages of the small sized prototype during backward operation	293
Fig.7-50	Estimated translator position during backward operation	293
Fig.8-1	Schematic of the micro mobile robot with tilted blades	297
Fig.8-2(a)	Frictional force on blade tip in forward motion	298
Fig.8-2(b)	Frictional force on blade tip in backward motion	298
Fig.8-3	Kinetic model of the microrobot	300
Fig.8-4	Forces in the microrobot	300
Fig.8-5	SIMULINK model of the microrobot	304
Fig.8-6	Block diagram of the microrobot	305
Fig.8-7	Implementation of the intermittent drive control in SIMULINK	305
Fig.8-8	SIMULINK model of the microrobot and its locomotion control system	306
Fig.8-9	Phase currents of the actuator during the locomotion	307
Fig.8-10	Actuation force generated by the actuator	307

Fig.8-11	Movement of the stator and translator during locomotion	308
Fig.8-12	Velocities of the stator and translator during locomotion	308
Fig.8-13	Translator position with respect to the stator during locomotion	309
Fig.8-14	SIMULINK RTI model used for the locomotion control	310
Fig.8-15	Actuator with locomotion mechanism for testing	311
Fig.8-16	Test system for the locomotion mechanism	311
Fig.8-17	Locomotion test on a smooth surface	312
Fig.8-18	Locomotion test on a uneven surface	312

LIST OF TABLES

Table 2-1	Comparison of conventional machine and micro machines	14
Table 2-2	Key parameters of three types of micro motors	65
Table 2-3	Characteristics of the wobble micro motor	67
Table 2-4	Comparison of actuation principles	85
Table 3-1	Comparison of scaling effects between the electromagnetic actuators with electromagnet and PM	102
Table 3-2	Properties and attainable energy density of some piezoelectric materials	103
Table 3-3	Properties of the piezoelectric material for evaluation	118
Table 3-4	Comparison of the piezoelectric and electromagnetic actuators	118
Table 3-5	Characteristic equations of the piezoelectric and electromagnetic actuators	119
Table 4-1	Comparison of PM linear machines	133
Table 4-2	General properties and characteristics of 2605SA1	140
Table 4-3	Key dimensions of the moving-coil linear actuator	142
Table 4-4	Radial flux densities within the moving coil and the generated forces in linear case	147
Table 4-5	Radial flux densities within the moving coil and the generated forces in non-linear case	149
Table 5-1	Major dimensions of the tubular linear actuator	178
Table 5-2	Switching sequence for the PM TLA	192
Table 5-3	Centre positions of the coil pairs in the phase windings	210
Table 7-1	Commutation truth table of A3932	283