

学位論文

Design and Control of a High-Performance  
Multi-Degree-of-Freedom Planar Actuator

(高性能な多自由度平面アクチュエータの設計と制御)

上田 靖人

# Design and Control of a High-Performance Multi-Degree-of-Freedom Planar Actuator

by

Yasuhito Ueda

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## Summary

There are a large number of drive systems employing numerous actuators in industry. As such, the performances of these actuators require constant improvement in terms of higher speed and precision, miniaturization, and lower energy consumption. In addition, most of these drive systems need a design that permits MDOF (Multi-Degree-Of-Freedom) motion. Motion controls allowing MDOF have been practically realized by using stacked multiple actuators. However, there are problems in attempting to improve the performance of these types of drive systems such as a larger and more complicated structure, fluctuation of the center of gravity, and Abbe errors in position measurement due to the multiple-moving parts. In order to eliminate these problems, MDOF actuators—which have only a single moving part, but are capable of being directly driven with MDOF—are emerging technologies for future applications.

This study deals with planar actuators, which have a mover capable of traveling over large translational displacements in a plane. Various types of planar actuators have been proposed, and synchronous planar actuators with a permanent-magnet mover are expected to offer good controllability of the motion controls. However, the movable area tends to be quite narrow due to the use of conventional magnetic circuits for the MDOF drives, which are spatially separated from one another, unless the planar actuator has a large number of armature coils as shown in Figs. S-1 and S-2. Table S-1

shows classifications of synchronous planar actuators according to mover type, coil, and degree-of-freedom of controlled motion.

With this in mind, this study is aimed at designing high-performance planar actuators that have the following drive performances:

- decoupled control for 3-DOF (Three-Degree-Of-Freedom) motions on a plane.
- wide movable area that can be extended regardless of the number of armature coils.
- ease of mover miniaturization.
- no problematic wiring that can negatively influence drive performance.
- small number of armature currents to control.

Next, I propose a design for a novel synchronous planar actuator having spatially superimposed magnetic circuits for the 3-DOF drives as shown in Fig. S-3. The magnetic circuits are a combination of a two-dimensional (2-D) Halbach permanent-magnet mover, and mutually overlapped stationary polyphase armature conductors. The movable area can be easily extended by increasing the length of the armature conductors, regardless of their number. However, independently controlling MDOF driving forces by means of superimposed magnetic circuits is very difficult and an extremely important issue in this study. This thesis demonstrates a design for a planar actuator that enables MDOF driving forces to be controlled by using spatially superimposed magnetic circuits.

First, based on the results of a numerical analysis of the driving forces, I design a decoupled control law for the 3-DOF driving forces on a plane by using two polyphase armature currents. I experimentally demonstrate that the 3-DOF motions of the mover can be independently controlled by using two polyphase armature currents. The movable area in the translational directions is infinitely wide, and that in the yaw direction is in the range within  $\pm 26$  deg, namely the planar actuator has the widest movable area of all planar actuators that have only two polyphase armature conductors. Second, in order to further improve drive characteristics, the planar actuator is theoretically redesigned so that the mover can be stably levitated and the 3-DOF motions above a plane can be controlled. The planar actuator can be made quite small because the permanent-magnet array and armature conductors for the MDOF drive are integrated. The planar actuator would provide a significant starting point when used with small electromechanical components in an MDOF drive.

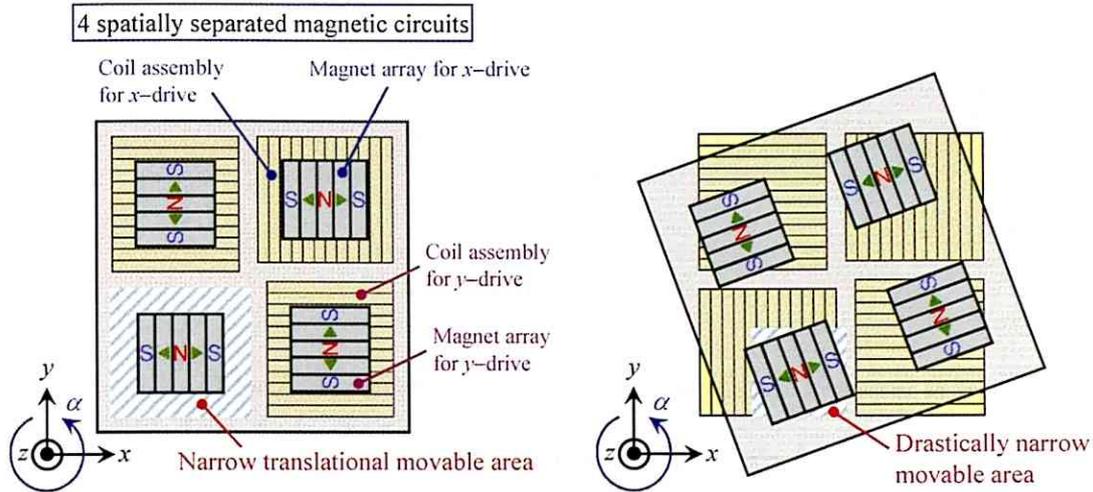


Fig. S-1: Configuration of a fundamental synchronous planar actuator with a permanent-magnet mover. The movable area tends to be quite narrow.

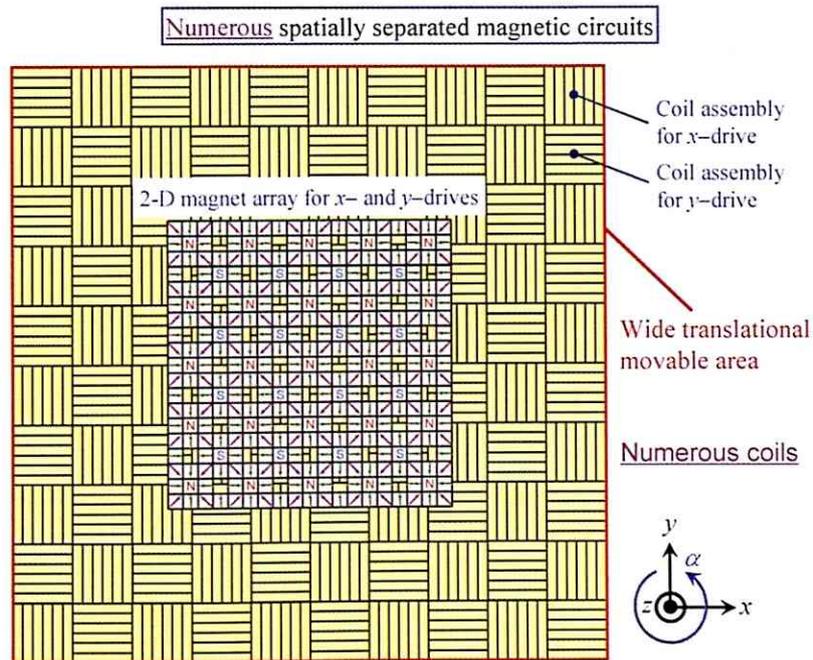


Fig. S-2: Configuration of a synchronous planar actuator with a permanent-magnet mover and numerous armature coils. The power-supply system often becomes complex.

Table S-1: Classification of synchronous planar actuators by mover type, coil, and degree-of-freedom of controlled motion.

Mover Type \ Coil Type	Moving-Magnet Type No problematic wiring			Moving-Coil Type Extendible movable area regardless of number of coils		
	Inventor	DOF	Coils	Inventor	DOF	Coils
Polyphase Coils Less dependence of driving forces on mover positions	Korenaga	2	$2 \times 2\phi$	Hinds	3	$4 \times 6\phi$
	Fujii	2	$2 \times 3\phi$	Jung	3	$4 \times 3\phi$
	Ohira	5	$2 \times 3\phi$ (+ 4)	Shikayama	3	$4 \times 3\phi$
	Kim	6	$4 \times 3\phi$	Compter	6	$4 \times 3\phi$
	Compter	6	$9 \times 3\phi$			
	Oh	6	$100 \times 3\phi$			
	Ueda (This study)	3 5	$2 \times 3\phi$ $3 \times 2\phi$			
Non-Polyphase Coils High design flexibility	Binnard	3	Many	Asakawa	3	4
	Ueta	3	Many	Ueta	6	Many
	Vandenput	6	84			

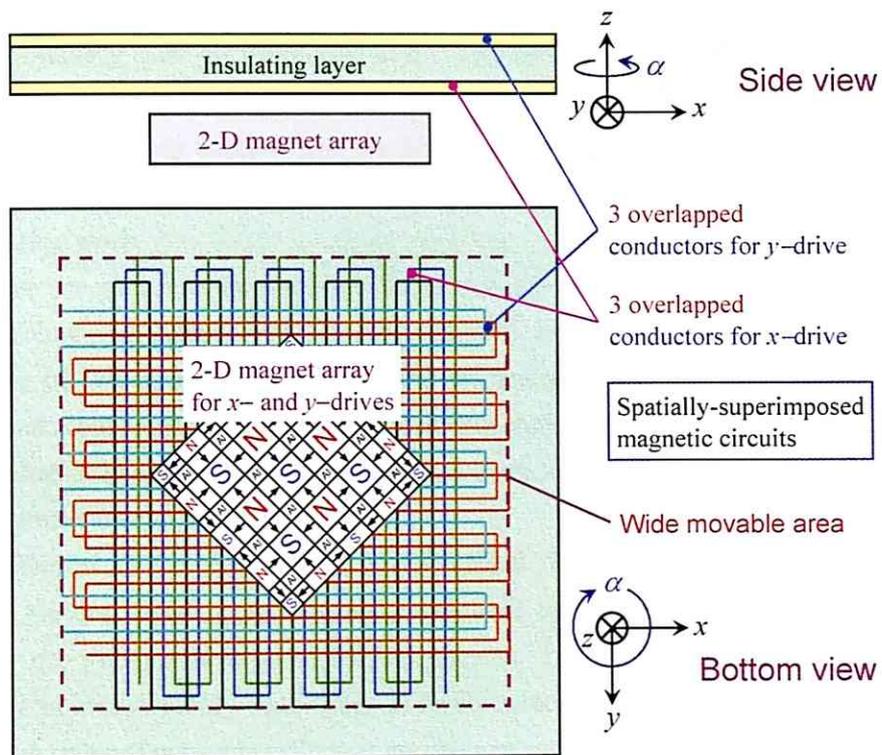


Fig. S-3: Configuration of proposed synchronous planar actuator with a permanent-magnet mover and a small number of armature coils.

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# Contents

<b>Summary</b>	<b>2</b>
<b>Acknowledgements</b>	<b>7</b>
<b>Contents</b>	<b>10</b>
<b>List of Figures</b>	<b>14</b>
<b>List of Tables</b>	<b>23</b>
<b>List of Symbols</b>	<b>24</b>
<b>1 Introduction</b>	<b>31</b>
1.1 Actuators with MDOF .....	32
1.2 Element Technologies of MDOF Actuators .....	34
1.2.1 Magnetic Materials .....	35
1.2.2 Magnetic Circuits .....	39
1.2.3 Position-Sensing Systems .....	41
1.2.4 Suspension and Guide Mechanisms .....	45
1.3 Technical Issues with MDOF Actuators .....	45
1.4 Contributions of this Thesis .....	46
1.4.1 Purpose of this Study .....	46
1.4.2 Procedures used in Conducting this Study .....	47
1.5 Thesis Overview .....	49
<b>2 Technical Trends in Motion Control with MDOF</b>	<b>51</b>
2.1 Multiple Moving-Part Actuators .....	52
2.2 Spherical Actuators .....	54
2.2.1 Stepping Type .....	54
2.2.2 Induction Type .....	57

2.2.3	Synchronous Type .....	60
2.2.4	Resonant Type .....	60
2.2.5	Piezoelectric Type .....	62
2.2.6	Magnetostrictive Type .....	66
2.3	Planar Actuators .....	68
2.3.1	Stepping Type .....	68
2.3.2	Direct-Current Type .....	73
2.3.3	Induction Type .....	78
2.3.4	Synchronous Type .....	81
2.3.5	Resonant Type .....	97
2.3.6	Piezoelectric Type .....	98
2.3.7	Electrostatic Type .....	99
2.4	Other MDOF Actuators .....	101
2.4.1	Linear and Rotary Actuators .....	101
2.4.2	6-DOF Actuators .....	105
2.5	Classifications of Previous MDOF Drive Systems .....	107
2.6	Summary of Chapter 2 .....	108
<b>3</b>	<b>Conceptual Design of Long-Stroke Planar Actuator</b> .....	<b>113</b>
3.1	Conceptual Design .....	114
3.1.1	Design Considerations .....	114
3.1.2	Basic Coreless Linear Synchronous Motor with Moving Magnets .....	115
3.1.3	Extension of Linear Motion to Planar Motion .....	117
3.2	Fundamental Structure .....	119
3.2.1	2-D Halbach Permanent-Magnet Mover .....	119
3.2.2	Stationary Overlapped Armature Conductors .....	121
3.2.3	Drive Principle .....	122
3.3	Static Force Characteristics .....	123
3.3.1	Analytical Model .....	123
3.3.2	Numerical Analysis Results .....	127
3.4	Decoupled Control for 3-DOF Motions .....	130
3.4.1	DQ Decomposition .....	130
3.4.2	3-DOF Force Control .....	133
3.5	Summary of Chapter 3 .....	135

<b>4</b>	<b>Design of Experimental System for Long-Stroke Planar Actuator</b>	<b>137</b>
4.1	Experimental Setup	138
4.1.1	Configuration of Experimental System	138
4.1.2	Experimental Apparatuses	141
4.2	3-DOF Position Sensing	143
4.2.1	Alignment of Sensors	143
4.2.2	Measurable Area for Mover Position	144
4.2.3	Calculation of Mover Position	146
4.2.4	Position-Sensing Test	147
4.3	Summary of Chapter 4	148
<b>5</b>	<b>Experimental Motion Control of Long-Stroke Planar Actuator</b>	<b>150</b>
5.1	3-DOF Motion Control	151
5.1.1	Experimental Conditions	151
5.1.2	Experimental Results	152
5.2	Long-Stroke Yaw Motion Control	161
5.2.1	Experimental Conditions	161
5.2.2	Experimental Results	162
5.3	Issues toward Incremental Improvements	169
5.3.1	Eliminating Friction Forces	169
5.3.2	Calibrating Position Sensing	170
5.4	Summary of Chapter 5	170
<b>6</b>	<b>Feasibility Study on Magnetically Levitated Planar Actuator</b>	<b>171</b>
6.1	Conceptual Design of Magnetically Levitated Planar Actuator	172
6.1.1	Design Considerations	172
6.1.2	6-DOF Force Analysis	173
6.1.3	Conceptual Design of Fundamental Structure	188
6.2	Dynamic Behavior of Mover	194
6.2.1	Mass and Inertia Tensor	194
6.2.2	Euler Angle and Angular Velocity	197
6.2.3	Equation of Motion	201
6.3	Planar Motion Control with Stable Magnetic Levitation	202
6.3.1	Translational Motion Control	202

6.3.2 Torque Characteristics and Rotational Motion Control .....	205
6.4 Numerical Analysis of Mover Motion .....	213
6.4.1 Analytical Model and Conditions .....	213
6.4.2 Numerical Analysis Results .....	215
6.5 Summary of Chapter 6 .....	220
<b>7 Conclusions</b>	<b>221</b>
7.1 Conclusions .....	222
7.2 Future Work .....	224
<b>Appendices</b>	<b>226</b>
<b>A Fabrication of the Smallest Halbach Permanent-Magnet Mover</b>	<b>227</b>
<b>B Structure of Manufactured Printed Circuit Board</b>	<b>229</b>
<b>C 6-DOF Position Sensing Utilizing Laser-Displacement Sensors</b>	<b>237</b>
<b>Bibliography</b>	<b>247</b>
<b>Publications</b>	<b>261</b>

# List of Figures

Fig. S-1:	Configuration of a fundamental synchronous planar actuator with a permanent-magnet mover. The movable area tends to be quite narrow. ....	4
Fig. S-2:	Configuration of a synchronous planar actuator with a permanent-magnet mover and numerous armature coils. The power-supply system often becomes complex. ....	4
Fig. S-3:	Configuration of proposed synchronous planar actuator with a permanent-magnet mover and a small number of armature coils. ..	6
Fig. 1.2.1-1:	Magnetic characteristics of ferromagnetic materials [Sag07]. ....	36
Fig. 1.2.1-2:	Status of $(BH)_{\max}$ of Nd-Fe-B sintered magnets [Kan04]. ....	36
Fig. 1.2.1-3:	Production of Nd-Fe-B sintered magnets for motors [Kan04]. ....	38
Fig. 1.2.1-4:	Production process of Nd-Fe-B sintered permanent magnets [Sag07]. ....	38
Fig. 1.2.1-5:	Production process of Nd-Fe-B bonded permanent magnets [Sag07]. ....	39
Fig. 1.2.2-1:	2-D Halbach permanent-magnet array. ....	40
Fig. 1.2.2-2:	Magnetic fields of Halbach and NS magnet arrays [Jan07]. ....	40
Fig. 1.2.3-1:	Configuration of a position-sensing system using multiple laser interferometers [Kim97]. ....	42
Fig. 1.2.3-2:	Optical arrangement of a surface encoder [Kiy05]. ....	43
Fig. 1.2.3-3:	Configuration of synchronous planar actuators with a position-sensing system that has multiple Hall elements [Com07, Jan07]. ....	43
Fig. 1.2.3-4:	Mover configuration of variable reluctance-stepping-type planar actuators with a position-sensing system that has multiple differential transformers [Hol98]. ....	44
Fig. 1.2.3-5:	Configuration of synchronous spherical actuators with a position-sensing system that has multiple optical encoders [Yan07]. ....	44
Fig. 1.5.0-1:	Thesis structure. ....	50

Fig. 2.1.0-1:	MDOF drive system achieved by stacking 1-DOF actuators [MDD08]. .....	53
Fig. 2.2.1-1:	Stepping spherical actuator developed by Lee [Lee08, Lee91].	55
Fig. 2.2.1-2:	Stepping spherical actuator developed by Doncker [Don00, Don02]. .....	56
Fig. 2.2.1-3:	Polyhedron samples [Yan08b].	56
Fig. 2.2.1-4:	Stepping spherical actuator developed by Chirikjian [Chi99].	57
Fig. 2.2.2-1:	Induction spherical actuator developed by Raucent [Rau06].	58
Fig. 2.2.2-2:	Induction spherical actuator developed by Ebihara [MDD05, Yan04]. .....	59
Fig. 2.2.3-1:	Synchronous spherical actuator developed by Yano [Yan07, Yan08a]. .....	60
Fig. 2.2.4-1:	Resonant spherical actuator developed by Hirata [Hir08, MDD08]. .....	61
Fig. 2.2.5-1:	Non-resonant piezoelectric spherical actuator developed by Sasae [Sas96].	63
Fig. 2.2.5-2:	Non-resonant piezoelectric spherical actuator developed by Nishimura [Nis08].	63
Fig. 2.2.5-3:	Spherical ultrasonic motor developed by Toyama [Toy07].	64
Fig. 2.2.5-4:	Spherical ultrasonic motor with a cylindrical vibrator developed by Ueha and Maeno [Mae01].	64
Fig. 2.2.5-5:	Spherical ultrasonic motor with a small plate-shaped vibrator developed by Maeno [Mae04].	65
Fig. 2.2.5-6:	Piezoelectric spherical actuator with a disk-shaped vibrator developed by Aoyagi [Aoy03, Aoy04].	66
Fig. 2.2.6-1:	Magnetostrictive spherical actuator developed by Higuchi [Hig08b]. .....	67
Fig. 2.3.1-1:	Stepping-type planar actuator proposed by Sawyer [Saw68].	69
Fig. 2.3.1-2:	Stepping planar actuator developed by Higuchi [Hig89].	70

Fig. 2.3.1-3:	Stepping planar actuator developed by Ebihara [Ebi89, Ebi91].	71
Fig. 2.3.1-4:	Stepping planar actuator developed Kimura [Tsu07].	72
Fig. 2.3.2-1:	Direct-current planar actuator proposed by Buckley [Buc89].	73
Fig. 2.3.2-2:	Direct-current planar actuator proposed by Galburt [Gal85].	74
Fig. 2.3.2-3:	Direct-current planar actuator developed by Tomita [Tom94, Tom96].	76
Fig. 2.3.2-4:	Direct-current planar actuator developed by Kiyono [Kiy04].	77
Fig. 2.3.3-1:	2-D primary windings of induction planar actuator developed by Ohira [Ohi04].	78
Fig. 2.3.3-2:	Induction planar actuator developed by Fujii [Fuj99].	79
Fig. 2.3.3-3:	6-DOF induction planar actuator proposed by Koseki [Kos04].	80
Fig. 2.3.4-1:	Synchronous planar actuator proposed by Asakawa [Asa85].	82
Fig. 2.3.4-2:	Synchronous planar actuator proposed by Binnard [Bin03].	83
Fig. 2.3.4-3:	6-DOF synchronous planar actuator developed by Vandenput [Jan07, Van07a, Van07b].	84
Fig. 2.3.4-4:	Synchronous planar actuator proposed by Hinds [Hin87].	86
Fig. 2.3.4-5:	Synchronous planar actuator developed by Shikayama [TSh06].	87
Fig. 2.3.4-6:	Synchronous planar actuator proposed by Ohira and Koseki [Ohi06, Kos01].	87
Fig. 2.3.4-7:	Synchronous planar actuator proposed by Jung [Jun02].	89
Fig. 2.3.4-8:	Moving-coil-synchronous planar actuator with 6 DOF developed by Compter [Com03, Com04].	90
Fig. 2.3.4-9:	Prototype of 6-DOF synchronous-type planar actuator developed by Kim [Tru96].	92
Fig. 2.3.4-10:	6-DOF synchronous planar actuator developed by Kim [Kim97, Kim98].	93
Fig. 2.3.4-11:	Moving-magnet-synchronous planar actuator with 6 DOF developed by Compter [Com07, Jan07, Phi06].	94
Fig. 2.3.4-12:	6-DOF synchronous-type planar actuator developed by Oh [HOh07].	95
Fig. 2.3.4-13:	Synchronous planar actuator proposed by Korenaga [Kor06].	96
Fig. 2.3.5-1:	Resonant planar actuator developed by Ebihara [Ebi03, Ebi05].	97

Fig. 2.3.6-1:	Piezoelectric planar actuator developed by Fontaine [Fon03].	98
Fig. 2.3.7-1:	Electrostatic planar actuator developed by Higuchi [Hig04].	100
Fig. 2.4.1-1:	Stepping linear-and-rotary actuator developed by Higuchi [Hig90].	102
Fig. 2.4.1-2:	Resonant linear-and-rotary actuator developed by Ebihara [Ebi05].	103
Fig. 2.4.1-3:	Resonant linear-and-rotary actuator developed by Hirata [Hir04, Hir05].	104
Fig. 2.4.2-1:	6-DOF actuator proposed by Vandenput [Van06, Van07c].	105
Fig. 2.4.2-2:	6-DOF actuator developed by Kim [Kim05].	106
Fig. 2.5.0-1:	Classifications of MDOF drive systems.	109
Fig. 2.5.0-2:	Movable area of 6-DOF magnetically levitated planar actuator developed by Kim [Kim97, Kim98].	111
Fig. 2.5.0-3:	Movable area of 6-DOF magnetically levitated planar actuator developed by Oh [HOh07].	111
Fig. 2.5.0-4:	Conceptual view of MDOF planar actuator proposed in this study.	112
Fig. 3.1.2-1:	Schematic view of a basic coreless linear synchronous motor with a permanent-magnet mover.	116
Fig. 3.1.2-2:	Supplied armature currents and flux density due to the magnet mover on the stator surface.	116
Fig. 3.1.3-1:	Fundamental structure of planar actuator dealt with in this study.	118
Fig. 3.1.3-2:	Mover and stator structures of planar actuator.	118
Fig. 3.2.1-1:	Dimension and magnetization of permanent-magnet mover.	120
Fig. 3.2.1-2:	Flux density distribution $B_z$ generated by the permanent-magnet mover on the plane 0.5 mm above the surface of the mover.	121
Fig. 3.3.1-1:	Configuration of mover and stator in the analysis model.	124

Fig. 3.3.1-2:	Configuration of supplied armature currents. ....	125
Fig. 3.3.1-3:	Definition of phase difference between magnetic fields generated by armature conductors and mover. ....	126
Fig. 3.3.2-1:	Translational force $F_x$ and torque $T_z$ vs. phase difference $\theta_{dx}$ . ....	128
Fig. 3.3.2-2:	Schematic views of driving force generation. ....	129
Fig. 3.3.2-3:	System constants $K_{Fx}$ and $K_{Tx}$ vs. yaw angle $\alpha$ . ....	130
Fig. 3.4.1-1:	Phasor diagrams showing relation between $dq$ -frame and $uvw$ -frame. ....	132
Fig. 3.4.1-2:	$dq$ -frame and $\alpha'\beta'$ -frame for $x$ - and $y$ -directional drives. ....	132
Fig. 3.4.2-1:	Degrees of freedom for armature-current control and mover motion. ....	133
Fig. 3.4.2-2:	Control block diagram for translational forces $F_x$ , $F_y$ and torques $T_z$ . ....	135
Fig. 4.1.1-1:	Configuration of experimental system for 2-D drives. ....	139
Fig. 4.1.1-2:	Fabricated experimental system for 2-D drives. ....	140
Fig. 4.1.2-1:	Circuit configuration of power amplifier for an armature conductor. ....	142
Fig. 4.2.1-1:	Alignment of three laser-displacement sensors. ....	144
Fig. 4.2.2-1:	Theoretical output signals of the three sensors $S_1$ , $S_2$ , $S_3$ for the yaw angle $\alpha$ at $(x, y) = (0, 0)$ . ....	145
Fig. 4.2.2-2:	Irradiated positions by laser-displacement sensors at $(x, y) = (0, 0)$ . ....	145
Fig. 4.2.3-1:	Theoretical calculated mover positions $x$ , $y$ , and $\alpha$ for the yaw angle $\alpha$ at $(x, y) = (0, 0)$ . ....	147
Fig. 4.2.4-1:	Configuration of experimental apparatuses for the position-sensing test. ....	148

Fig. 4.2.4-2:	Experimentally obtained sensor outputs of the three sensors $S_1, S_2, S_3$ at $(x, y) = (0, 0)$ for the yaw angle $\alpha$ . .....	149
Fig. 4.2.4-3:	Detected mover positions $x, y, \alpha$ at $(x, y) = (0, 0)$ for yaw angle $\alpha$ . .....	149
Fig. 5.1.2-1:	Experimental results of step response for $x$ -, $y$ - and $\alpha$ -directions. ...	155
Fig. 5.1.2-2:	Experimental results of sine response for $x$ -direction. ....	156
Fig. 5.1.2-3:	Experimental results of sine response for $y$ -direction. ....	157
Fig. 5.1.2-4:	Experimental results of sine response for $\alpha$ -direction. ....	158
Fig. 5.1.2-5:	Experimental results of simultaneous sine response for $x$ -, $y$ - and $\alpha$ -directions. ....	159
Fig. 5.1.2-6:	Frequency spectra of $x$ -position errors ( $x_{ref} - x$ ) and $q$ -axis currents $I_{qx}$ for $x$ -directional drive in Experiments (II) and (IV). ....	160
Fig. 5.2.1-1:	Characteristics of planar actuator for $\alpha$ -direction. ....	162
Fig. 5.2.2-1:	Experimental results of ramp response for $\alpha$ -direction at yaw angle $\alpha \approx 0$ deg. ....	165
Fig. 5.2.2-2:	Experimental results of ramp response for $\alpha$ -direction at yaw angle $\alpha > 20$ deg. ....	166
Fig. 5.2.2-3:	Experimental results of 90-deg stepping response for $\alpha$ -direction. ...	167
Fig. 5.2.2-4:	Experimental results of multiple 90-deg stepping response for $\alpha$ -direction. ....	168
Fig. 6.1.2-1:	Analytical model for 6-DOF driving forces. ....	174
Fig. 6.1.2-2:	Flux-density distribution on the plane 0.5 mm below the mover bottom. ....	175
Fig. 6.1.2-3:	Driving forces for yaw angle $\alpha$ at pitch and roll angles $\beta = \gamma = 0$ deg when the armature currents for the $x$ -directional drive are supplied. ....	178
Fig. 6.1.2-4:	Driving forces for yaw angle $\alpha$ at pitch and roll angles $\beta = \gamma = 0$ deg when the armature currents for the $y$ -directional drive are supplied. ....	179

Fig. 6.1.2-5:	Relation between pitch lengths of the meander shape and magnetic pole when the yaw angle $\alpha = 23.6$ deg. ....	180
Fig. 6.1.2-6:	Integration of flux density $B_z$ along a line $l_{jk}$ in armature conductors when the yaw angle $\alpha = 45$ deg. ....	180
Fig. 6.1.2-7:	Driving forces for pitch angle $\beta$ at yaw and roll angles $\alpha = \gamma = 0$ deg when the armature currents for the $x$ -directional drive are supplied. ....	181
Fig. 6.1.2-8:	Driving forces for pitch angle $\beta$ at yaw and roll angles $\alpha = \gamma = 0$ deg when the armature currents for the $y$ -directional drive are supplied. ....	182
Fig. 6.1.2-9:	Schematic views of generation of torques $T_y$ . ....	183
Fig. 6.1.2-10:	Driving forces for roll angle $\gamma$ at yaw and pitch angles $\alpha = \beta = 0$ deg when the armature currents for the $x$ -directional drive are supplied. ....	184
Fig. 6.1.2-11:	Driving forces for roll angle $\gamma$ at yaw and pitch angles $\alpha = \beta = 0$ deg when the armature currents for the $y$ -directional drive are supplied. ....	185
Fig. 6.1.2-12:	Schematic views of generation of torques $T_x$ . ....	186
Fig. 6.1.3-1:	Conceptual design of a magnetically levitated planar actuator. ..	189
Fig. 6.1.3-2:	Allowable maximum width of the armature conductors determined by pitch length of those. ....	190
Fig. 6.1.3-3:	New introduced armature conductors tilted in the yaw direction ....	190
Fig. 6.1.3-4:	Magnetically levitated planar actuator. ....	192
Fig. 6.2.1-1:	Mover with mover-coordinate axes $x_m y_m z_m$ and stationary-coordinate axes $x_s y_s z_s$ . ....	196
Fig. 6.2.1-2:	Rectangular prism with two mutually-parallel coordinate axes. ·	196
Fig. 6.2.2-1:	Definition of Euler angle $\phi = [\alpha \ \beta \ \gamma]^T$ . ....	197
Fig. 6.2.2-2:	Angular velocity $\omega_{sm}' = [\omega_x \ \omega_y \ \omega_z]^T$ and Euler angle $\phi = [\alpha \ \beta \ \gamma]^T$ . ....	200
Fig. 6.3.1-1:	$dq$ -frame and $\alpha'\beta'$ -frame for the $x$ -, $y$ -, and $\alpha$ -directional drives. ....	203

Fig. 6.3.1-2:	Phasor diagram showing relation between $dq$ -frame and $\alpha'\beta'$ -frame. .....	203
Fig. 6.3.1-3:	Control method for driving forces. ....	204
Fig. 6.3.2-1:	Analysis result of torque $T_z'$ due to the armature currents for the $x$ -directional drive for the Euler angle $\alpha$ . ....	206
Fig. 6.3.2-2:	Analysis result of torque $T_y'$ due to the armature currents for the $x$ -directional drive for the Euler angle $\beta$ . ....	207
Fig. 6.3.2-3:	Analysis result of torque $T_x'$ due to the armature currents for the $x$ -directional drive for the Euler angle $\gamma$ . ....	208
Fig. 6.3.2-4:	Analysis result of the torques from the armature conductors for the $\alpha$ -directional drive for the Euler angle $\alpha$ at $(\beta, \gamma) = (0, 0)$ . ....	211
Fig. 6.3.2-5:	Analysis result of the torques from the armature conductors for the $\alpha$ -directional drive for the Euler angle $\alpha$ at $(\beta, \gamma) = (2, 2)$ . ....	212
Fig. 6.4.1-1:	Flow chart of 6-DOF motion analysis. ....	214
Fig. 6.4.2-1:	Analytically-obtained mover motions under analysis condition (I). .. .....	216
Fig. 6.4.2-2:	Analytically-obtained armature currents under analysis condition (I). .....	217
Fig. 6.4.2-3:	Analytically-obtained mover motions under analysis condition (II). · .....	218
Fig. 6.4.2-4:	Analytically-obtained armature currents under analysis condition (II). .....	219
Fig. A-1:	Fabrication procedure for the smallest 2-D Halbach permanent- magnet array. ....	228
Fig. B-1:	Structure of the double-layered printed circuit board. The solid lines represent the copper film and the dashed lines represent external circuits. ....	230
Fig. B-2:	Photograph of the manufactured double-layered printed circuit board. .....	231
Fig. B-3:	Cross-section view of triple-layered printed circuit board. ....	232

Fig. B-4:	Structure of the first conductor layer. Red and pink lines represent the two-phase armature conductors for the $x$ -directional drive; dark and light green lines represent the two-phase armature conductors for the $y$ -directional drive; and dark and light blue lines represent the two-phase armature conductors for the $\alpha$ -directional drive. ....233
Fig. B-5:	Structure of the second conductor layer. Red and pink lines represent the two-phase armature conductors for the $x$ -directional drive; dark and light green lines represent the two-phase armature conductors for the $y$ -directional drive; and dark and light blue lines represent the two-phase armature conductors for the $\alpha$ -directional drive. ....234
Fig. B-6:	Structure of the third conductor layer. Dark and light blue lines represent the two-phase armature conductors for the $\alpha$ -directional drive. ....235
Fig. B-7:	Photographs of the manufactured triple-layered printed circuit board. ....236
Fig. C-1:	Position relation among the six laser beams and mover. ....240
Fig. C-2:	Definition of displacements in the measurement points of Sensors 4, 5, and 6 from the base positions ( $\Delta S_4$ , $\Delta S_5$ , and $\Delta S_6$ ). ....241
Fig. C-3:	Displacements in the measurement points of Sensors 4, 5, and 6 from the base positions ( $\Delta S_4$ , $\Delta S_5$ , and $\Delta S_6$ ). ....241
Fig. C-4:	Definition of the normal vector of each surface $n_{msi}$ and the position vector of each surface center $r_{msi}$ with respect to the sensor coordinate $x y z t$ . ....242
Fig. C-5:	Calculation procedure for the 6-DOF position from the output signals of the six laser-displacement sensors. ....245
Fig. C-6:	Fabrication of position-sensing system with 6 DOF. ....246

# List of Tables

Table S-1:	Classification of synchronous planar actuators by mover type, coil, and degree-of-freedom of controlled motion. ....	5
Table 1.2.1-1:	Magnetic characteristics of rare-earth magnets [Fuk04]. ....	36
Table 2.5.0-1:	Classification of synchronous planar actuators by mover type, coil, and DOF of controlled motion. ....	110
Table 2.5.0-2:	Classification of synchronous planar actuators by magnet array and coil assembly. ....	110
Table 3.2.1-1:	Specifications of 2-D permanent-magnet mover. ....	120
Table 3.2.2-1:	Specifications of double-layered printed circuit board. ....	122
Table 6.1.3-1:	Specifications of miniaturized permanent-magnet mover. ....	193
Table 6.1.3-2:	Specifications of triple-layered printed circuit board. ....	193

## List of Symbols

$a$	side of square mover (m) or first element of displacement vector $d_i$ (m)
$\mathbf{B}$	vector of flux density (T)
$B$	flux density (T)
$(BH)_{\max}$	maximum magnetic energy product (kJ/m <sup>3</sup> )
$B_r$	residual flux density (T)
$B_x$	flux density in $x$ -direction (T)
$B_y$	flux density in $y$ -direction (T)
$B_z$	flux density in $z$ -direction (T)
$B_{zm}$	maximum flux density in $z$ -direction due to magnet arrays dealt with in this study (T)
$B_{zm1}$	maximum of flux density $B_{z1}$ (T)
$B_{zm2}$	maximum of flux density $B_{z2}$ (T)
$B_{z0}$	maximum flux density in $z$ -direction due to magnet array shown in Fig. 3.1.2-1 (T)
$B_{z1}$	flux density in $z$ -direction due to Jung's proposed magnet array (T)
$B_{z2}$	flux density in $z$ -direction due to Compter's proposed magnet array (T)
$b$	second element of displacement vector $d_i$ (m)
$c$	third element of displacement vector $d_i$ (m)
$D_F$	differential parameters of PID controller for translational force (Ns/m)
$D$	reference distance of laser-displacement sensor (m)
$D_{T\alpha}$	differential parameters of PID controller for torque (1/s)
$d_i$	displacement vector (m)
$d\mathbf{F}$	vector of translational force acting on line element $dl_{jk}$ (N)
$db_4$	distance between sensor head and measurement point in Sensors 4 (m)
$db_5$	distance between sensor head and measurement point in Sensors 5 (m)
$db_6$	distance between sensor head and measurement point in Sensors 6 (m)
$dl_{jk}$	line element of armature conductor $l_{jk}$ (m), where $j$ ( $= x$ or $y$ ) and $k$ ( $= u, v, \text{ or } w$ ) express driving direction and phase name of three-phase currents, respectively
$d\mathbf{T}$	vector of torque acting on line element $dl_{jk}$ (N·m)
$dt$	time step in motion analysis (s)
$E$	unit matrix
$F$	vector of translational force with respect to stationary coordinate (N)

$F_g$	forces of gravity acting on mover (N)
$F_L$	Lorentz force (N)
$F_{sm}$	vector of translational force with respect to stationary coordinate (N)
$F_x$	translational force in $x_s$ -direction (N)
$F_y$	translational force in $y_s$ -direction (N)
$F_z$	translational force in $z_s$ -direction (N)
$g$	acceleration of gravity ( $m/s^2$ )
$H$	intensity of magnetic field (A/m)
$H_c$	coercive force (A/m)
$h$	height of mover (m)
$I_c$	current limit (A)
$I_j$	amplitude of three-phase current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$I_{1j}$	first two-phase current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$I_{2j}$	second two-phase current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$I_{dj}$	direct-axis current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$I_{qj}$	quadrature-axis current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$I_0$	amplitude of three-phase current (A)
$i$	vector of armature current (A)
$i_j$	two-phase armature current (A), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$i_{jk}$	vector of armature current (A), where $j$ ( $= x \text{ or } y$ ) and $k$ ( $= u, v, \text{ or } w$ ) express driving direction and phase name of three-phase current, respectively
$i_{ju}$	first three-phase armature current (A), where $j$ ( $= x \text{ or } y$ ) expresses driving direction
$i_{jv}$	second three-phase armature current (A), where $j$ ( $= x \text{ or } y$ ) expresses driving direction
$i_{jw}$	third three-phase armature current (A), where $j$ ( $= x \text{ or } y$ ) expresses driving direction
$i_k$	three-phase armature current in basic coreless linear synchronous motor (A), where $k$ ( $= u, v, \text{ or } w$ ) expresses driving direction
$J_m'$	inertia tensor of mover with respect to mover coordinate $x_m y_m z_m$ ( $kg \cdot m^2$ )
$J_s'$	inertia tensor of mover with respect to stationary coordinate $x_s y_s z_s$ ( $kg \cdot m^2$ )
$J_O'$	inertia tensor of rectangular prism with respect to stationary coordinate $x_s y_s z_s$ ( $kg \cdot m^2$ )
$J_{O_t}'$	inertia tensor rectangular prism with respect to coordinate $x_t y_t z_t$ ( $kg \cdot m^2$ )

$J_{jk}$	element of inertia tensor of mover ( $\text{kg}\cdot\text{m}^2$ ), where $j$ and $k$ ( $= x, y, \text{ or } z$ ) express mover-coordinate axes
$K$	$6 \times 6$ matrix of system constant (N/A or N·m/A)
$K_{FT}$	$6 \times 4$ matrix of system constant (N/A or N·m/A)
$K_{FC}$	approximated system constant (N/A)
$K_{Fx}$	system constant in translational force due to armature current for $x$ -directional drive (N/A)
$K_{Fy}$	system constant in translational force due to armature current for $y$ -directional drive (N/A)
$K_{TC}$	approximated system constant (N·m/A)
$K_{TP}$	approximated system constant per rotational angle (N·m/rad·A)
$K_{Tx}$	system constant in torque due to armature current for $x$ -directional drive (N·m/A)
$K_{Ty}$	system constant in torque due to armature current for $y$ -directional drive (N·m/A)
$K_{ab}$	$a \times b$ element of matrix of system constant (N/A or N·m/A), where $a$ and $b$ are 1, 2, 3, 4, 5, or 6
$K_u$	magnetic anisotropic energy ( $\text{MJ}/\text{m}^3$ )
$l$	length of mover (m)
$l_{jk}$	armature conductor, where $j$ ( $= x$ or $y$ ) and $k$ ( $= u, v, \text{ or } w$ ) express driving direction and phase name of three-phase current, respectively
$l_x$	length of first edge of rectangular prism (m)
$l_y$	length of second edge of rectangular prism (m)
$l_z$	length of third edge of rectangular prism (m)
$M_i$	infinitesimal rotation generator, where $i$ is 1, 2, or 3
$M$	magnetic polarization (A/m) or mass of mover (kg)
$M_r$	residual magnetic polarization (A/m)
$M_s$	saturation magnetic polarization (A/m)
$N_i$	positive number
$\mathbf{n}_{msi,0}$	normal vector $\mathbf{n}_{msi}$ when mover is not displaced from base position
$\mathbf{n}_{msi}$	normal vector of surface $i$ with respect to sensor coordinate $x_j y_j z_j$ , where $i$ is 1, 2, 3, 4, 5, or 6
$n$	number of armature conductors
O	origin of stationary coordinate or origin of laser coordinate
O'	origin of mover coordinate
$P_F$	proportional parameters of PID controller for translational force (N/m)

$P_{T\alpha}$	proportional parameters of PID controller for torque (1/s <sup>2</sup> )
$R$	rotational matrix
$R_{lm}$	orientation of mover with respect to laser coordinate $x_l y_l z_l$
$R_{ms}$	orientation of stationary coordinate $x_s y_s z_s$ with respect to mover coordinate $x_m y_m z_m$
$R_{sl}$	orientation of laser coordinate $x_l y_l z_l$ with respect to stationary coordinate $x_s y_s z_s$
$R_{sm}$	orientation of mover coordinate $x_m y_m z_m$ with respect to stationary coordinate $x_s y_s z_s$
$R_{s1}$	rotation matrix from stationary coordinate $x_s y_s z_s$ to coordinate $x_1 y_1 z_1$
$R_{\omega\phi}$	3 × 3 matrix relating angular velocity to differential of Euler angle
$R_\psi$	rotational matrix as $\psi$ counterclockwise rotation about rotational vector $\lambda$
$R_{12}$	rotation matrix from coordinate $x_1 y_1 z_1$ to coordinate $x_2 y_2 z_2$
$R_{2m}$	rotation matrix from coordinate $x_2 y_2 z_2$ to mover coordinate $x_m y_m z_m$
$R$	resistance of armature conductor ( $\Omega$ )
$r$	position vector from rotation center with respect to mover-coordinate axes (m)
$r_i$	vector of initial position of mover (m)
$r_{jk}$	position vector of line element $dl_{jk}$ (m)
$r_{li}$	path of laser beam from Sensor $i$ with respect to sensor coordinate $x_l y_l z_l$ (m), where $i$ is 1, 2, 3, 4, 5, or 6
$r_{lm}$	mover position with respect to laser coordinate $x_l y_l z_l$ (m)
$r_{lsi}$	position vector of arbitrary point on a surface $i$ with respect to the sensor coordinate $x_l y_l z_l$ , where $i$ is 1, 2, 3, 4, 5, or 6
$r_{msi,0}$	position vector $r_{msi}$ when mover is not displaced from base position (m)
$r_{msi}$	position vector of center of surface $i$ with respect to sensor coordinate $x_l y_l z_l$ , where $i$ is 1, 2, 3, 4, 5, or 6 (m)
$r_m$	position vector of mover center (m)
$r_{sm}$	position vector of mover with respect to stationary coordinate $x_s y_s z_s$ (m)
$r$	radial coordinate (m)
$S_1$	output signal of laser-displacement sensor 1 (m), commuted from voltage signal to position signal
$S_2$	output signal of laser-displacement sensor 2 (m), commuted from voltage signal to position signal
$S_3$	output signal of laser-displacement sensor 3 (m), commuted from voltage signal to position signal
$T$	vector of torque with respect to stationary coordinate (N·m)
$T_{sm}'$	vector of torque with respect to mover coordinate (N·m)

$T_x$	torque around $x_s$ -axis (N·m)
$T_x'$	torque around $x_m$ -axis (N·m)
$T_{xa}'$	torque due to armature currents $i_x$ and $i_y$ around $x_m$ -axis (N·m)
$T_y$	torque around $y_s$ -axis (N·m)
$T_y'$	torque around $y_m$ -axis (N·m)
$T_z$	torque around $z_s$ -axis (N·m)
$T_z'$	torque around $z_m$ -axis (N·m)
$T_{za}'$	torque due to armature currents $i_x$ and $i_y$ around $z_m$ -axis (N·m)
$T_c$	Curie temperature (°C)
$t$	time in experiment or analysis (s)
$t_c$	control period (s)
$V$	volume of mover (m <sup>3</sup> )
$v_{sm}$	velocity vector of mover with respect to stationary coordinate (m/s)
$v_{jk}$	armature voltage (V), where $j$ (= $x$ or $y$ ) and $k$ (= $u$ , $v$ , or $w$ ) express driving direction and phase name of three-phase current, respectively
$w$	width of mover
$X_1$	$x$ -position of measurement point of Sensor 1 (m)
$x$	first coordinate (m)
$x_l$	first coordinate of 2-D Halbach permanent-magnet array (m) or first laser coordinate (m)
$x_m$	first mover coordinate (m)
$x_s$	first stationary coordinate (m)
$x_\alpha$	first coordinate of armature conductors for $\alpha$ -directional drive (m)
$x_0$	position of multipole permanent-magnet array (m)
$x_1$	first immediate coordinate after first rotation (m)
$x_{12}$	relative distance between Sensor 1 and Sensor 2 in $x$ -direction (m)
$x_2$	first immediate coordinate after second rotation (m)
$x_{23}$	relative distance between Sensor 2 and Sensor 3 in $x$ -direction (m)
$x_{45}$	relative distance between Sensor 4 and Sensor 5 in $x$ -direction (m)
$Y_2$	$y$ -position of measurement point of Sensor 2 (m)
$Y_3$	$y$ -position of measurement point of Sensor 3 (m)
$y$	second coordinate (m)
$y_{L1}$	first length defined by Fig. C-3
$y_{L2}$	second length defined by Fig. C-3
$y_l$	second coordinate of 2-D Halbach permanent-magnet array (m) or second laser coordinate (m)

$y_m$	second mover coordinate (m)
$y_s$	second stationary coordinate (m)
$y_\alpha$	second coordinate of armature conductors for $\alpha$ -directional drive (m)
$y_1$	second immediate coordinate after first rotation (m)
$y_{12}$	relative distance between Sensor 1 and Sensor 2 in $y$ -direction (m)
$y_2$	second immediate coordinate after second rotation (m)
$y_{23}$	relative distance between Sensor 2 and Sensor 3 in $y$ -direction (m)
$y_{56}$	relative distance between Sensor 5 and Sensor 6 in $y$ -direction (m)
$z$	third coordinate (m)
$z_l$	third laser coordinate (m)
$z_m$	third mover coordinate (m)
$z_s$	third stationary coordinate (m)
$z_1$	third immediate coordinate after first rotation (m)
$z_2$	third immediate coordinate after second rotation (m)
$\alpha$	yaw angle (rad) or first Euler angle (rad)
$\alpha_l$	first Euler angle defined by rotations around $z_l$ -, $y_l$ -, and $x_l$ -axes (rad)
$\alpha_l'$	tilted angle about $z_l$ -axis in $x_l$ - $y_l$ plane (rad)
$\alpha_{\min}$	yaw angle defined by Eq. (4.2.2-1) (rad)
$\alpha_{\max}$	yaw angle defined by Eq. (4.2.2-2) (rad)
$\alpha_s$	phase of magnetic field due to magnet mover for $\alpha$ -directional drive (m)
$\alpha_0$	yaw angle defined by Eq. (6.1.2-1) (rad)
$\beta$	pitch angle (rad) or second Euler angle (rad)
$\beta_l$	second Euler angle defined by rotations around $z_l$ -, $y_l$ -, and $x_l$ -axes (rad)
$\beta_l'$	tilted angle of mover to $x_l$ - $y_l$ plane about $y_l$ -axis (rad)
$\Delta S_4$	displacement in measurement point of Sensor 4 from base position (mm)
$\Delta S_5$	displacement in measurement point of Sensor 5 from base position (mm)
$\Delta S_6$	displacement in measurement point of Sensor 6 from base position (mm)
$\delta_{jk}$	Kronecker delta, where $j$ and $k$ ( $= x, y, \text{ or } z$ ) express mover-coordinate axes
$\gamma$	roll angle (rad) or third Euler angle (rad)
$\gamma_l$	third Euler angle defined by rotations around $z_l$ -, $y_l$ -, and $x_l$ -axes (rad)
$\gamma_l'$	tilted angle about $x_l$ -axis in cross-section B-B' shown in Fig. C-3 (rad)
$\phi$	vector of Euler angle (rad)
$\phi_0$	vector of initial Euler angle (rad)
$\phi_l$	vector of Euler angle defined by rotations around $z_l$ -, $y_l$ -, and $x_l$ -axes (rad)
$\phi$	electrical phase

$\varphi$	tilted angle of armature conductors for $\alpha$ -directional drive from those for $x$ -directional drive (rad)
$\lambda$	rotational vector
$\lambda_{lx}$	unit vector of $x_s$ -axis with respect to laser coordinate $x_l y_l z_l$
$\lambda_{ly}$	unit vector of $y_s$ -axis with respect to laser coordinate $x_l y_l z_l$
$\lambda_{ms}$	unit vector of $x_s$ -axis with respect to coordinate $x_2 y_2 z_2$
$\lambda_{1s}$	unit vector of $z_s$ -axis with respect to stationary coordinate $x_s y_s z_s$
$\lambda_{2s}$	unit vector of $y_s$ -axis with respect to coordinate $x_1 y_1 z_1$
$\theta_s$	phase of three-phase current (rad)
$\theta_{sj}$	phase of three-phase current (rad), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$\theta_{dj}$	phase difference between magnetic fields generated by armature conductors and mover (rad), where $j$ ( $= x, y, \text{ or } \alpha$ ) expresses driving direction
$\theta_4$	tilted angle of laser beam from Sensors 4 to $z_l$ -axis (rad)
$\theta_5$	tilted angle of laser beam from Sensors 5 to $z_l$ -axis (rad)
$\theta_6$	tilted angle of laser beam from Sensors 6 to $z_l$ -axis (rad)
$\rho$	mass density of mover ( $\text{kg/m}^3$ )
$\tau$	length of pitch of planar actuator (m)
$\tau_{PM}$	length of pole pitch due to 2-D Halbach permanent-magnet array in $x_l$ - or $y_l$ -directions (m)
$\tau_0$	length of pitch of multipole permanent-magnet array (m)
$\omega_{sm}'$	angular velocity of mover with respect to mover coordinate (rad/s)
$\chi$	magnetic susceptibility
$\psi$	rotational angle (rad)

In this thesis, superscript "\*" and subscript "ref" indicate reference signal.

# Chapter 1

## Introduction

This chapter introduces the background to this study, which includes general features, element technologies, and technical issues related to MDOF actuators. Next, the purpose and position of this study against this background, and the contribution of this thesis are presented.

# 1. Introduction

Conventionally, linear drives have been realized by a combination of rotary motors and reduction gears. Continual advances are being made to improve the speed of the drives and the precision of the positioning of motion controls, however, these drive systems have extremely complicated nonlinear phenomena such as friction and backlash, which makes it difficult to attain satisfactory drive performance. Against this background, direct drives have been attracting attention because they are high-performance drives that do not use reduction gears, and drive systems utilizing linear motors have replaced drive systems that use a combination of rotary motors and reduction gears in industry applications, for example in robots and machine tools.

Most industry applications require that drive systems be able to control MDOF motion. Motion controls with MDOF have to date been practically realized by stacking multiple linear motors. Looking ahead, MDOF actuators, which have only a single mover capable of being directly driven in MDOF, are emerging technologies for the future. MDOF actuators offer the following advantages: the center of mass of the mover does not fluctuate, easier creation of smaller structure, and a saving on energy consumption [MDD05].

This chapter introduces the general features, element technologies, and technical issues of MDOF actuators. Next, the purpose and position of this study against this background, and the contribution of this thesis are presented.

## 1.1. Actuators with MDOF

In an MDOF drive system built using stacked rotary and linear motors (one-degree-of-freedom, or 1-DOF, drive), the motor on the lower side of the drive system requires a high degree of torque to suspend the mass of the motor on the upper side of the drive system. Consequently the drive system tends to have a much larger structure than the load of its drive system [MDD05]. Furthermore, these drive systems have more complicated multi-body dynamics, which make it difficult to realize high-performance motion controls. On the other hand, MDOF actuators have only a single mover, which can be directly driven with MDOF, and they are therefore expected to gain acceptance as MDOF drive systems offering a simple structure and high performance [MDD05].

Most MDOF actuators can be classified into two prominent types [MDD05]: a planar actuator that can drive in two-degrees-of-freedom (2-DOF) translational directions; and,

a spherical actuator that can drive in 2-DOF rotational directions. As for the drive principles, electromagnetic, piezoelectric, magnetostrictive, and electrostatic types of MDOF actuators have been proposed. Most models are of the electromagnetic actuator type [MDD05, MDD07, MDD08].

Planar actuators have been studied with the primary objective of application in high-precision and high-speed stages in fields such as semiconductor manufacturing equipment, machine tools, and conveyance systems [MDD08]. To date, various types of planar actuators have been proposed, including stepping, induction, and synchronous types. In stepping planar actuators, the mover can be positioned without position sensors to a positioning accuracy of several tens of  $\mu\text{m}$ . In induction planar actuators, the mover consists of a single aluminum plate including a back iron, and the structure tends to be simple and solid. In synchronous planar actuators, the driving forces have a proportional dependence on the amplitude of polyphase current, and a sinusoidal dependence on the phase difference between the magnetic field generated by the stator and the mover. Therefore, synchronous planar actuators are often adopted because of their good controllability in terms of motion control. The mover of the planar actuator is suspended on ball bearings, air bearings, or magnetic bearings. The position of the mover is measured using a combinations of optical sensors (for example, laser interferometers, photodetectors, encoders, or 2-D angle sensors), and magnetic sensors (for example, Hall elements, or differential transformers), inductive sensors or capacitance sensors.

Spherical actuators have been studied with the primary objective of usage in robot components, for example, their joints and eyes [MDD08]. Various types of planar actuators have been proposed including stepping, induction, synchronous, piezoelectric, and magnetostrictive models. The driving forces of electromagnetic spherical actuators (that is to say, stepping, induction, and synchronous types) have the same features as planar actuators. However, it is very difficult to suspend the mover and to sense position.

Piezoelectric actuators can drive the mover in close contact with the stator by controlling the piezoelectric strain on the stator, which is made of a piezoelectric material [Act04]. Piezoelectric actuators are generally small (less than several-cm in size), and can generate high-power driving forces and retaining forces with the power supply turned off. Therefore, piezoelectric actuators are suitable for small actuators used for short-stroke precise positioning. The mover is often precompressed by electromagnetic forces so that the mover is in close contact with the stator.

Magnetostrictive actuators drive the mover in close contact with the stator by

controlling the magnetostrictions of the stator, which is a magnetic material [Hig07]. Magnetostrictive actuators often have superior temperature characteristics and mechanical characteristics to those of piezoelectric actuators [Hig08a].

In electrostatic actuators, the driving force (electrostatic forces) per volume (unit:  $\text{m}^3$ ) is inversely proportional to their length (unit: m) [Act04]. When the dimensions of electrostatic actuators decrease, the driving force per mover weigh increases. Therefore, electrostatic actuators are being studied for use in micro-electro-mechanical systems (MEMS). In addition, high-power electrostatic actuators having dimensions of a few cm can be realized by integrating micro-electrostatic actuators. To generate a sufficient driving force, however, it is necessary to supply several kV of power across the gap between the moving and stationary electrodes, which is a sub-mm gap, and to design electrostatic actuators that are not subject to dielectric breakdown.

## 1.2. Element Technologies of MDOF Actuators

To construct MDOF actuators, various technologies such as driving force generation, position sensing, and suspension and guide mechanisms are absolutely essential [MDD07]. First, driving forces with some degree of freedom need to be independently generated. Second, the mover position in all driving directions needs to be detected precisely within a short time period. Finally, the mover motion—except in the driving directions—should be constrained, having less influence on the mover motion in the driving directions. In electromagnetic actuators with MDOF, the performance of the driving forces depends on the characteristics of the magnetic material used and the configuration of the magnetic circuits. This section introduces element technologies of electromagnetic MDOF actuators such as magnetic materials, magnetic circuits, position-sensing methods, and suspension and guide mechanisms.

### 1.2.1. Magnetic Materials

Most electromagnetic actuators with MDOF make use of permanent magnets to achieve both a compact structure and high-power driving forces [MDD05, MDD07]. Thus, permanent magnets are essential for these actuators, and they are created by magnetizing magnetic materials. The magnetic characteristics of these magnetic materials are vitally important in the design of high-performance actuators.

As we know, ferromagnetic materials polarize in a magnetic field  $H$ . Figure 1.2.1-1 shows the magnetic polarization  $M$ , and flux density  $B$ , of a ferromagnetic material when the material is positioned in the magnetic field  $H$ ; the  $M$ - $H$  curve and  $B$ - $H$  curve have hysteretic properties. In Fig. 1.2.1-1, the residual flux density, coercive force, residual magnetic polarization, saturation magnetic polarization, and magnetic susceptibility are expressed as  $B_r$ ,  $H_c$ ,  $M_r$ ,  $M_s$ , and  $\chi$ , respectively [Sag07].

To evaluate the performance of a permanent magnet, a maximum energy product  $(BH)_{\max}$  is often utilized, which expresses the maximum magnetic energy stored in a permanent magnet, and depends on the residual flux density  $B_r$  and coercive force  $H_c$ . Rare-earth magnets, which are alloys with rare-earth metals and 3d transition metals, have the highest  $(BH)_{\max}$  of all known permanent magnets [Edw01, Sag07, Taw05]. To date, rare-earth magnets in which the main phase is  $\text{SmCo}_5$ ,  $\text{Sm}_2\text{Co}_{17}$ ,  $\text{Nd}_2\text{Fe}_{14}\text{B}$ , or  $\text{Sm}_2\text{Fe}_{17}\text{N}_3$  have been presented [Fuk04]. Table 1.2.1-1 shows the magnetic characteristics and theoretical limitations of  $(BH)_{\max}$  of alloys with rare-earth and a transition metal [Fuk04]. Table 1.2.1-1 shows that a  $\text{Nd}_2\text{Fe}_{14}\text{B}$  magnet has a maximum limitation of  $(BH)_{\max}$ . In fact, a  $\text{Nd}_2\text{Fe}_{14}\text{B}$  magnet in which the  $(BH)_{\max}$  is more than 400  $\text{kJ/m}^3$  has been reported, and the  $(BH)_{\max}$  is developed further every year as shown in Fig. 1.2.1-2 and is close to the theoretical limit [Kan04].

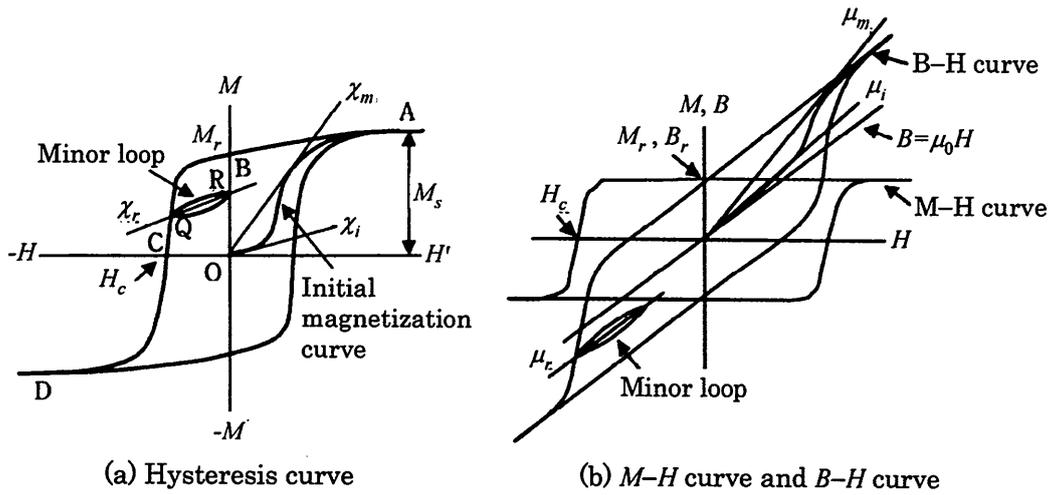


Fig. 1.2.1-1: Magnetic characteristics of ferromagnetic materials [Sag07].

Table 1.2.1-1: Magnetic characteristics of rare-earth magnets [Fuk04].

Material	$M_s$ (T)	$K_u$ (MJ/m <sup>3</sup> )	$T_c$ (°C)	$(BH)_{\max}$ (KJ/m <sup>3</sup> )
SmCo <sub>5</sub>	1.14	11–20	727	259
Sm <sub>2</sub> Co <sub>17</sub>	1.25	3.2	920	311
Nd <sub>2</sub> Fe <sub>14</sub> B	1.60	4.5	313	509
Sm <sub>2</sub> Fe <sub>17</sub> N <sub>3</sub>	1.57	21	474	490

$K_u$  : Magnetic anisotropic energy,  $T_c$  : Curie temperature

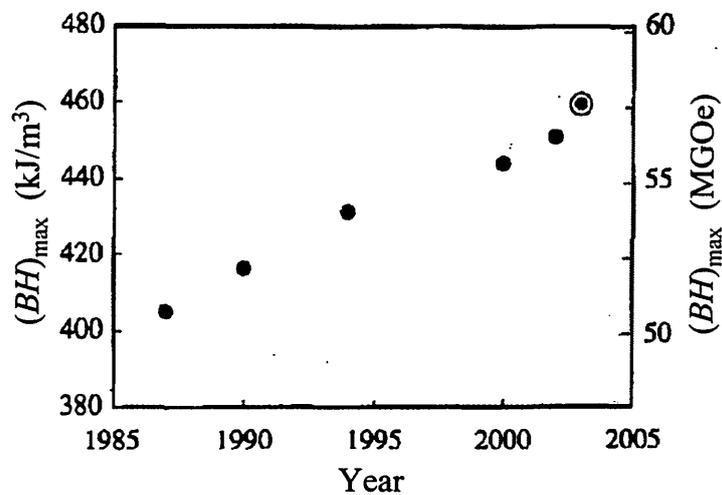


Fig. 1.2.1-2: Status of  $(BH)_{\max}$  of Nd-Fe-B sintered magnets [Kan04].

Enormous Nd-Fe-B permanent magnets are used in various types of motors and actuators in some industry applications, consumer electronics, and electronic devices, and absolutely contribute to the development of their miniaturization and high-power output. Permanent magnets are classified according to manufacturing process as major types [Edw01, Sag07, Taw05]: one is a sintered magnet, which has a high density of magnetic materials and high-performance magnetic characteristics; and the other is a bonded magnet, which has high mechanical strength and a great deal of flexibility in geometry. Recently, Nd-Fe-B sintered magnets are being increasingly used in motors as shown in Fig. 1.2.1-3, and are essential for the construction of electrical machines [Kan04]. In electronic devices such as computers, cameras, and cell-phones Nd-Fe-B bonded magnets, which have a great deal of flexibility are often applied [Joh97].

Figure 1.2.1-4 shows the production process of Nd-Fe-B sintered permanent magnets [Sag07]. The production process is classified as: powdering, forming, sintering, machining, surface treatment, and magnetization. In the sintering process, the formed powder is sintered at about 1100 °C, and contracts due to directional anisotropy, and therefore a machining process is required after the sintering process. Figure 1.2.1-5 shows the production process of Nd-Fe-B bonded permanent magnets, which does not include the machining process because there is no sintering process [Sag07].

In fact, permanent magnets should have a high heat resistance. The Curie temperature of Nd-Fe-B magnets is less than that of Sm-Co magnets. Furthermore, the coercive force of Nd-Fe-B magnets drastically decreases with an increase in temperature ( $-0.69\%/K$  in  $Nd_{15}Fe_{77}B_8$  magnets). To compensate for heating resistance, Dy or Tb are substituted for part of the Nd, and Sm-Fe-N magnets, which have about the same saturation magnetic polarization  $M_s$ , a high Curie temperature  $T_c$ , and a high corrosion resistance are expected to be substituted for Nd-Fe-B magnets. The addition of Dy or Tb to Nd-Fe-B magnets, however, decreases the saturation magnetic polarization  $M_s$ , and it is difficult to manufacture Sm-Fe-N sintered magnets because the Sm-Fe-N materials dissolve into Sm-N and Fe at 600 °C [Oza08]. Hence, it is necessary to improve the magnetic characteristics of permanent magnets.

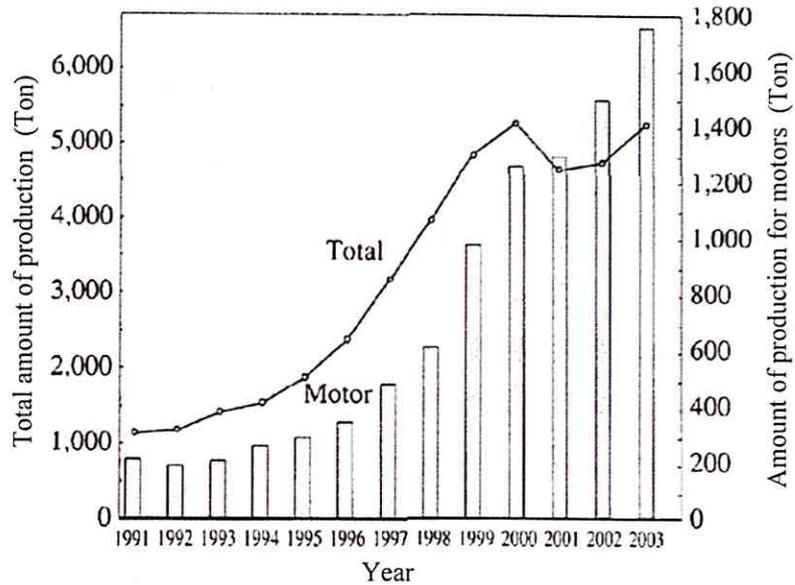


Fig. 1.2.1-3: Production of Nd-Fe-B sintered magnets for motors [Kan04].

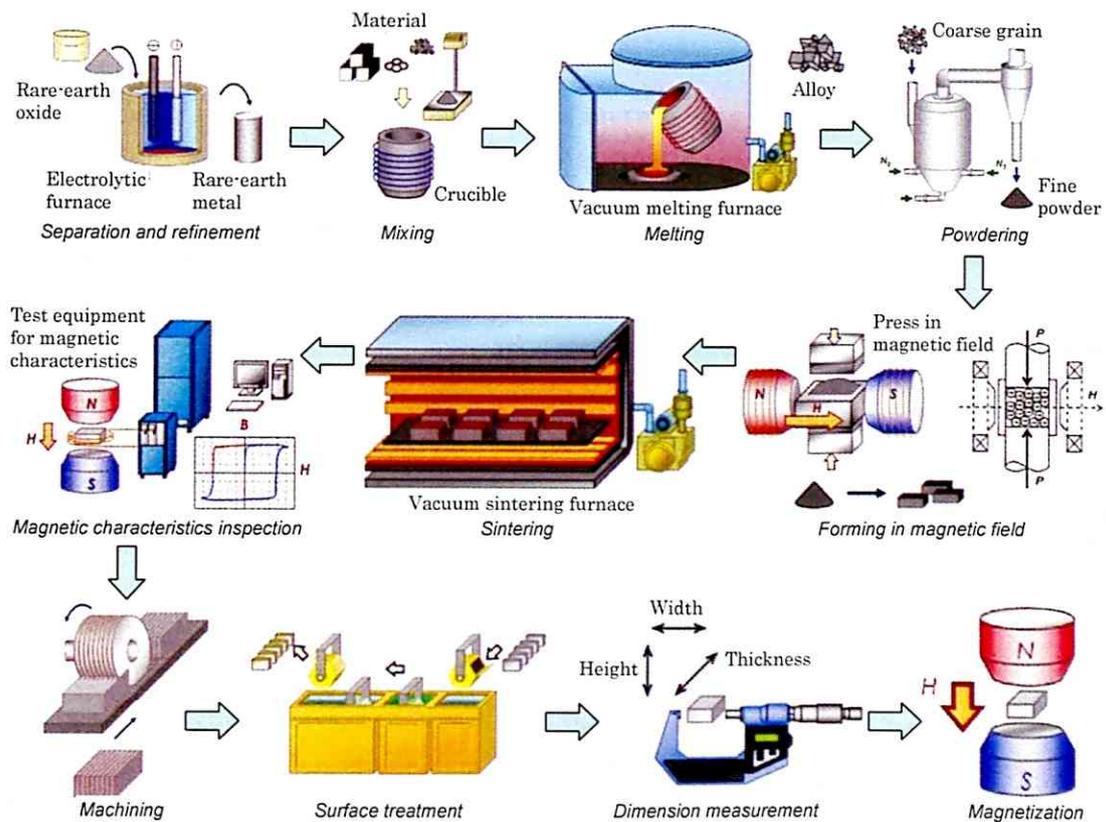


Fig. 1.2.1-4: Production process of Nd-Fe-B sintered permanent magnets [Sag07].

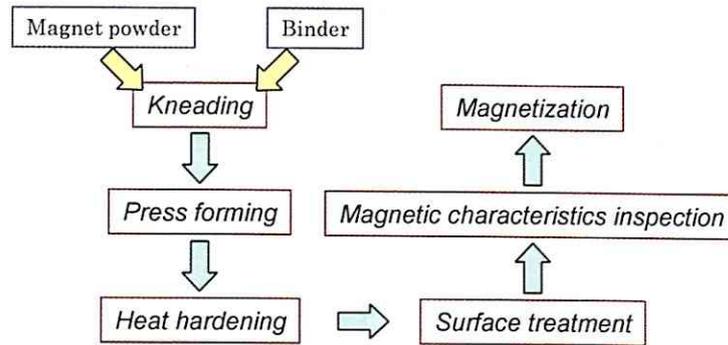


Fig. 1.2.1-5: Production process of Nd-Fe-B bonded permanent magnets [Sag07].

### 1.2.2. Magnetic Circuits

In MDOF actuators, the design of magnetic circuits, which involve magnetic materials, is absolutely essential in generating the MDOF driving forces. MDOF actuators have a magnetic circuit structure that basically extends the magnetic circuit of linear or rotary motors, and is based on drive principles such as stepping type, induction type, or synchronous type.

Stepping MDOF actuators can position a mover without position sensors, and were first put into practical use as drafting tools [MDD05]. Induction MDOF actuators have a simple, firm secondary conductor, and are being studied for application in transport switch systems in factories. Synchronous MDOF actuators offer good controllability of the driving forces, and therefore are being studied for use in the high-precision stages of semiconductor manufacturing, and in robot elements such as joints and eyes. Synchronous MDOF actuators often include permanent magnets to simplify and miniaturize their structure. Furthermore, to improve their drive performance in terms of such factors as speed and precision, synchronous MDOF actuators with a 2-D Halbach permanent-magnet array as shown in Fig. 1.2.2-1 have been studied. A Halbach permanent-magnet array generates a higher flux density and quasi-sinusoidal distribution with lower harmonic in the arranging direction than a NS permanent-magnet array does. Figure 1.2.2-2 shows the flux lines of NS and quasi-Halbach permanent-magnet arrays, and shows that the flux lines of the Halbach magnet array on one side are more densely and smoothly drawn than those of the NS magnet array [Jan07]. These Halbach magnetized actuators generate larger electromagnetic forces with less force ripples [How01].

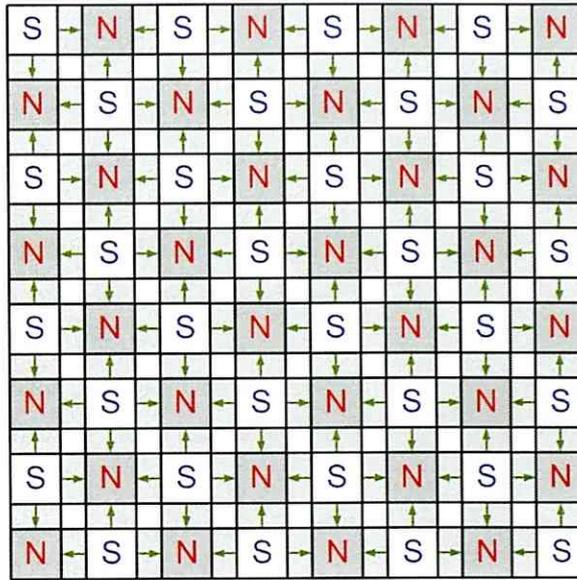
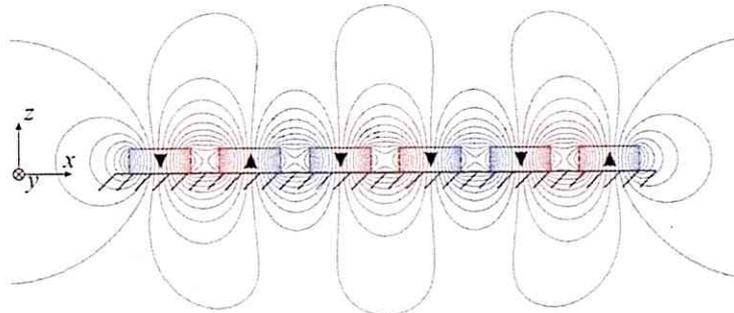
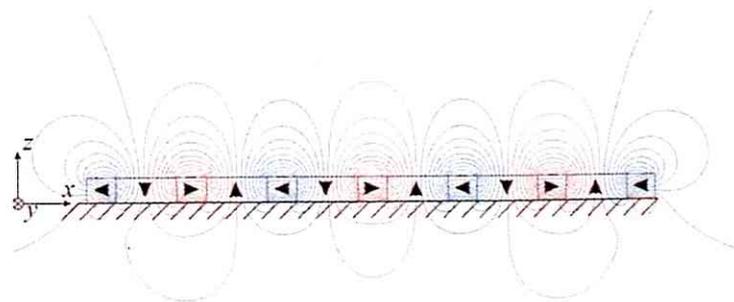


Fig. 1.2.2-1: 2-D Halbach permanent-magnet array.



(a) Flux lines of a NS magnet array.



(b) Flux lines of a quasi-Halbach magnet array with two magnet segments per pole.

Fig. 1.2.2-2: Magnetic fields of Halbach and NS magnet arrays [Jan07].

### 1.2.3. Position-Sensing Systems

The MDOF position-sensing systems of a mover are of particular importance for high-performance motion control. To date, the following method of position sensing with MDOF have been used:

- Laser interferometer [Has01, HOh07, Kim97, Kim98, Tom94, Tom96].
- Combination of laser and photodetector [Ebi03, Ebi05, Ebi89, Ebi91, GK101, GK194, Ohi06].
- Magnetic sensor [Com03, Com04, Com07, Ish97, Hol98, Phi06].
- Inductive sensor or capacitance sensor [HOh07, Kim97, Kim98, Jan07, Van07a, Van07b].
- Optical encoder [Chi99, Don00, Don02, Kiy04, Kiy05a, Kiy05b, Nis07, Toy07, Toy95, Toy96, TSh06, Yan07].

In the high-precision stages of semiconductor manufacturing, for which planar actuators are mostly applied, position-sensing systems are required to measure the mover position with resolutions of several nanometers, and therefore often include multiple laser interferometers, as shown in Fig. 1.2.3-1 [Kim97]. In these applications, a position-sensing method with MDOF that utilizes a 2-D angle grid and a 2-D angle sensor, called a Surface Encoder, as shown in Fig. 1.2.3-2, is an emerging technology [Kiy04, Kiy05a, Kiy05b]. The surface of the 2-D angle grid installed on the mover is patterned three-dimensionally and cyclically. The five-degrees-of-freedom positions of the mover, which are the  $x$ -,  $y$ -,  $\alpha$ -,  $\beta$ -, and  $\gamma$ -positions defined by Fig. 1.2.3-2, can be measured by detecting the diffraction pattern generated by irradiating the surface of the 2-D angle grid with multiple laser beams.

Some synchronous MDOF actuators with permanent magnets measure six-degree-of-freedom (6-DOF) mover positions by detecting the magnetic field using Hall elements, as shown in Fig. 1.2.3-3 [Com03, Com04, Com07]. Some variable reluctance-stepping-type planar actuators, often called Sawyer Motors, measure the  $x$ - and  $y$ -positions of the mover using multiple differential transformers, which are extremely easy to install in variable reluctance-stepping-type planar actuators, as shown in Fig. 1.2.3-4 [Hol98]. Most spherical actuators measure the mover position using optical encoders, as shown in Fig. 1.2.3-5 [Yan07].

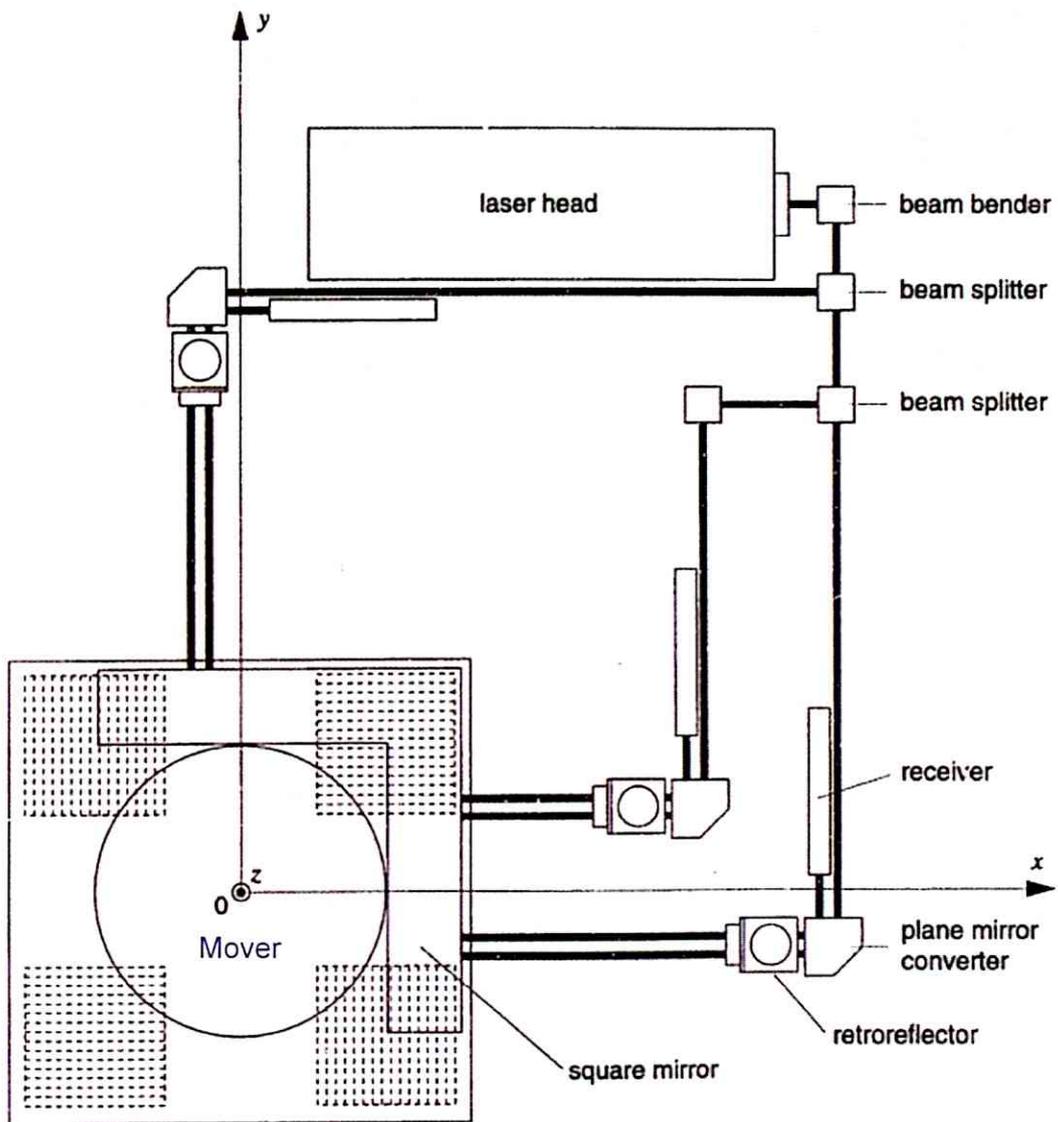


Fig. 1.2.3-1: Configuration of a position-sensing system using multiple laser interferometers [Kim97].

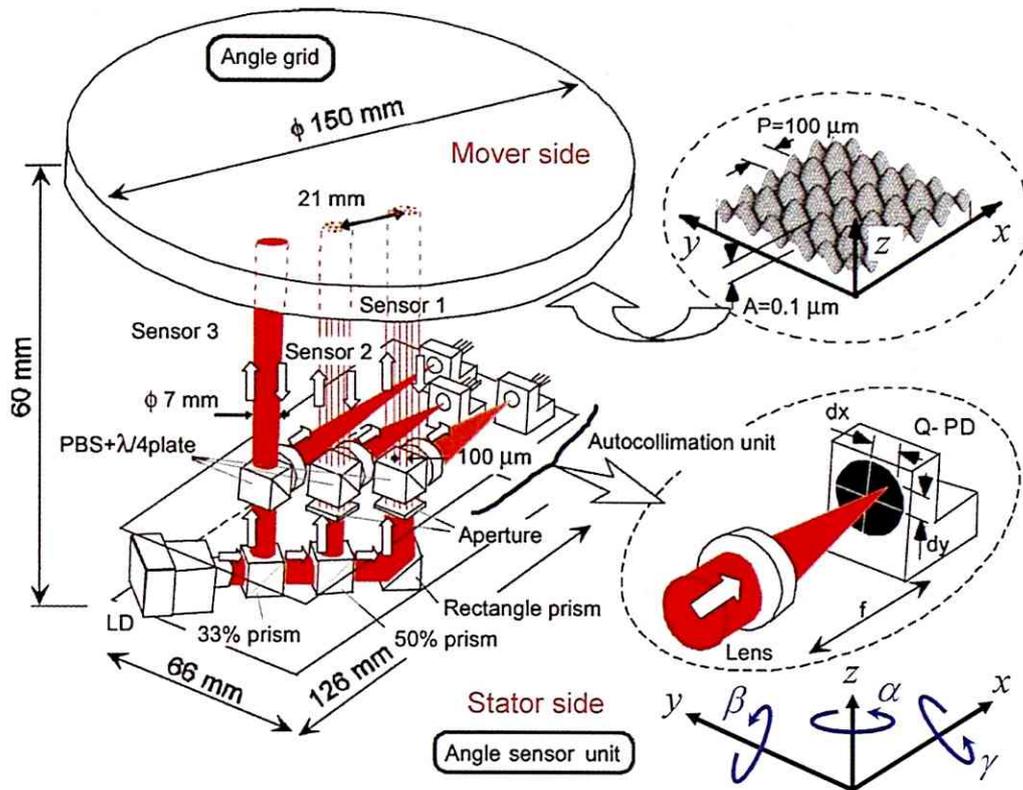


Fig. 1.2.3-2: Optical arrangement of a surface encoder [Kiy05].

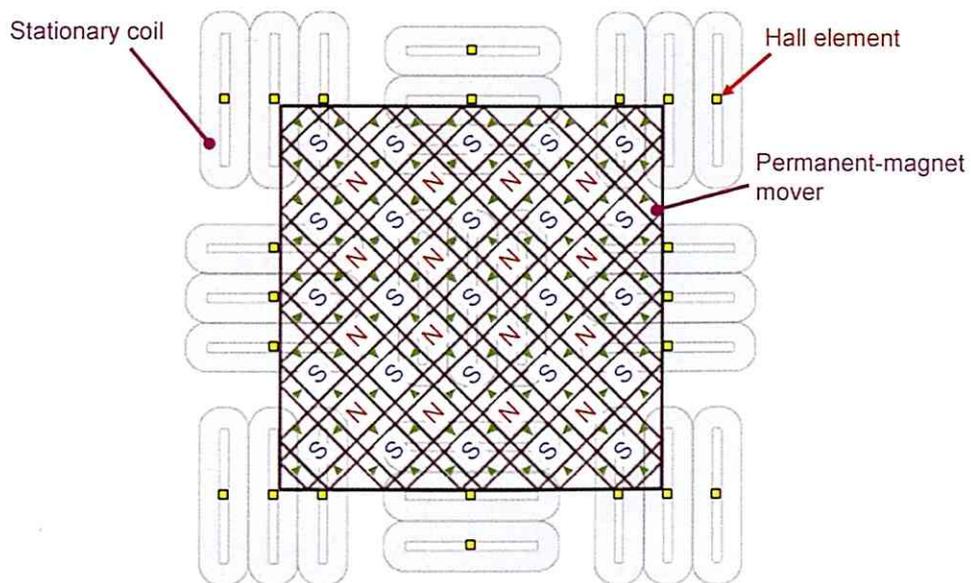


Fig. 1.2.3-3: Configuration of synchronous planar actuators with a position-sensing system that has multiple Hall elements [Com07, Jan07].

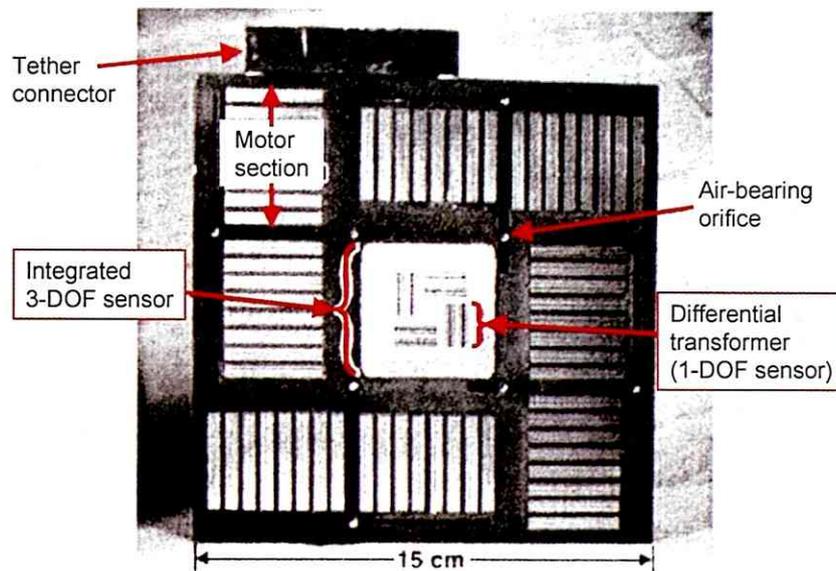


Fig. 1.2.3-4: Mover configuration of variable reluctance-stepping-type planar actuators with a position-sensing system that has multiple differential transformers [Hol98].

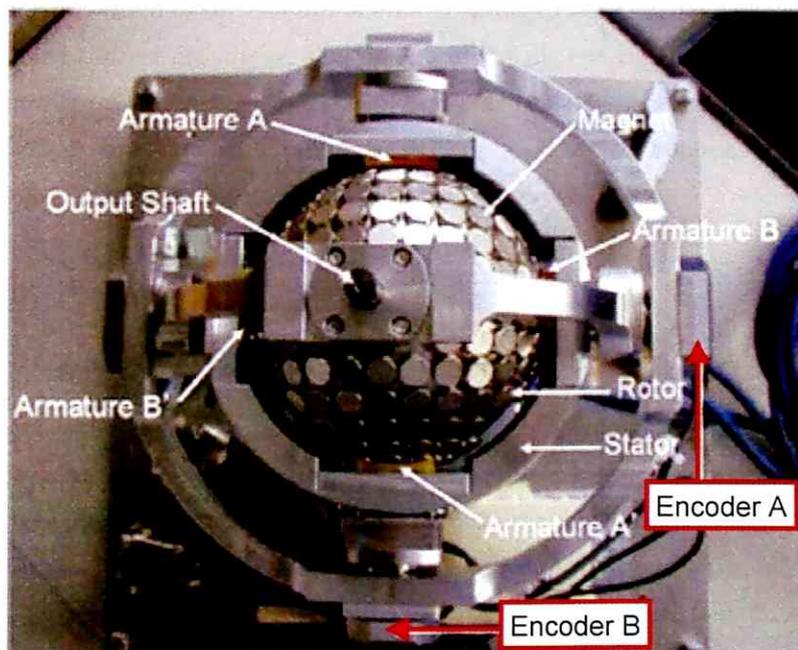


Fig. 1.2.3-5: Configuration of synchronous spherical actuators with a position-sensing system that has multiple optical encoders [Yan07].

#### 1.2.4. Suspension and Guide Mechanisms

Suspension mechanisms, which guide a mover in the driving directions and suppress it in the other directions, are a particularly important part of MDOF actuators. So far, the following methods of suspension and guide for the mover have been used:

- Oil lubrication [Don00, Don02]
- Ball bearings [Chi99, Ebi89, Ebi91, GK101, GK194, Ohi98, Rau06, Yan07]
- Air bearings [Has01, Hol98, Kiy04, Kiy05a, Kiy05b, Ohi98, Saw68, Tsh06, Tom94, Tom96]
- Magnetic bearings [Com03, Com04, Com07, Hig90, HOh07, Kim05, Kim97, Kim98, Kor06, Kos04, Ohi06, Phi06, Tru06, Van06, Van07a, Van07b]

Oil lubrication on a contact surface between the stator and mover is extremely easy to realize, although it cannot be expected to smoothly drive the mover because of the viscosity resistance [MDD07]. Ball bearings are relatively easy to install in the stator or mover and they can suspend and guide the mover relatively smoothly [MDD07].

Contactless suspension of the mover by air bearings or magnetic bearings enables the mover to smoothly move because there is no friction between the mover and stator [MDD07]. Air suspension has a much higher stiffness at a shorter gap between the mover and stator, which is several  $\mu\text{m}/\text{N}$  on a 10- $\mu\text{m}$  gap [Kiy04]. Therefore, air bearings are used in most planar actuators. The design of the air conduit and the compressor are extremely important parts of air bearings. Magnetic suspension requires not the design of an air conduit, but that of a magnetic circuit so that the suspension forces of the mover are generated without interfering with the driving forces.

### 1.3. Technical Issues with MDOF Actuators

MDOF actuators have three principally important element technologies: MDOF driving force generation, MDOF position sensing, and mover suspension and guides. Currently, the driving forces are generated multi-directionally, forming multiple magnetic circuits for unidirectional drive; mover positions are detected by a combination of position sensors for unidirectional displacement; and most movers are suspended and guided with ball bearings.

In most MDOF actuators that have been proposed, the magnetic circuits are all spatially separated from one another to make it easy to independently control the

driving forces with each degree of freedom. The configuration of the magnetic circuits, however, often makes the movable area of the mover extremely narrow, unless numerous coils are used. If numerous coils were utilized to extend the movable area, then the power-supply system would become more complicated. In an MDOF position-sensing system that combines multiple-position sensors for unidirectional displacement, the measurable area, where all position sensors can measure each displacement, also is extremely narrow.

As stated above, the following improvements in MDOF actuators are required:

- Extension of the MDOF movable area without a complicated power-supply system.
- Extension of the measurable area with MDOF.

## 1.4. Contributions of this Thesis

This section presents the purpose of this study and the approach taken to this goal, and clarifies the assertions and contributions of this thesis.

### 1.4.1. Purpose of this Study

This study targets the design of driving force-generation mechanisms and motion-control systems of a planar actuator that has a mover capable of traveling over large displacements along a plane. In this study, to realize a high-performance drive for the mover, a planar actuator that has the following specifications is designed;

- decoupled control for 3-DOF motions on a plane.
- a wide movable area that can be extended regardless of the number of armature coils.
- ease of mover miniaturization.
- absence of problematic wiring that can hinder drive performance.
- a small number of armature currents to control.

First, to realize a planar actuator that can control the driving forces over a wide movable area, I have to design the planar actuator so that the movable area can be given, regardless of the number of the armature coils. For that purpose, I propose magnetic circuits that are not separated spatially due to overlapped armature conductors. The configuration of the magnetic circuits is the most novel feature in this

study and enables the extension of the movable area by lengthening all the conductors, regardless of the number of conductors. However, the configuration of the magnetic circuits is not suitable for decoupled control of the MDOF driving forces because the magnetic fields, as a result of armature currents, are superimposed, and so a planar actuator with this type of magnetic circuit configuration has never been studied. This study asserts that it is possible to design a planar actuator so that the MDOF driving forces can be independently controlled using spatially superimposed magnetic circuits, and this assertion is the main contribution of this thesis.

Spatially superimposed magnetic circuits also allow the miniaturization of planar actuators, which was conventionally difficult. I see an application for this planar actuator for use as lens-driving-actuators in electronic devices, and this study involves the design of a planar actuator with a small mover—in the order of several tens of mm.

Finally, as a fundamental investigation of incremental improvements and to avoid deterioration of the drive characteristics caused by friction forces between the mover and stator, this study includes an investigation into the feasibility of magnetic suspension of the mover. This magnetically levitated planar actuator is defined as having six armature conductors, which is the minimum number of armature conductors needed to realize both magnetic suspension and planar motion control.

To perform an experimental verification of this planar actuator, I have to design the driving force-control system and position-sensing system with MDOF. In this study, the MDOF mover positions are detected using multiple laser-displacement sensors because of their fine precision. This sensing method gives a relatively wide measurable area, which is wide enough to investigate the drive characteristics of the proposed planar actuator.

#### 1.4.2. Procedures used in Conducting this Study

This thesis presents an investigation into the feasibility of my targeted planar actuator by going through the following four, ordered stages:

(I) Conceptual Design of a Long-Stroke 3-DOF Planar Actuator:

In this stage, a planar actuator with spatially superimposed magnetic circuits for 3-DOF motion control is conceptually designed to drive the mover over a wide movable area on a plane by controlling only two pairs of three-phase currents. Then, the fundamental characteristics

of the planar actuator are clarified and a 3-DOF decoupled motion-control system is designed.

(II) Design of an Experimental System for Verification of the Motion-Control Characteristics of the Planar Actuator:

In this stage, an experimental system for the verification of the motion-control characteristics of the planar actuator proposed in Stage (I) is designed, for example, the position-sensing system and the suspension and guide mechanisms. Specifications and characteristics of all the experimental apparatuses are described.

(III) Experimental Verification of the 3-DOF Motion-Control Characteristics of the Planar Actuator:

In this part, experiments on the motion-control characteristics of the planar actuator proposed in Stage (I) are conducted. There are two major experimental objectives: first, verification of decoupled control for the 3-DOF motion of the mover; and, second, investigation of the movable area of the mover in the yaw direction.

(IV) Feasibility Study on Planar Motion Control of the Planar Actuator with the Mover Magnetically Levitated:

In this stage, a planar actuator having the same configuration as the magnetic circuits for planar motion control is conceptually designed so that the mover can be magnetically suspended. The mover has 6-DOF motions (3-DOF translational and rotational motions), and so this stage introduces the 3-DOF translational and 1-DOF rotational motion-control system, which offers the other 2-DOF stable rotational motion, and an investigation of the motion-control characteristics by numerical analysis.

## 1.5. Thesis Overview

First of all, Chapter 1 comments upon the background and purpose of this study, and clarifies positions, assertions, and contributions of this thesis. Chapter 2 introduces previous techniques used in motion control with MODF, and comments upon their features and issues in detail. Chapter 3 presents fundamentally conceptual design of a long-stroke 3-DOF planar actuator. Chapter 4 presents the design of an experimental system for verification of the motion-control characteristics of the planar actuator. Chapter 5 describes experimental results of the motion-control characteristics of the planar actuator, and suggests incremental improvements to the planar actuator. Chapter 6 proposes conceptual design of the planar actuator with the same configuration of magnetic circuits for the planar motion control, so that the mover can be magnetically suspended, and presents a feasibility verification of the motion-control characteristics by numerical analysis. Finally, Chapter 7 concludes this thesis and suggests future work. Figure 1.5.0-1 shows the structure of this thesis.

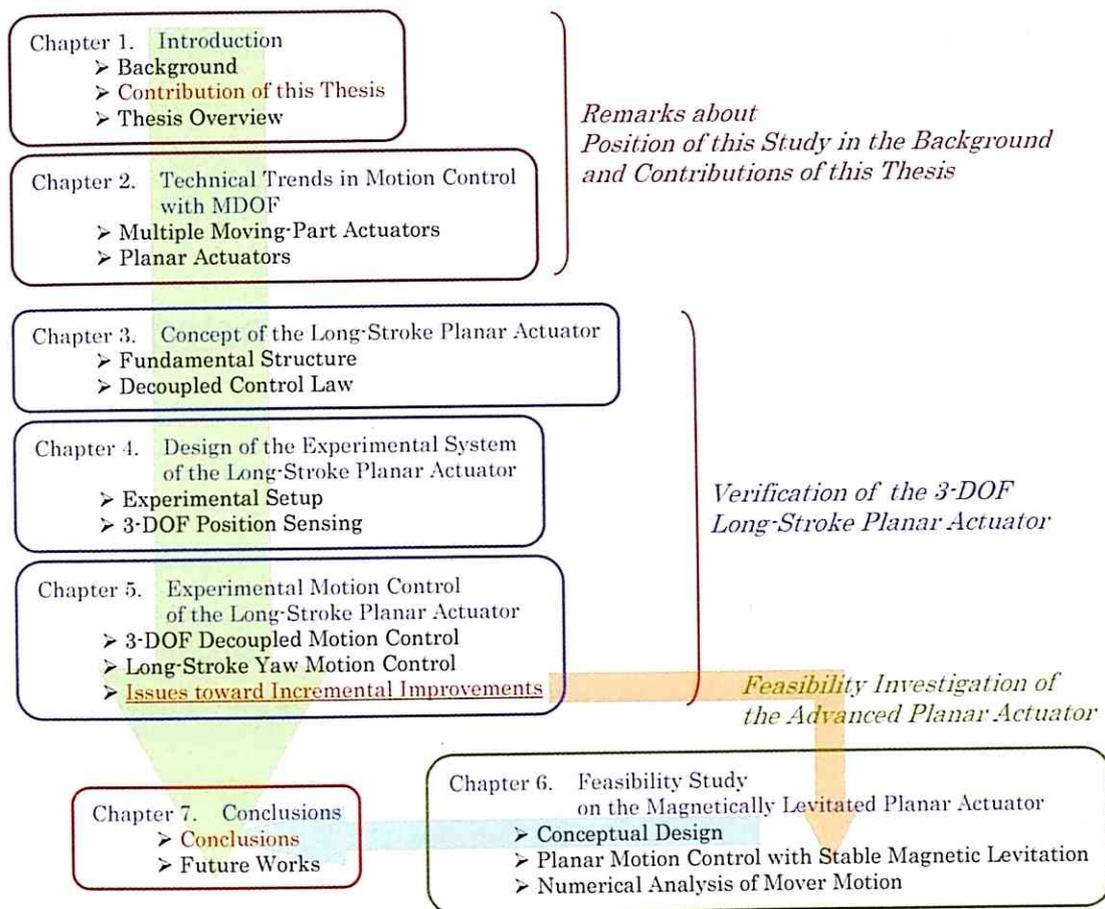


Fig. 1.5.0-1: Thesis structure.