論文内容の要旨

論文題目　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）

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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.

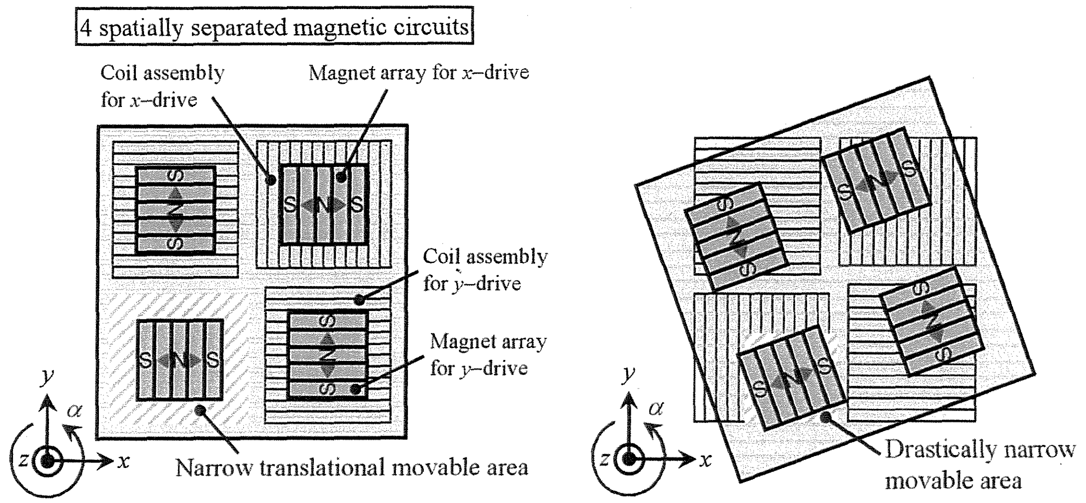
With this in mind, this study is aimed at designing high-performance planar actuators that have the following drive performances:

- 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 ±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.



(a) When not displaced in the yaw direction. (b) When displaced in the yaw direction.

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

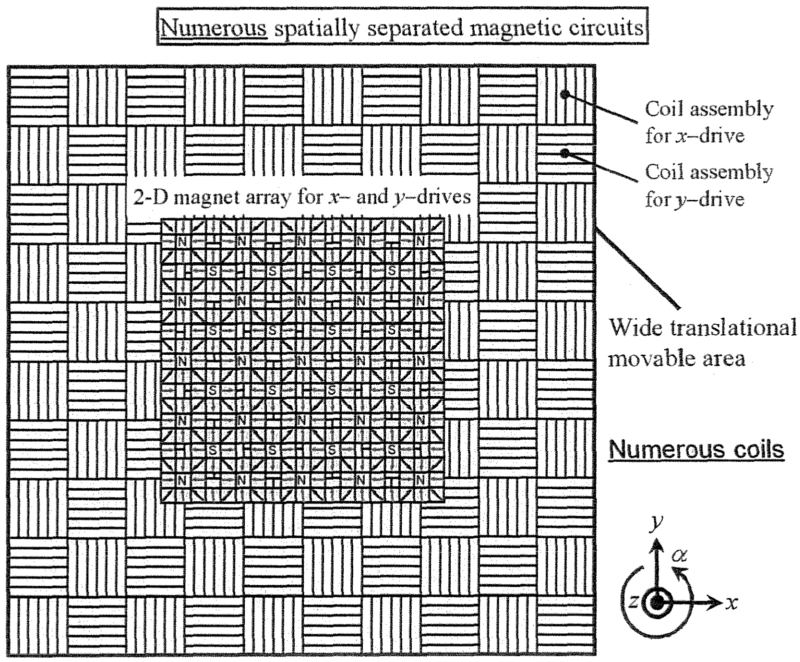


Fig. S-2: Configuration of a synchronous planar actuator with a permanent-magnet mover and numerous armature coils. The power-supply system often becomes complex.

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

Coil Type \ Mover 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	$4 \times 3\phi$
				Compter	6	$4 \times 3\phi$
	Kim	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			

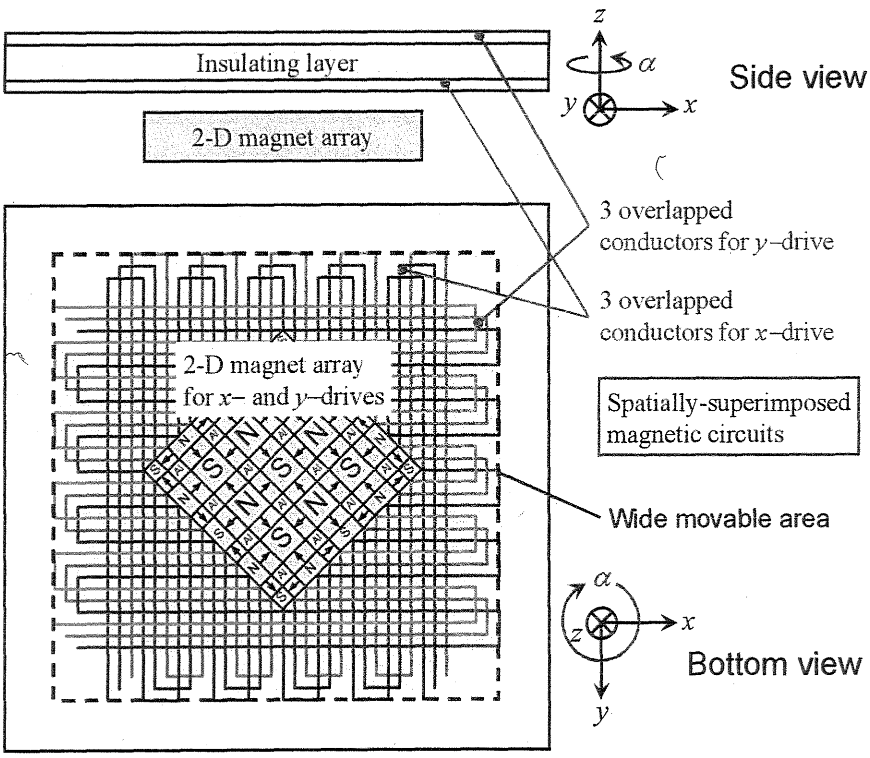


Fig. S-3: Configuration of proposed synchronous planar actuator with a permanent-magnet mover and a small number of armature coils.