Chapter 2

Technical Trends in Motion Control with MDOF

This chapter introduces previous techniques used in motion control with MDOF, and remarks upon their features and issues in detail.

2. Technical Trends in Motion Control with MDOF

One-degree-of-freedom translational or rotational motion controls are the most basic, and have been researched and developed actively. The motion-control performance of 1-DOF actuators has been completely improved.

MDOF motion controls are conventionally realized by a combination of multiple 1-DOF actuators. Recently, however, technical demands for improvements in MDOF-drive technologies have become increasingly sophisticated, and various actuators that have a novel structure suitable for MDOF drives have been proposed.

This chapter introduces previous techniques used in motion control with MDOF, and comments upon their features and issues in detail. In this thesis, previous techniques are classified by the number of moving parts (multiple or single), driving direction (translation or rotation), and drive principle (stepping, induction, synchronous, and so on). First, multiple moving-part actuators, which conventionally combine 1-DOF actuators, are commented upon. Then, single moving-part actuators, called MDOF actuators in this thesis, are commented upon and classified as follows: one is a planar actuator that can drive in 2-DOF translational directions, another is a spherical actuator that can drive in 2-DOF rotational directions, and the other is an actuator that can drive in 1-DOF translational and rotational directions.

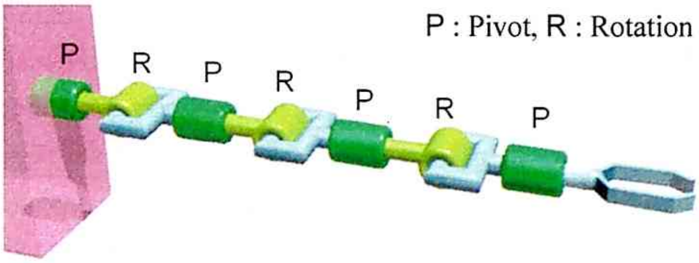
2.1. Multiple Moving-Part Actuators

Generally, MDOF motion can be realized by combination of 1-DOF motions. Therefore, it is practically easy to realize a MDOF drive system by a combination of 1-DOF actuators. In fact, most MDOF drive systems used in machine tools and industrial robots have been fabricated by stacking 1-DOF actuators as shown in Fig. 2.1.0-1 [MDD05, MDD07, MDD08].

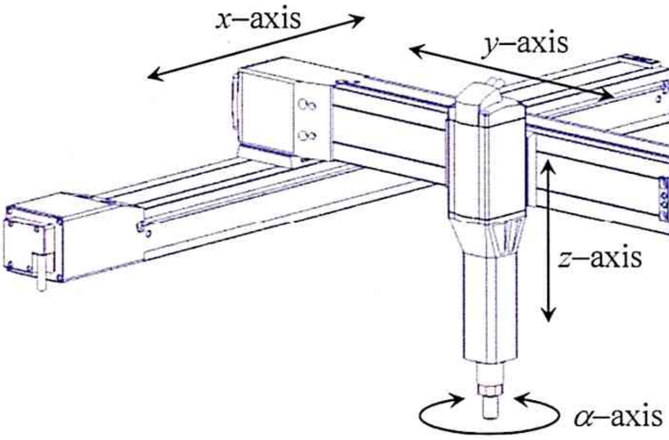
MDOF drive systems, however, often have the following three serious problems [MDD05]:

- Larger and heavier structures.
- Complicated multi-body dynamics (fluctuation of center of gravity).
- Often generating Abbe errors.

These problems make it difficult to improve upon their drive performance in such terms as high speed and high precision, and therefore need to be solved.



(a) Robot manipulator with seven degrees of freedom.



(b) Pick-and-place equipment.

Fig. 2.1.0-1: MDOF drive system achieved by stacking 1-DOF actuators [MDD08].

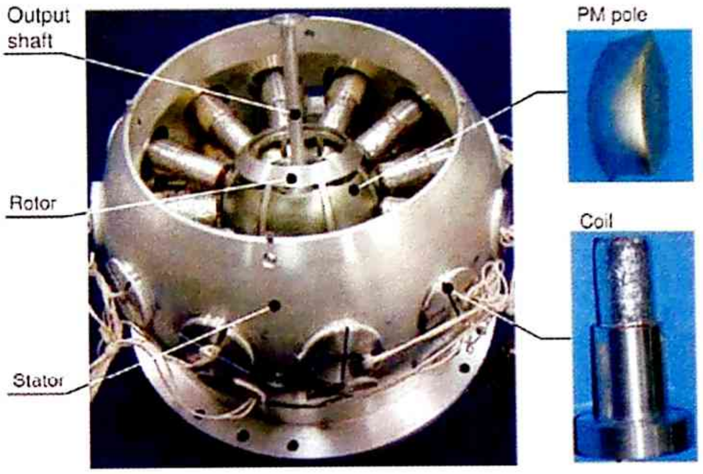
2.2. Spherical Actuators

Spherical actuators directly drive a mover in 2- or 3-DOF rotational directions, and have been studied for applications in robot elements such as joints and eyes [MDD08]. To date, various types of spherical actuators [Yan04], including electromagnetic types (stepping, induction, synchronous, and resonant), piezoelectric types (non-resonant or resonant), and magnetostrictive type, have been proposed. Electromagnetic spherical actuators often have a magnetic circuit, in which the magnetic circuits of rotary motors are two-dimensionally extended so that driving torque can be generated. The spherical mover often is suspended by ball bearings because it is extremely difficult to practically fabricate a contactless suspension mechanisms for the mover [MDD07]. In piezoelectric spherical actuators, the mover is always in contact with the stator, and therefore no additional suspension mechanism is required. Most spherical actuators detect mover positions by using optical encoders [MDD07].

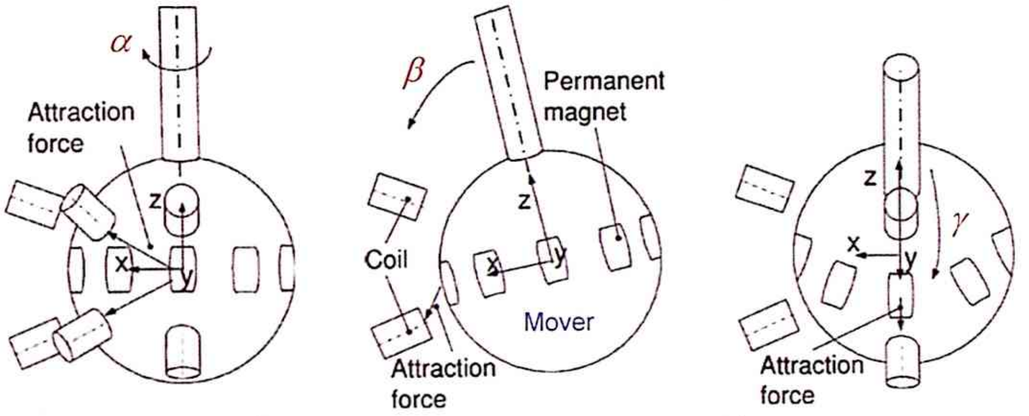
2.2.1. Stepping Type

Lee, Georgia Institute of Technology, developed a stepping spherical actuator with 3-DOF rotation, as shown in Fig. 2.2.1-1 [Lee08, Lee91]. The mover has eight permanent magnets along an "equator," as on a globe, and the stator has 24 air-core coils arranged on two circumferences of the stator. Xia, Tianjin University, proposed the application of a Halbach permanent-magnet array on the equator to this type of (developed by Lee) spherical actuator [Xia07].

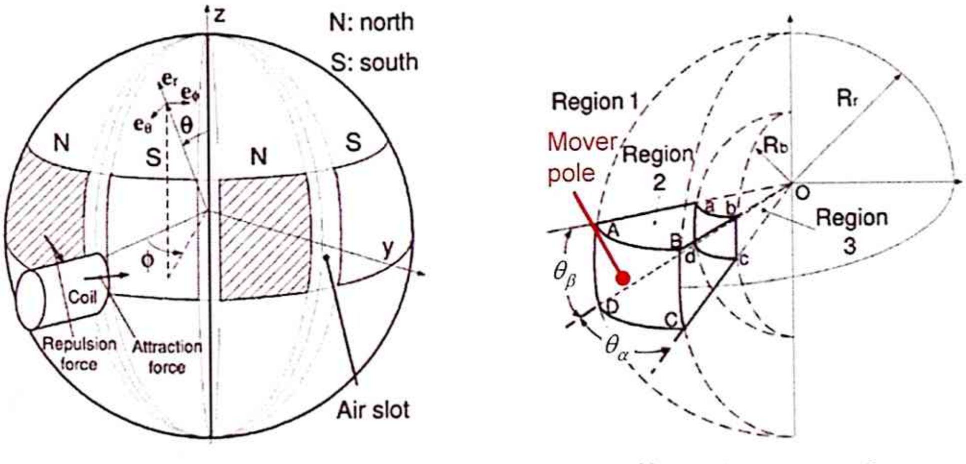
Doncker, RWTH Aachen, developed a stepping spherical actuator with 3-DOF rotation as shown in Fig. 2.2.1-2 [Don00, Don02]. The mover is supported by hydrostatic oil bearings and has 112 permanent magnets arranged in longitudinal and latitudinal lines, again as on a globe. The stator has 96 electromagnets controlled individually because of the variable pole pitch resulting from the different sizes of the magnets and the variable tilt of the mover.



(a) Prototype of a stepping spherical actuator.



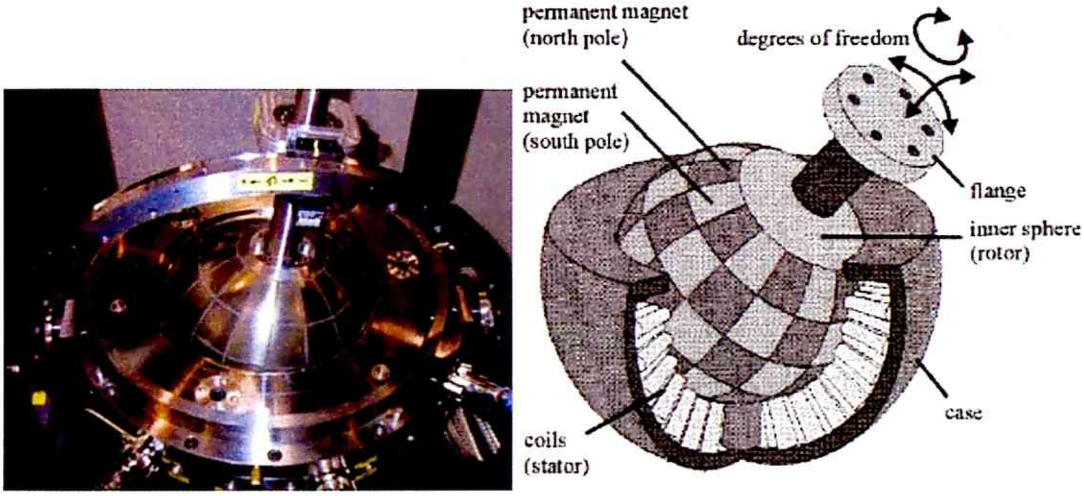
(b) Spinning motion.   (c) First tilting motion.   (d) Second tilting motion.



(e) Mover poles along equator.   (f) Single mover pole.

Fig. 2.2.1-1: Stepping spherical actuator developed by Lee [Lee08, Lee91].

Chirikjian, Johns Hopkins University, and Yano, the National Institute of Advanced Industrial Science and Technology, proposed stepping spherical actuators based on a polyhedron [Chi99, Yan08b]. Concretely, electromagnets on the stator and permanent magnets on the mover are arranged on vertices of different polyhedra (for example, as shown in Fig. 2.2.1-3). They suggested that this kind of spherical actuators could drive the mover over infinite rotational displacements with 3 DOF. Chirikjian prototyped a spherical actuator with 16 electromagnets arranged on the stator and 80 permanent magnets arranged on the inner side of the hollow spherical mover as shown in Fig. 2.2.1-4 [Chi99].



(a) Prototype [Don02]. (b) Fundamental structure [Don00].

Fig. 2.2.1-2: Stepping spherical actuator developed by Doncker [Don00, Don02].

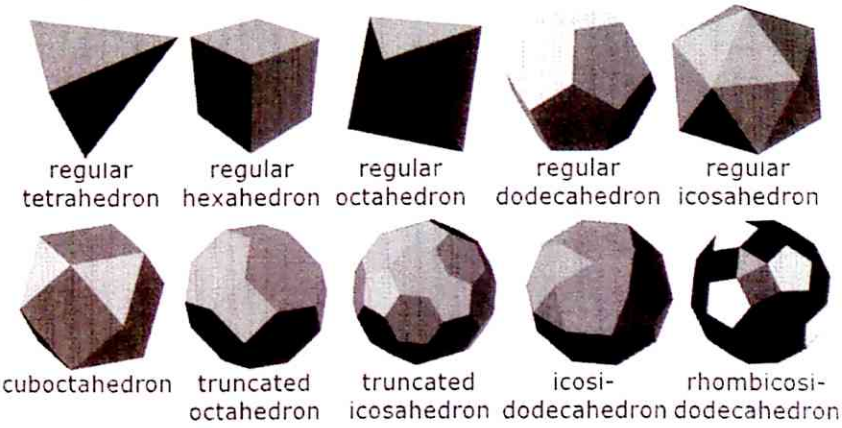
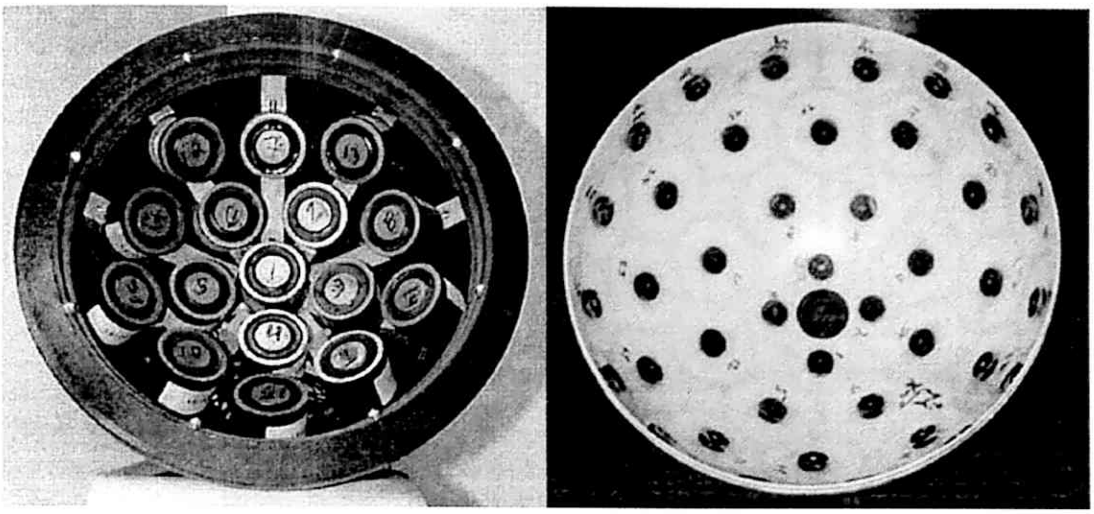


Fig. 2.2.1-3: Polyhedron samples [Yan08b].



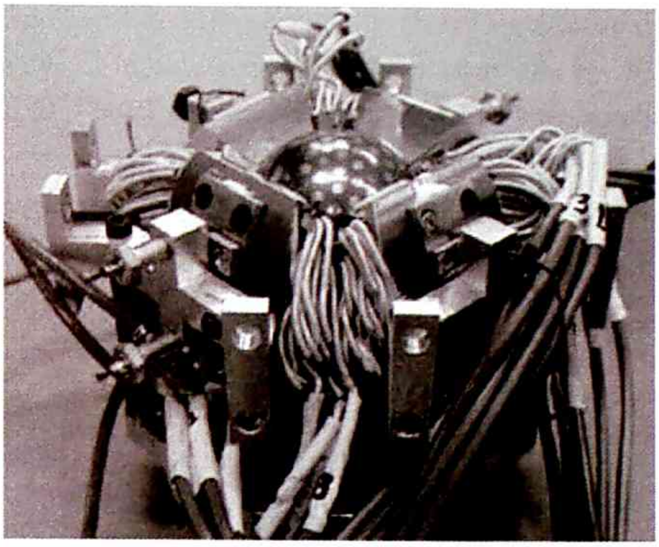
(b) Stator assembly [Chi99]. (c) Inside of half mover [Chi99].

Fig. 2.2.1-4: Stepping spherical actuator developed by Chirikjian [Chi99].

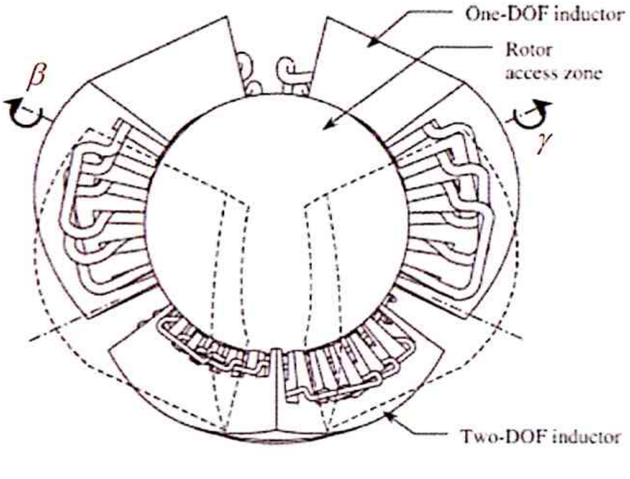
2.2.2. Induction Type

An induction spherical actuator consists of primary windings and structurally simple secondary conductors, including an iron core. Therefore, the mover is designed as a secondary conductive sphere to simplify the mover structure. (Although the mover is designed to use squirrel-cage windings, fabrication of multi-dimensionally squirrel-cage windings is difficult in practice [Yan93].)

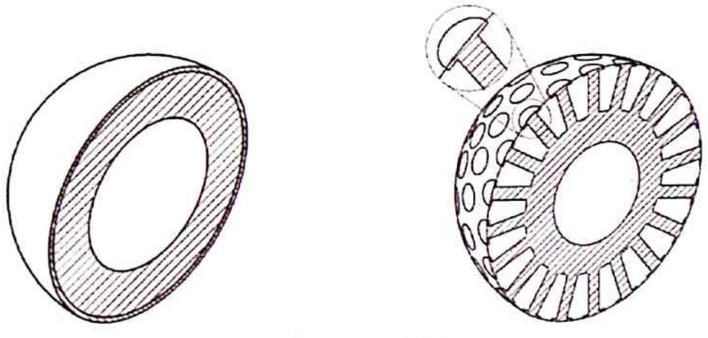
Raucent, Catholic University of Leuven, developed induction spherical actuators with a mover capable of infinite-stroke 2-DOF rotation (the β– and γ–directions shown in Fig. 2.2.2-1) [Rau06]. Exciting two mutually-orthogonal three-phase windings on the bottom, and four three-phase windings on the lateral sides of the stator generates β– and γ–directional torques. Spherical actuators potentially have applications to omnimobile robot platforms at crossroads in industrial conveyors. Raucent prototyped two spherical movers; one is manufactured by welding Cu-Sn-Zn alloy, which has a high electrical conductivity, excellent weldability and high mechanical hardness, onto the surface of a hollow iron sphere [Rau02]; and the other has ferromagnetic teeth and is made from magnetic powder and pure copper to improve actuator performance by reducing the equivalent air gap [Rau06].



(a) Prototype of an induction spherical actuator.



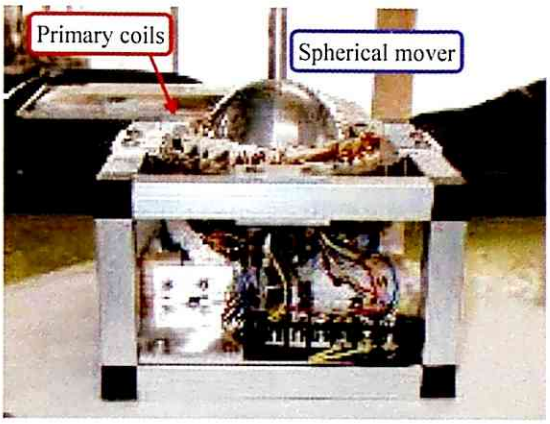
(b) Fundamental structure of induction spherical actuator.



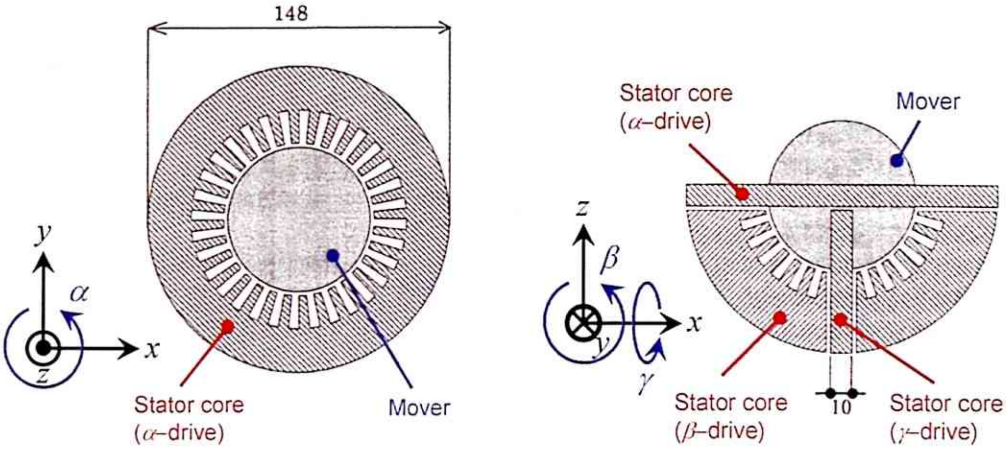
(c) Mover with welded Cu-Sn-Zn alloy. (d) Mover with ferromagnetic teeth.

Fig. 2.2.2-1: Induction spherical actuator developed by Raucent [Rau06].

Ebihara, Musashi Institute of Technology, developed an induction spherical actuator with a mover capable of infinite-stroke 3-DOF rotation (the α–, β– and γ–directions shown in Fig. 2.2.2-2) [Ebi02]. The spherical actuator has three windings; one is for the α–directional drive and is installed around the z–axis, the others are for the β– and γ–directional drives, and are installed halfway around the y– and x–axes, respectively.



(a) Prototype of induction spherical actuator [Yan04].



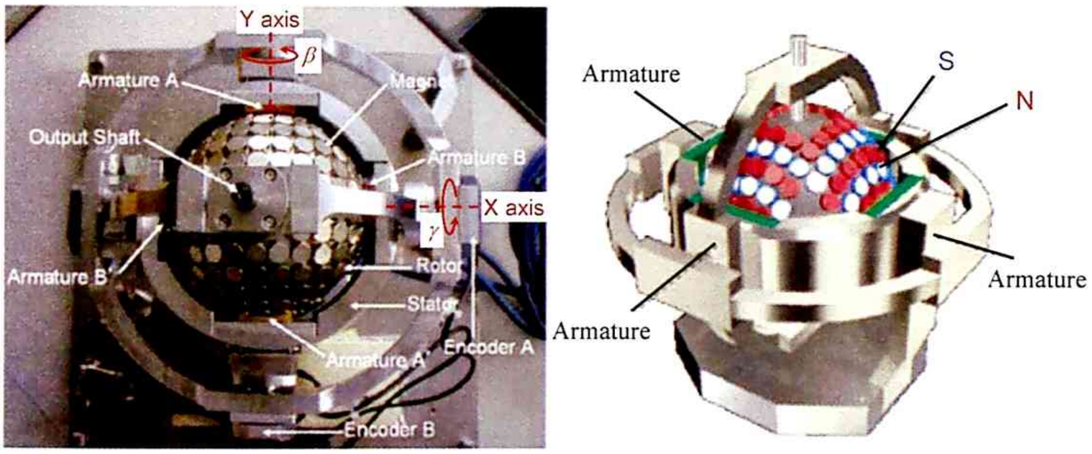
(b) Top view [MDD05].

(c) Side view [MDD05].

Fig. 2.2.2-2: Induction spherical actuator developed by Ebihara [MDD05, Yan04].

2.2.3. Synchronous Type

Yano, the National Institute of Advanced Industrial Science and Technology, prototyped a synchronous spherical actuator with a mover capable of infinite-stroke 2-DOF rotation (the β– and γ–directions shown in Fig, 2.2.3-1) [Yan07, Yan08a]. The stator has two armature windings (Armature A and A') for the rotational drive around the x–axis, and two armature windings (Armature B and B') for the rotational drive around the y–axis. There are 260 permanent magnets arranged in a concentric pattern around the x– and y–axes. The pole pitch is always constant, regardless of displacements around the x– and y–axes because of the concentric pattern of the permanent magnets. The mover positions are detected by two optical encoders. Two PWM (Pulse-Width-Modulation) inverters supply three-phase alternating current to the armature windings for the rotational drive around the x– and y–axes.

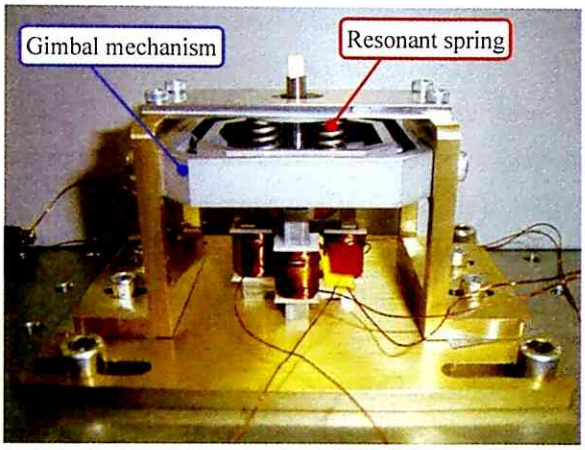


(a) Prototype. (b) Fundamental structure.

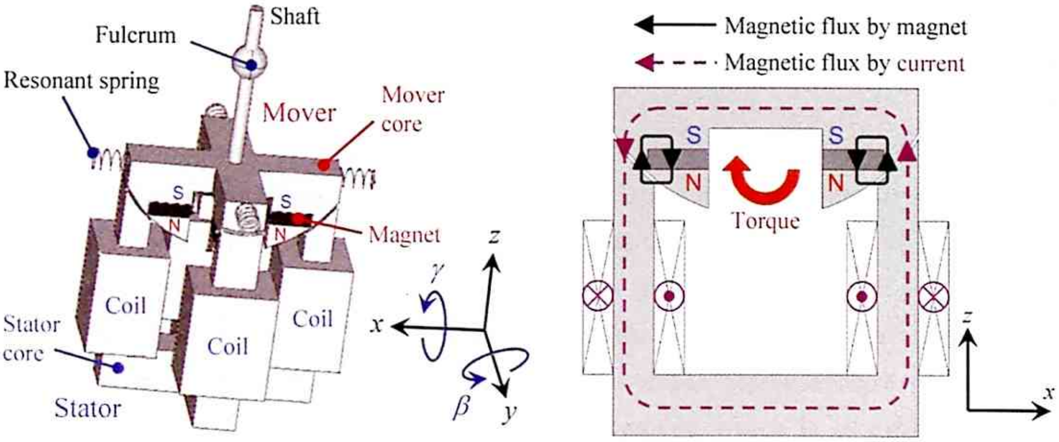
Fig. 2.2.3-1: Synchronous spherical actuator developed by Yano [Yan07, Yan08a].

2.2.4. Resonant Type

Hirata, Osaka University, developed a resonant spherical actuator with 2 DOF as shown in Fig. 2.2.4-1 [Hir08]. The configuration of the mover and stator is centrally symmetric. The mover has a cross-shape iron core and four permanent magnets with iron cores. The stator has a cross-shape iron core with four coils. Figure 2.2.4-1 (c) shows a cross-section of the actuator at x–z plane and indicates the drive principle. When not exciting the coils, the magnetic circuits expressed by solid lines in Fig. 2.2.4-1 (c) are formed, and therefore torque cannot be generated. Exciting the coils as shown in Fig. 2.2.4-1 (c) forms an additional magnetic circuit expressed by a dashed line, and therefore clockwise torque is generated. Inverting the direction of the exciting currents generates counterclockwise torque. Reciprocating motions of the mover can be realized by AC excitation, and controlled by the four currents.



(a) Prototype of resonant spherical actuator.



(b) Fundamental structure. (c) Drive principle (cross-section).

Fig. 2.2.4-1: Resonant spherical actuator developed by Hirata [Hir08, MDD08].

2.2.5. Piezoelectric Type

Piezoelectric actuators drive the mover by means of the inverse piezoelectric effect, and generally have advantages in terms of precise positioning because of the minute strain output, high-torque driving, and high retaining forces [MDD05]. They are often classified as resonant or non-resonant types. The non-resonant type of piezoelectric actuators directly output minute piezoelectric strains as their actuations. Resonant-type piezoelectric actuators expand the piezoelectric strains by means of resonance and are also known as ultrasonic motors.

Sasae, Kawasaki Heavy Industries Ltd., and Nishimura, Toshiba Corporation, developed non-resonant piezoelectric spherical actuators with 3 DOF as shown in Figs. 2.2.5-1 [Sas96] and 2.2.5-2 [Nis08]. These spherical actuators have more than three drive units. The drive unit consists of three piezoelectric elements assembled like a truss structure, and can be displaced in the 3-DOF translational direction by supplying the piezoelectric elements with voltage. The spherical mover is supported by the tips of the piezoelectric elements. When displacing the drive units, the mover can be driven in the 3-DOF rotational direction.

Toyama, Tokyo University of Agriculture and Technology, developed a 3-DOF spherical ultrasonic motor (non-resonant-type piezoelectric actuator) as shown in Fig. 2.2.5-3 [Toy07, Toy95, Toy96]. The spherical actuator has three ring-shaped vibrators surrounding the spherical mover. Exciting the vibrations of the stator supplies the mover driving torque through the friction forces between the mover and the stator. The 3-DOF rotational motions of the mover can be controlled by a combination of the driving torque generated by each vibrator. Toyama proposed applying the spherical actuator for use in surgical robots [Toy07].

Ueha, Tokyo Institute of Technology, and Maeno, Keio University, developed 3-DOF spherical ultrasonic motors using longitudinal vibration and two bending vibrations as shown in Fig. 2.2.5-4 [Mae01, Ueh05]. The ultrasonic motors consist of a cylindrical stator and a spherical mover. Figure 2.2.5-4 shows the drive principle of the ultrasonic motors for rotation around the z– and x–axes. Combining the two natural vibration modes A and B, generates the rotational motions of the stator around the z–axis as shown in Fig. 2.2.5-4 (a), and then the spherical mover, which is in contact with the stator head, also rotates around the axis due to friction forces. Similarly, combining the two natural vibration modes C and B generates the rotational motions of the mover around the x–axis as shown in Fig. 2.2.5-4 (b).

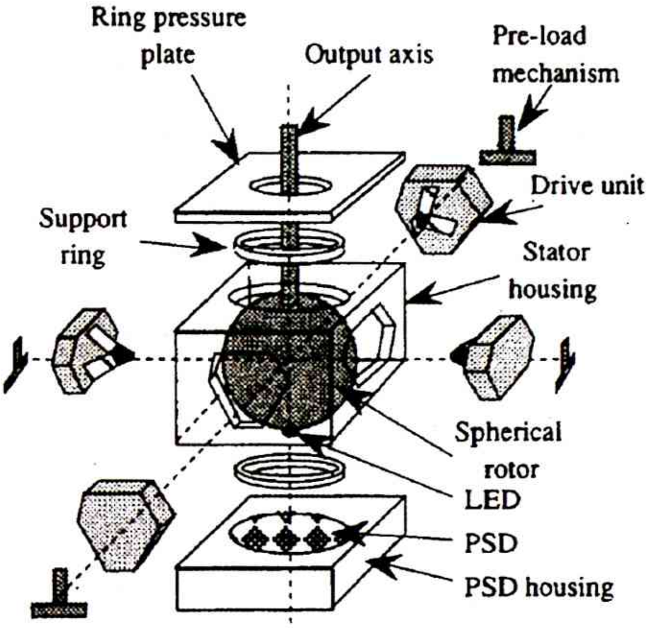


Fig. 2.2.5-1: Non-resonant piezoelectric spherical actuator developed by Sasae [Sas96].

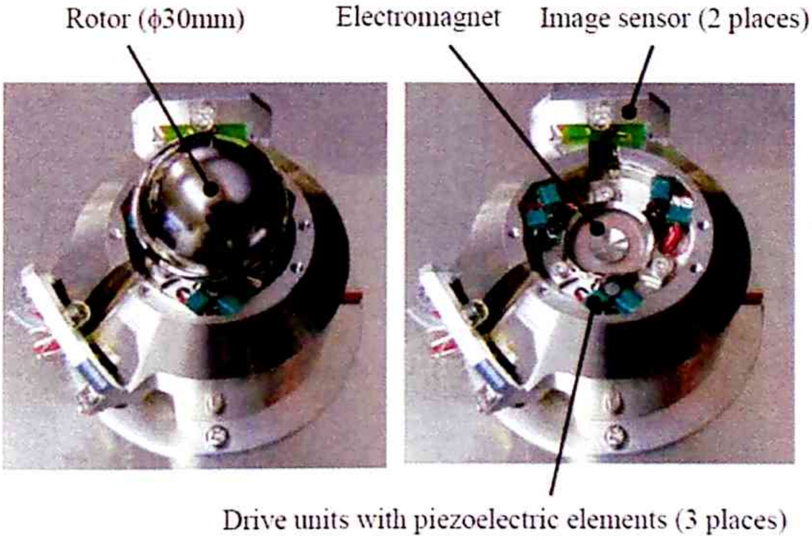


Fig. 2.2.5-2: Non-resonant piezoelectric spherical actuator developed by Nishimura [Nis08].

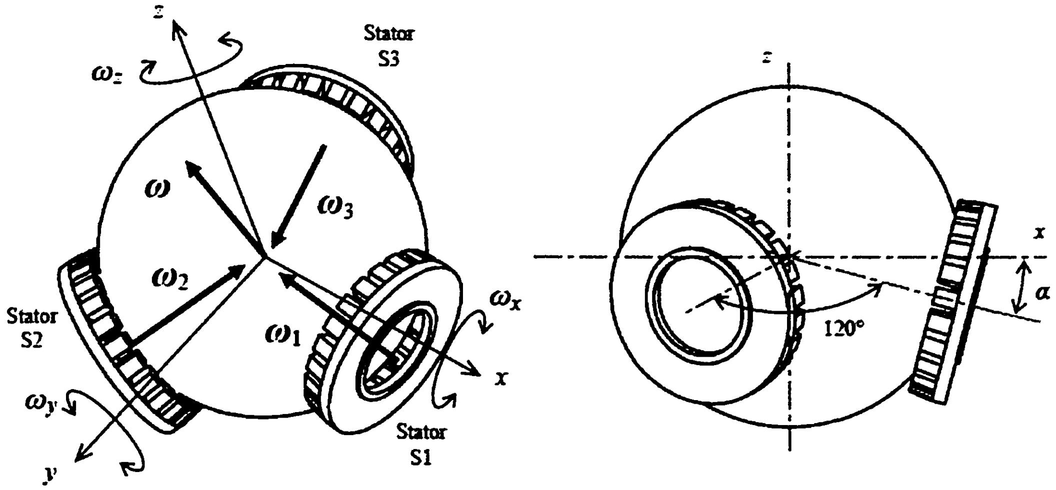
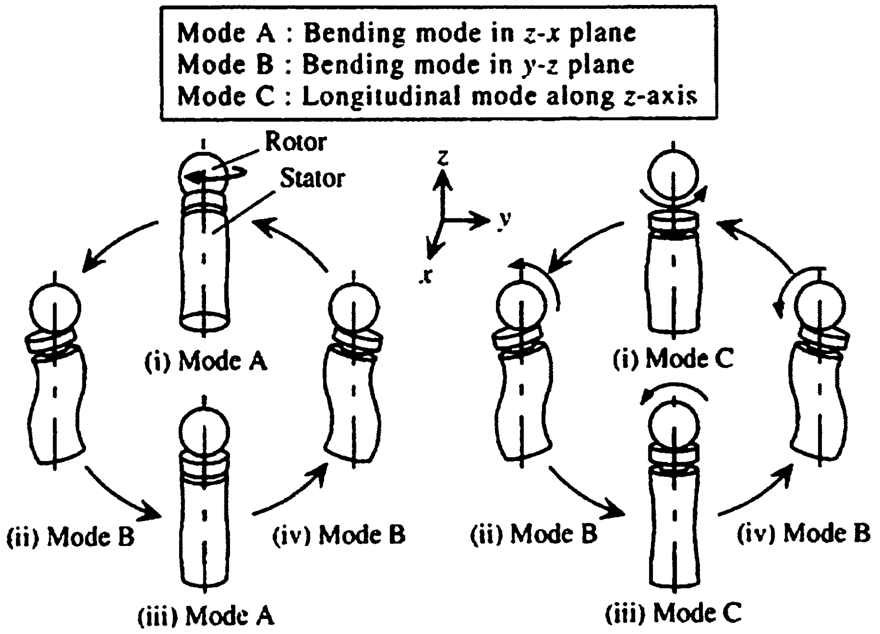


Fig. 2.2.5-3: Spherical ultrasonic motor developed by Toyama [Toy07].

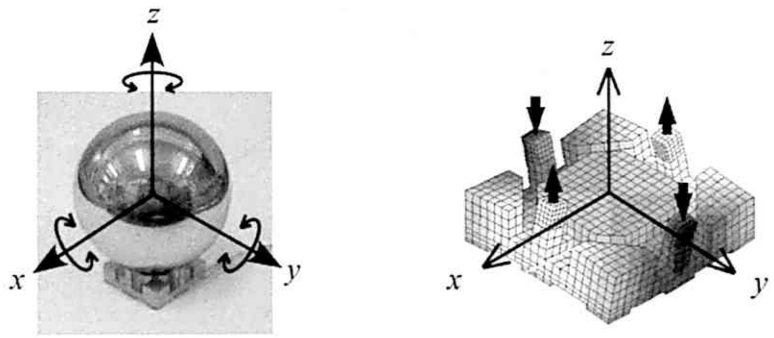


(a) Rotation around the z–axis. (b) Rotation around the x–axis.

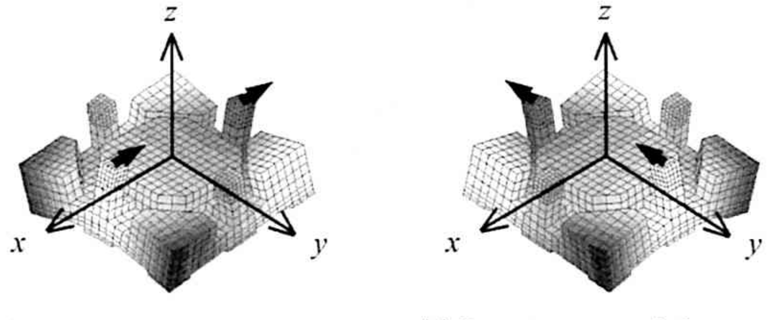
Fig. 2.2.5-4: Spherical ultrasonic motor with a cylindrical vibrator developed by Ueha and Maeno [Mae01].

Maeno, Keio University, developed a 3-DOF spherical ultrasonic motor with a small plate-shaped stator as shown in Fig. 2.2.5-5 [Mae04, Mae05]. The spherical actuator drives the mover in the 3-DOF direction by the three out-of-plane vibration modes shown in Fig. 2.2.5-5. The volume of the stator is 0.66 time as large as that of the mover, and so the spherical actuator is extremely compact.

Aoyagi, Muroran Institute of Technology, developed a disk-shaped 3-DOF ultrasonic motor as shown in Fig. 2.2.5-6 [Aoy03, Aoy04]. The disk vibrator excites three vibration modes independently and simultaneously. Combining two or three vibration modes generates driving torques around each axis.

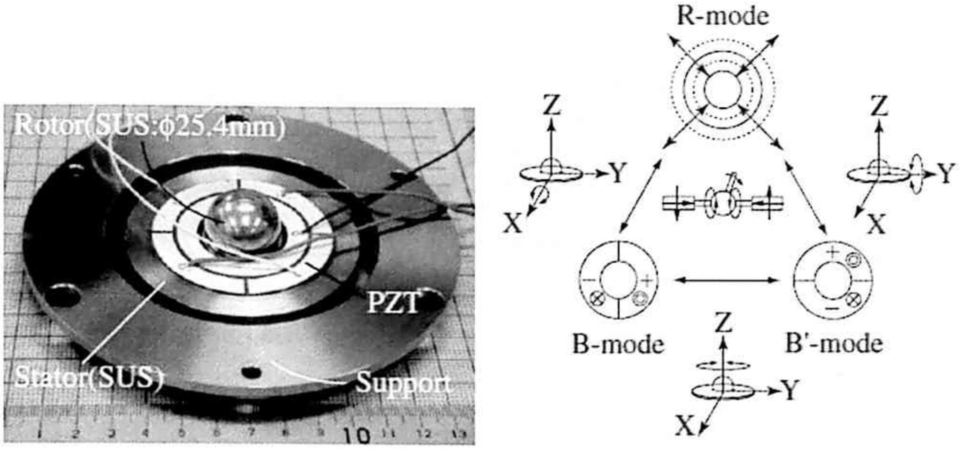


(a) Prototype. (b) Rotation around the z–axis.



(c) Rotation around the y–axis. (d) Rotation around the x–axis.

Fig. 2.2.5-5: Spherical ultrasonic motor with a small plate-shaped vibrator developed by Maeno [Mae04].

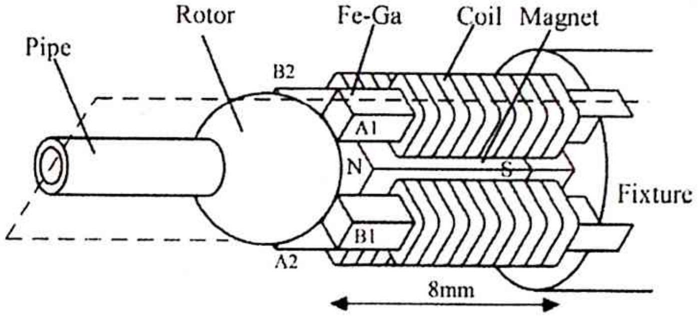


(a) Prototype. (b) Drive principle.

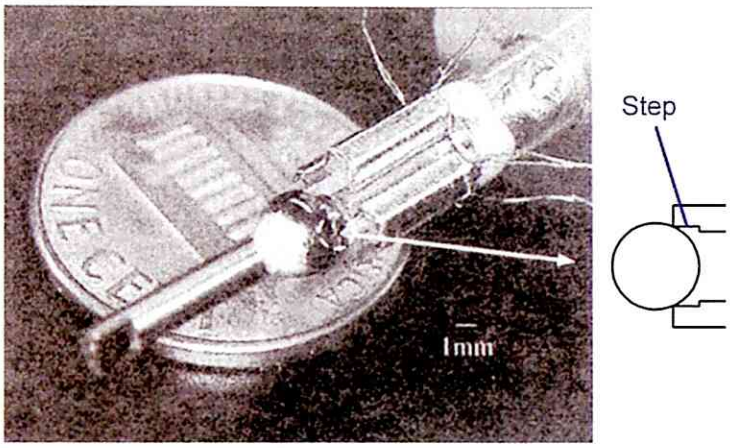
Fig. 2.2.5-6: Piezoelectric spherical actuator with a disk-shaped vibrator developed by Aoyagi [Aoy03, Aoy04].

2.2.6. Magnetostrictive Type

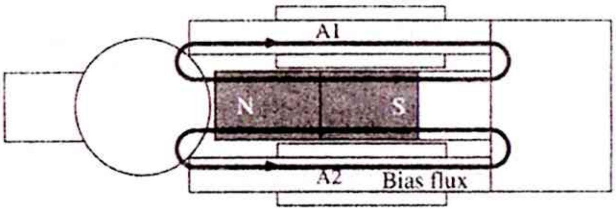
Magnetostrictive actuators drive the mover by means of the magnetostriction effect, and generally have higher mechanical and temperature characteristics than piezoelectric actuators [Hig07, Hig08a, Hig08b]. Higuchi, The University of Tokyo, developed a magnetostrictive spherical actuator as shown in Fig. 2.2.6-1. The spherical actuator has four stationary Galfenol (Iron–Gallium alloy) rods, which are a magnetostrictive material, and have axis of easy magnetization along the longitudinal direction. Exciting a coil extends the rod in the longitudinal direction due to the magnetostriction effect. A permanent magnet placed in center of the four rods forms the magnetic circuits shown in Fig. 2.2.6-1 (c), attracting the iron spherical mover to the four stationary rods and generating magnetostriction in the four rods. Exciting two coils as shown in Fig. 2.2.6-1 (d) generates an extension of rod A1 and shrinkage of rod A2, and, consequently torque that acts upon the mover.



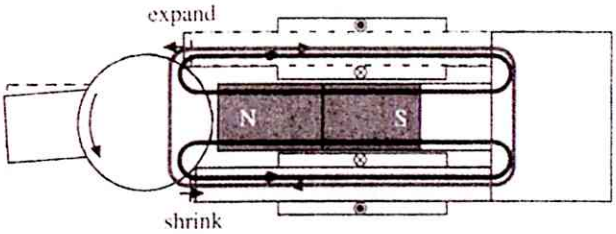
(a) Fundamental structure of a magnetostrictive spherical actuator.



(b) Prototype of a magnetostrictive spherical actuator.



(c) Magnetic circuits without excitation.



(d) Magnetic circuits with excitation.

Fig. 2.2.6-1: Magnetostrictive spherical actuator developed by Higuchi [Hig08b].

2.3. Planar Actuators

Planar actuators directly drive the mover in 2-DOF translational directions on a plane, and have been studied for application in the high-precision stages of semiconductor manufacturing, transport and switch devices in factories, and other applications [MDD08]. They are often classified by their drive principle, such as electromagnetic type (including stepping, direct-current, induction, synchronous, and resonant types), piezoelectric type, and electrostatic type. Electromagnetic planar actuators have magnetic circuits corresponding to the two-dimensionally extending magnetic circuits of linear motors. Each type of electromagnetic actuator (stepping, direct-current, induction, synchronous, and resonant) has the same drive characteristics as its respective linear motor. Piezoelectric planar actuators often have a small structure (less than several cm), generate high propulsion forces and retaining forces, and position movers with high precision. Electrostatic planar actuators generate larger driving-force density in minute scale and a high vacuum according to Paschen's law [Act04].

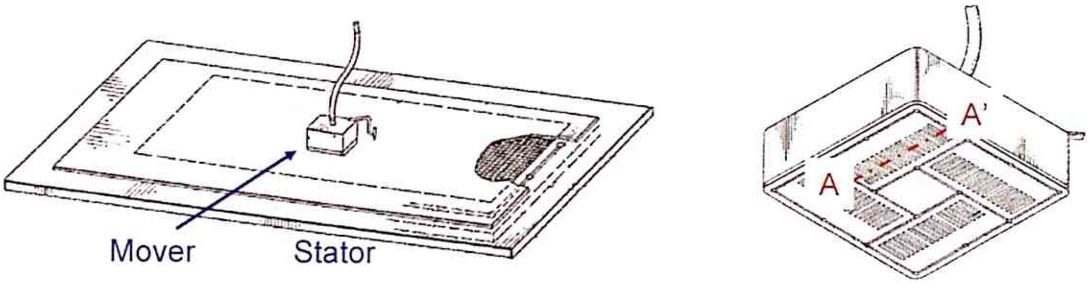
2.3.1. Stepping Type

Stepping-type planar actuators are classified into three major types; variable reluctance, permanent magnet, and hybrid. Variable-reluctance planar actuators were invented earliest by B. A. Sawyer [Saw68], and are often called "Sawyer motors." Since the original invention, many planar actuators based on the Sawyer motor have been developed [MDD05]. A Sawyer motor has two mutually-orthogonal magnetic circuits arranged according to the magnetic circuits of variable-reluctance linear stepping motors as shown in Fig. 2.3.1-1. The mover has armature windings for the x– and y–directional drives, and there is a stationary iron core slotted into a lattice pattern.

Exciting the armature coils generates strong attraction forces between the mover and the stator. The mover has pneumatic lines for the air bearings, and is suspended and guided on a plane by air bearings. The excitation pattern of the armature coils determines the mover positions, and therefore the planar actuators do not always require position sensors for their positioning [MDD05]. In fact, the positions of the mover are often detected using differential transformers and laser interferometers for position-feedback controls because they offer high-precision positioning. In the feedback controls, the micro-step-drive method is often utilized, which controls mover positions with higher positioning resolution by finely controlling the amplitude of the exciting currents.

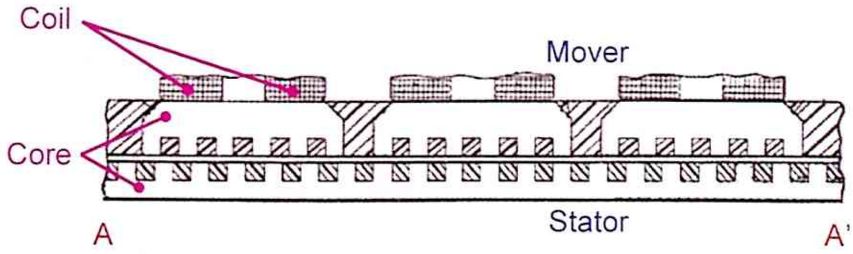
In a Sawyer motor, the mover can travel over a wide stator area. Therefore, two-dimensionally extending the stationary iron core also extends the movable area on the plane. However, wires for feeding power to the armature coils and pneumatic lines for the air bearings in practical terms limit the movable area, and the tension caused by these problematic wires and lines often deteriorate drive characteristics.

Higuchi, The University of Tokyo, developed a variable-reluctance-stepping planar actuator with a magnetically levitated mover as shown in Fig. 2.3.1-2 [Hig89]. Figure 2.3.1-2 (b) shows the one-dimensional drive principle of the planar actuator. The combination of the magnetic circuits of the double-sided linear stepping motors generates suspension and propulsion forces simultaneously. Controlling the currents in the upper and lower stators offsets the strong attraction forces between the stators and the mover. The two orthogonal-axis magnetic circuits from the stepping motors control the 2-DOF translational motion of the mover. The mover positions are detected with multiple induction sensors. Higuchi proposed applying the planar actuator to linear conveyer systems, x–y table, direct-drive robots, product handling machines, and so on.



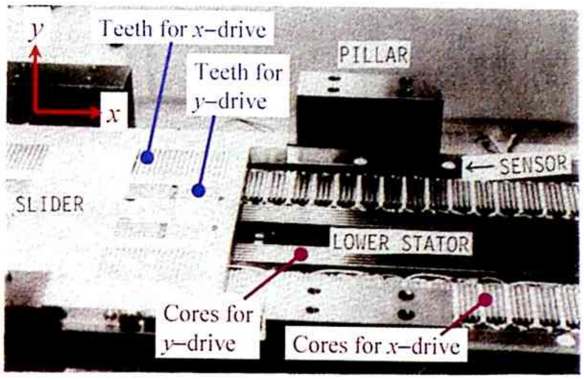
(a) Perspective view of the planar actuator.

(b) Mover structure.

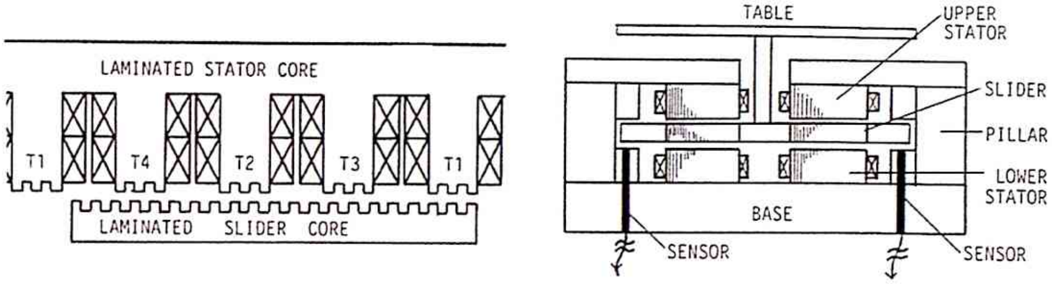


(c) Cross-section view of the planar actuator along the line A–A'.

Fig. 2.3.1-1: Stepping-type planar actuator proposed by Sawyer [Saw68].



(a) Mover (Slider) and inner structure of the stator.

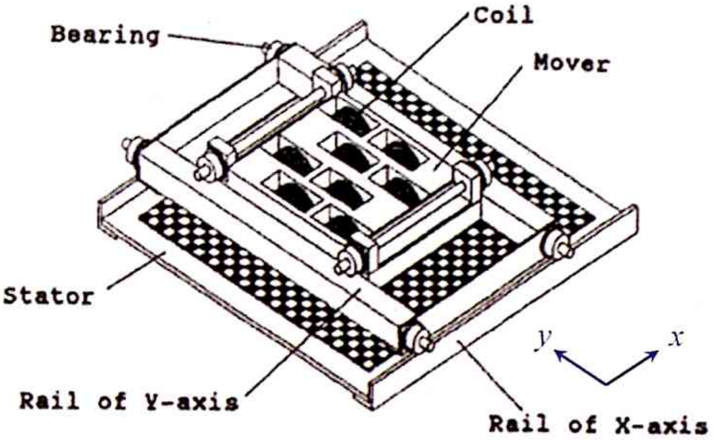


(b) Drive principle of the planar actuator.

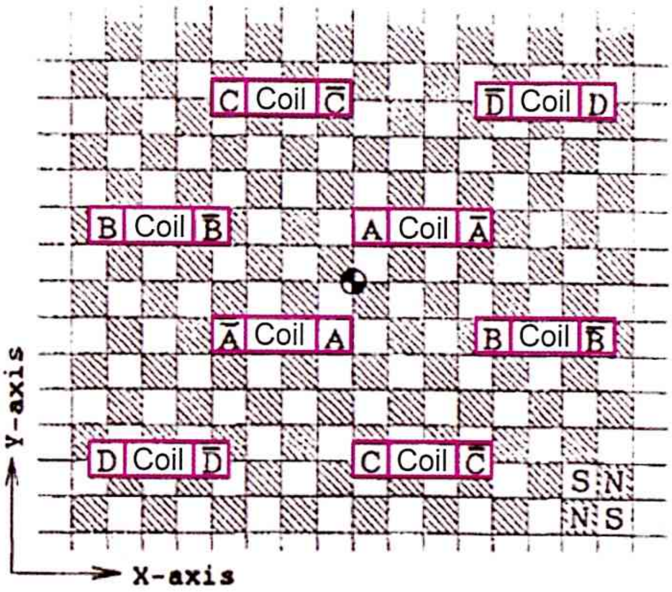
(c) Cross-section view.

Fig. 2.3.1-2: Stepping planar actuator developed by Higuchi [Hig89].

Ebihara, Musashi Institute of Technology, developed a permanent-magnet stepping planar actuator with 2-DOF translational motions as shown in Fig. 2.3.1-3 [Ebi89, Ebi91]. The planar actuator has stationary permanent magnets arranged checker-wise on a back iron, and a single mover with eight electromagnets. The mover is suspended on two rails and on bearings for the x– and y–directional guides. The mover positions in the x– and y–directions are detected with laser-displacement sensors. Figure 2.3.1-3 (b) shows the positional relation of the poles of the permanent magnets and electromagnets. Four-phase (phase A, B, C, or D) currents are supplied to the eight electromagnets. The electromagnets of phases B and C are arranged at a position half the distance of the pole pitch from those of phase A in the x– and y–directions, respectively. The electromagnets of phase D are arranged at a position half the distance of the pole pitch from those of phase A in both the x– and y– directions. Therefore, this planar actuator operates like a permanent-magnet stepping motor in both the x– and y–directions.



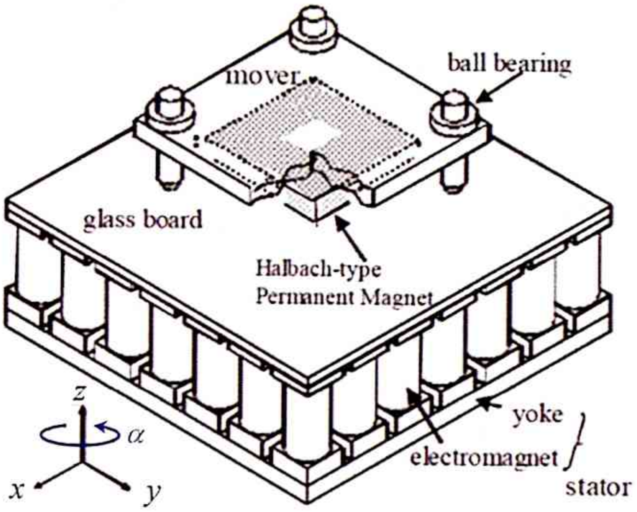
(a) Fundamental structure of planar actuator.



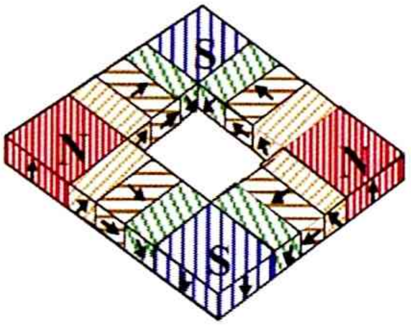
(b) Positional relation of poles of stator and mover.

Fig. 2.3.1-3: Stepping planar actuator developed by Ebihara [Ebi89, Ebi91].

Kimura and Tsuchiya, Tokyo Metropolitan University, developed a permanent-magnet stepping planar actuator with 2-DOF translational and 1-DOF rotational motions as shown in Fig. 2.3.1-3 [GKi01, GKi94, Tsu07]. The mover has two single-pole (five segments) Halbach permanent magnets in both the x– and y–directions. There are 49 stationary electromagnets arranged at regular interval. Independent excitation of these electromagnets controls the 3-DOF (x, y, and α) motions of the mover. The mover is suspended on four ball bearings. The 3-DOF mover positions are detected using a laser-scan microsensor. Fundamentally, the excitation pattern of the electromagnets determines the mover positions without position sensing.



(a) Perspective view of the planar actuator.



(b) Halbach-magnetized permanent-magnet mover.

Fig. 2.3.1-4: Stepping planar actuator developed Kimura [Tsu07].

2.3.2. Direct-Current Type

Direct-current planar actuators often have permanent magnets and armature coils, and utilize Lorentz forces, which can be calculated simply, for motion control.

Buckley, Perkin-Elmer Corporation, developed a 3-DOF (x, y, and α) direct-current planar actuator with two permanent magnets as shown in Fig. 2.3.2-1 [Buc89]. The stator has two pairs of mutually-orthogonal two armature coils for the x– and y–directions. Exciting the four coils independently controls the translational forces in the x– and y–directions and torque in the α–direction. The mover is suspended and guided on the x–y plane by air bearings.

Galburt, Perkin-Elmer Corporation, proposed a 3-DOF (x, y, and α) direct-current planar actuator with permanent-magnet assemblies that apply a unipolar magnetic field to each armature coil as shown in Fig. 2.3.2-2 [Gal85]. The mover has four armature coils in unipolar magnetic fields, and is suspended by four air bearings at each corner. Exciting the four coils independently controls the translational forces in the x– and y–directions and torque in the α–direction.

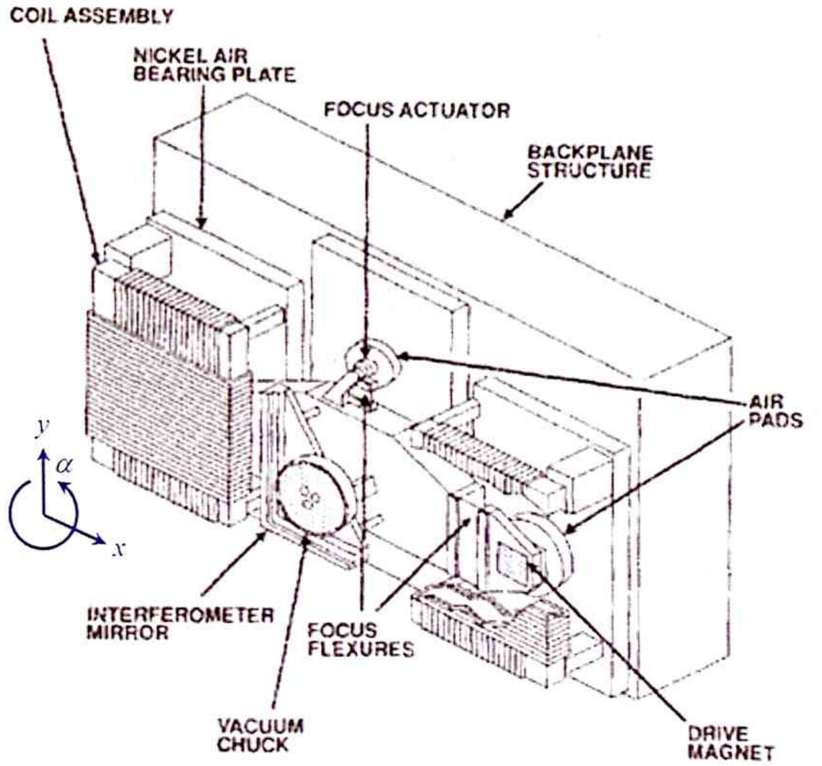
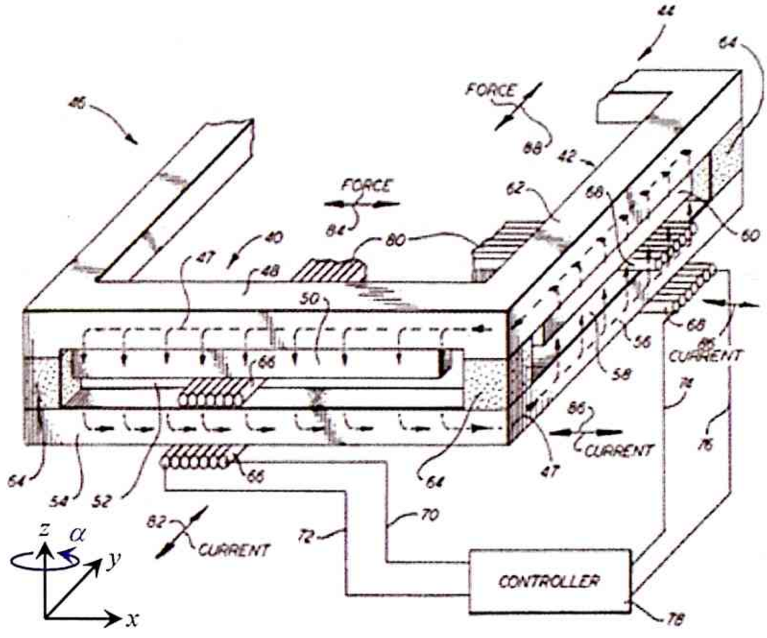
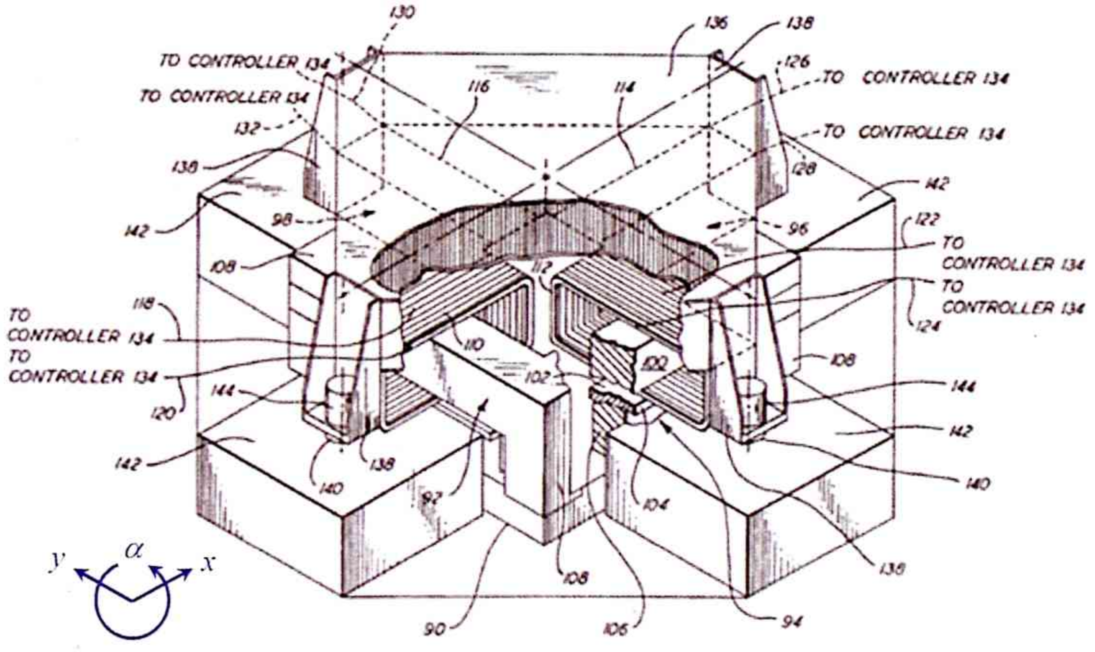


Fig. 2.3.2-1: Direct-current planar actuator proposed by Buckley [Buc89].



(a) Drive principle (magnetic circuits, exciting currents and driving forces).



(b) Perspective view of planar actuator.

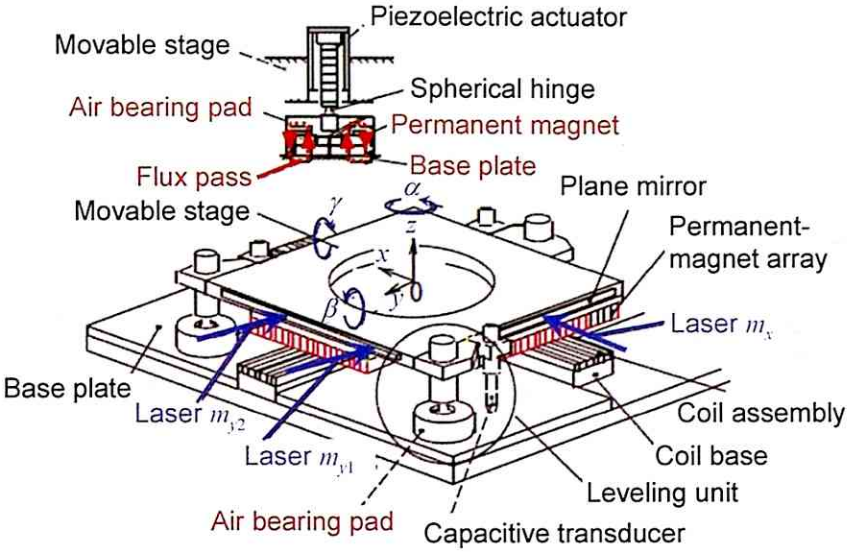
Fig. 2.3.2-2: Direct-current planar actuator proposed by Galburt [Gal85].

Tomita, Sumitomo Heavy Industries, Ltd., developed a 3-DOF (*x*, *y*, and *α*) direct-current planar actuator shown in Fig. 2.3.2-3 [Tom94, Tom96]. The planar actuator consists of three pairs of armature-coil assemblies and permanent-magnet arrays (one for the *x*–directional drive, and two for the *y*– and *α*–directional drives), which form the same magnetic circuits as two-phase linear direct-current motors. The mover has pneumatic lines for air bearings, and is suspended and guided on a plane by three air bearings. The mover positions are precisely detected by three laser interferometers. Two-phase excitations of the armature-coil assemblies generate the translational forces in the *x*– and *y*–directions and torque in the *α*–direction, and control the 3-DOF motions of the mover.

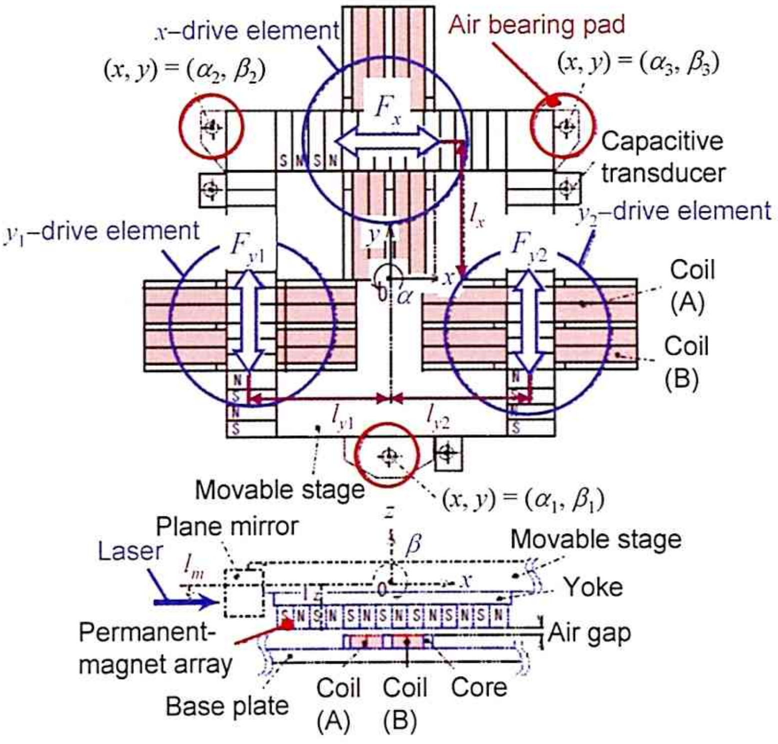
Furthermore, Tomita developed a 6-DOF planar actuator by applying three leveling units to a previously developed 3-DOF planar actuator [Tom96]. Each leveling unit consists of a piezoelectric element with a spherical hinge, expanding displacement by means of piezoelectric strain and permanent magnets as a precompression mechanism. There are capacitance sensors on the mover to detect the *z*–, *β*–, and *γ*–displacements. The combination of three leveling units precisely controls the *z*–, *β*–, and *γ*–positions of the mover.

Kiyono, Tohoku University, developed a 3-DOF (*x*, *y*, and *α*) direct-current planar actuator with a sophisticated position sensor as shown in Fig. 2.3.2-4 [Kiy04]. As mentioned in Subsection 1.2.3, the position sensor, called a surface encoder, consists of a 2-D angle grid and a 2-D angle sensor. The surface encoder detects MDOF displacements, and simplifies the position-sensing system. The mover is suspended by four air bearings, and has four permanent-magnet arrays, a 2-D angle grid, and no problematic wires. Excitations of the four stationary armature-coil assemblies control the 3-DOF motions of the mover.

Various types of surface encoders have been developed, offering three (*x*, *y*, and *α*) [Kiy04, Kiy05a] or five (*x*, *y*, *α*, *β*, and *γ*) [Kiy05b] degrees-of-freedom detection. There is an extremely thin angle grid, made from 100-μm polyethylene terephthalate (PET) inserted in the angle grid in the air gap through which the flux passes [Kiy05a].

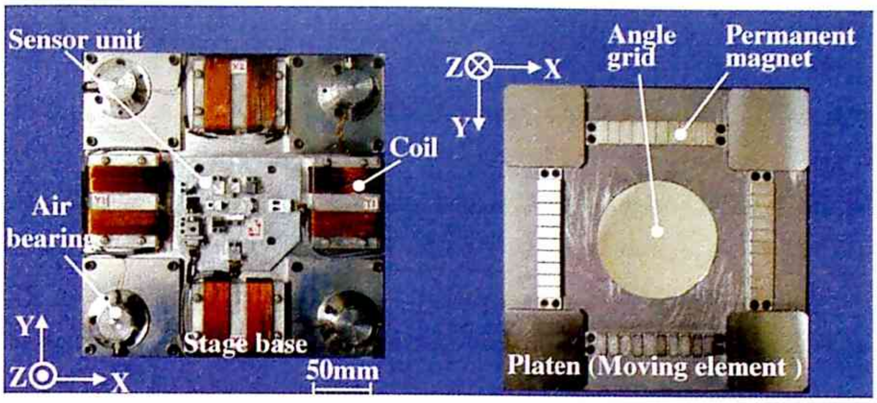


(a) Configuration of planar actuator.

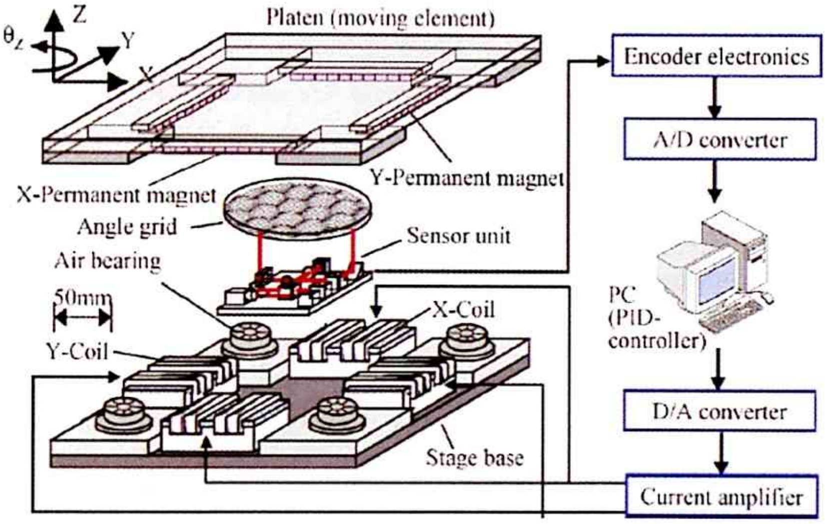


(b) Arrangement of drive elements on a plane.

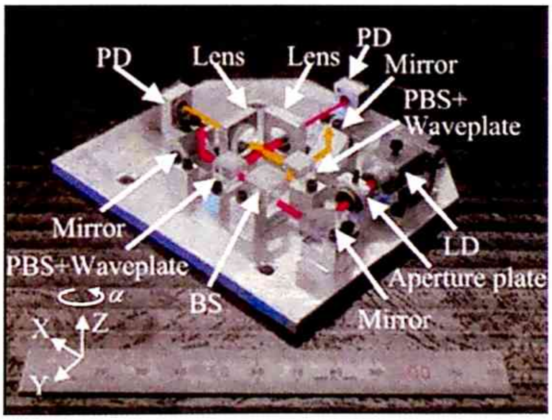
Fig. 2.3.2-3: Direct-current planar actuator developed by Tomita [Tom94, Tom96].



(a) Configuration of planar actuator.



(b) Experimental system of planar actuator.



(c) Configuration of 3-DOF (x, y, α) surface encoder.

Fig. 2.3.2-4: Direct-current planar actuator developed by Kiyono [Kiy04].

2.3.3. Induction Type

Induction planar actuators have a structurally simple secondary, often consisting of a conductive plate including an iron core. Ohira and Inui, Nihon University, developed an induction planar actuator with 2-DOF translational motions [Ohi04, Ohi98]. Figure 2.3.3-1 shows the primary windings of the planar actuator, which structurally corresponds to the two-dimensionally extending primary windings of linear motors. The primary core consists of a yoke and teeth, which are made by laminating multiple magnetic steel sheets along the x– and y–directions, respectively. Therefore, exciting the armature windings for the x– and y–directional drives by applying three-phase alternating current generates strong propulsion forces in the x– and y–directions with less eddy-current losses. The mover is suspended by ball bearings or air bearings.

Fujii, Kyushu University, proposed a circular induction planar actuator with 2-DOF translational and 1-DOF rotational motions as shown in Fig, 2.3.3-2 [Fuj99]. The primary windings structurally correspond to circularly closed primary windings of linear motors. A rotational magnetic field around the z–axis, which excites the armature windings as shown in Fig. 2.3.3-2 (c), generates torque around the z–axis, and two mutually-opposite rotational magnetic fields around the z–axis, as shown in Fig. 2.3.3-2 (d), generate translational forces on the plane. Therefore, appropriate combination of multiple rotational magnetic fields independently controls the 2-DOF translational forces and 1-DOF torques on the plane.

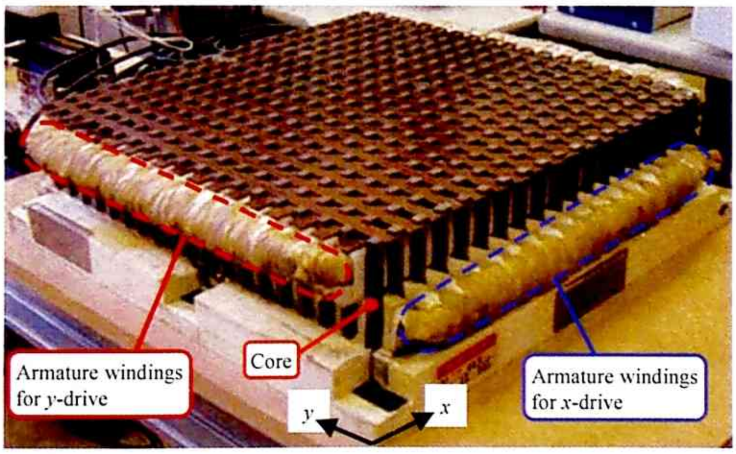
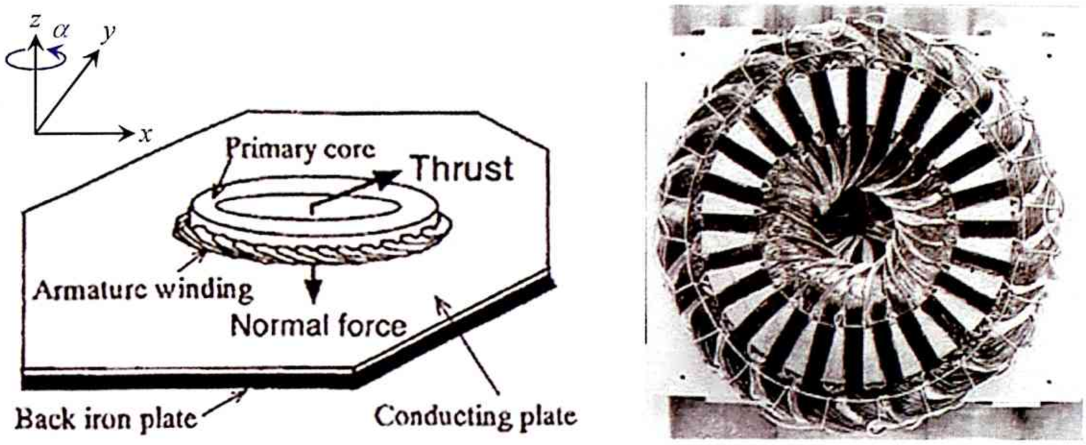
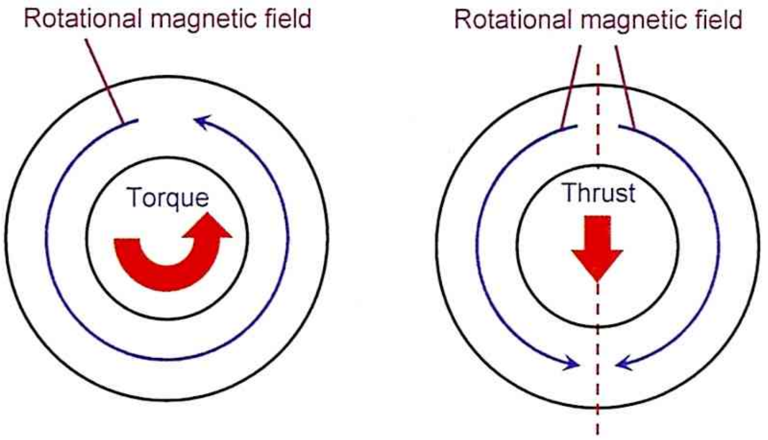


Fig. 2.3.3-1: 2-D primary windings of induction planar actuator developed by Ohira [Ohi04].



(a) Fundamental structure. (b) Primary windings.



(c) Principle of the α–drive. (d) Principle of the x– or y–drives.

Fig. 2.3.3-2: Induction planar actuator developed by Fujii [Fuj99].

Koseki, The University of Tokyo, proposed an induction-type planar actuator with 6 DOF as shown in Fig. 2.3.3-3 [Kos04]. The mover has three primary windings from linear induction motors (LIM) for the x–, y–, and α–motion controls, and three hybrid electromagnets for the z–, β–, and γ–motion controls. The stator consists of a structurally simple iron plate. The hybrid electromagnets, which have permanent magnets and coils with iron cores, generate suspension forces equal to the force of gravity acting on the mover without excitation at the nominal position. This system is often referred to as "zero-power-controlled magnetic levitation."

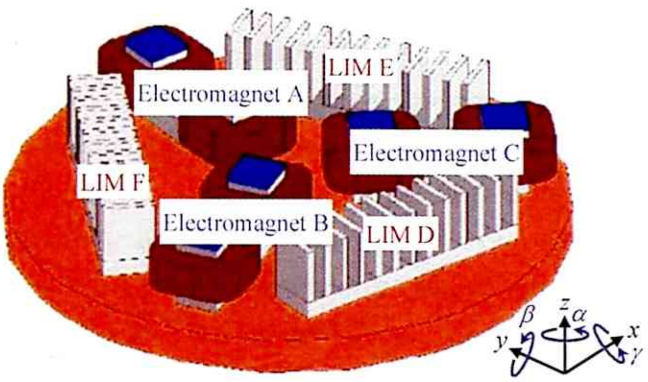


Fig. 2.3.3-3: 6-DOF induction planar actuator proposed by Koseki [Kos04].

2.3.4. Synchronous Type

Synchronous planar actuators consist of armature conductors that supply multiple currents and a permanent-magnet array that generates multipole magnetic fields, and these components are two-dimensionally arranged. The driving forces are proportional to the intensity of the magnetic field generated by the armature currents, and sinusoidal to their phase. Therefore, synchronous-type planar actuators offer good controllability of their driving forces, and are absolutely suitable for high-performance (high-speed, high-precision) drives.

The mover is often suspended by air bearings or magnetic bearings. The mover positions are detected by various sensors; laser interferometers, optical encoders, magnetic sensors, capacitance sensors, induction sensors, and photodetectors (laser triangulation). These position-sensing methods are selected by detection resolution, detectable area, ease of installation, and other means.

To generate multipole magnetic fields, various 2-D permanent-magnet arrays have been proposed; a checkerboard type [Asa85, Chi99], the Halbach type [Tru97, Com03], and another type [Jun02]. A Halbach permanent-magnet array generates a higher flux density with a distribution that is more similar to that of a sinusoidal wave, and therefore generates higher driving forces with fewer force ripples [How01, Jan07].

Synchronous planar actuators are classified into two types; those which utilize polyphase alternating currents for the armature conductors [Com04, Com07, Hin87, HOh07, Jun02, Kim97, Kor06, Ohi06, TSh06], and those which do not [Asa85, Bin03a, Bin03b, Uet03a, Uet03b, Van07a].

Although synchronous planar actuators that do not use polyphase currents have a high flexibility in their structural design, their driving forces often has a strongly nonlinear dependence on their mover positions, and consequently the control system for their driving forces becomes more complicate [Van07b].

Asakawa, Binnard, and Ueta proposed 3-DOF synchronous planar actuators that did not use polyphase currents [Asa85, Bin03a, Uet03a, Uet03b]. Their proposed planar actuators have a mover with more than four coils as shown in Figs. 2.3.4-1 and 2.3.4-2, they claimed that independent excitation of the coils controls the x–, y–, and α–positions of the mover (including the coils) [Asa85]. Furthermore, Binnard claimed that feeding eight different sources of current to the armature conductors controls the mover motions with six degrees of freedom (3-DOF translations and rotations) [Bin03b].

Vandenput, Eindhoven University of Technology, developed a 6-DOF planar actuator with a 2-D Halbach permanent-magnet array levitated magnetically as shown in Fig. 2.3.4-3 [Jan07, Van07a, Van07b]. The mover has Halbach magnetizations along the x– and y–directions. The stator has 84 armature conductors separately connected to 84 power supplies. The dimensions of each permanent-magnet component and armature coil are designed so that the driving-force ripples and power dissipations are optimally decreased [Jan07, Van07a]. Exciting 15 to 24 armature coils below the mover independently controls the 6-DOF forces, which nonlinearly depend upon the 6-DOF positions of the mover. The planar actuator has numerous armature coils on the plane, and therefore switching the armature coils to the mover positions allows the mover to travel over large displacements on the plane. Conversely, increasing the number of the armature coils is required to extend the movable area, and consequently results in making the power-supply system more complicated.

The 6-DOF mover positions over the wide movable area are detected by eight induction sensors installed on a sensor frame positioned by a long-stroke H-shaped-gantry x–y stage.

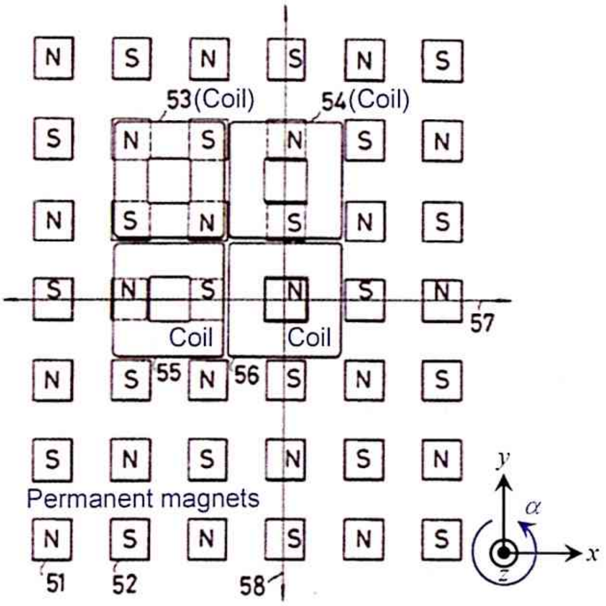
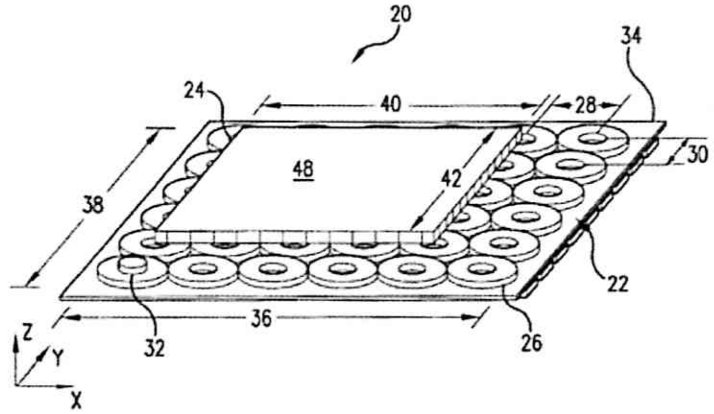
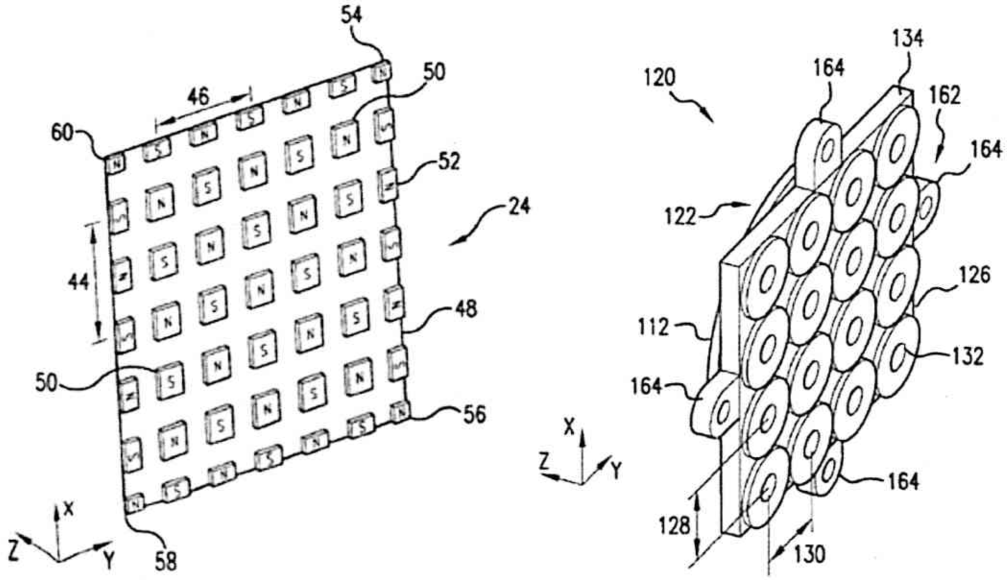


Fig. 2.3.4-1: Synchronous planar actuator proposed by Asakawa [Asa85].

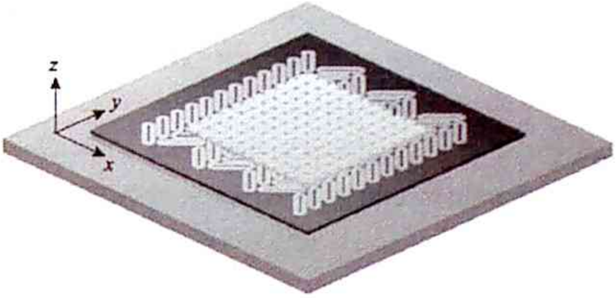


(a) Perspective view of planar actuator.

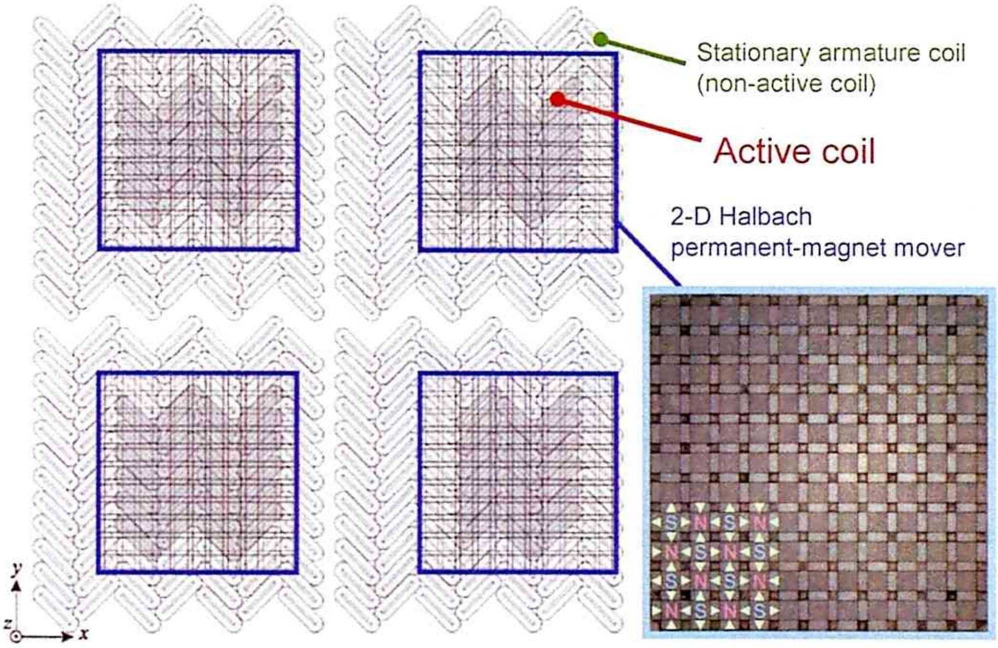


(b) Permanent-magnet assemblies. (c) Armature-coil assemblies.

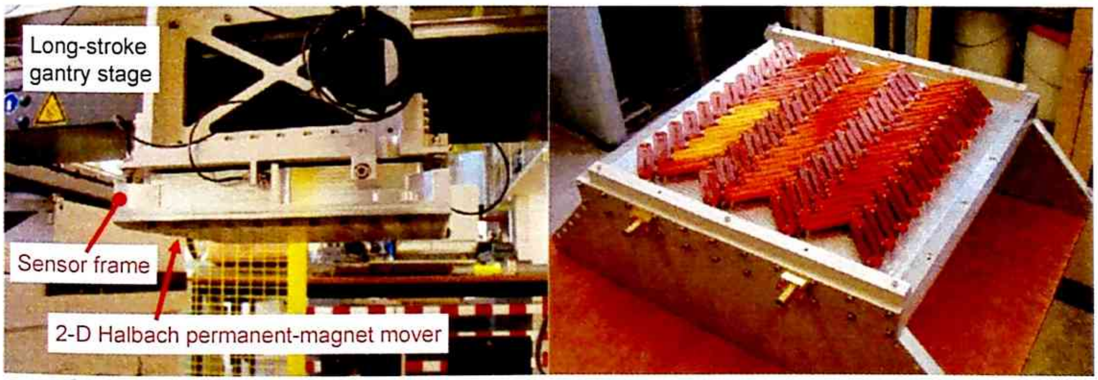
Fig. 2.3.4-2: Synchronous planar actuator proposed by Binnard [Bin03].



(a) Fundamental structure.



(b) Active coils (dark gray coils) at transitions between different sets of coils.



(c) 2-D magnets array with sensor frame. (d) Independent 84 armature coils.

Fig. 2.3.4-3: 6-DOF synchronous planar actuator developed by Vandenput [Jan07, Van07a, Van07b].

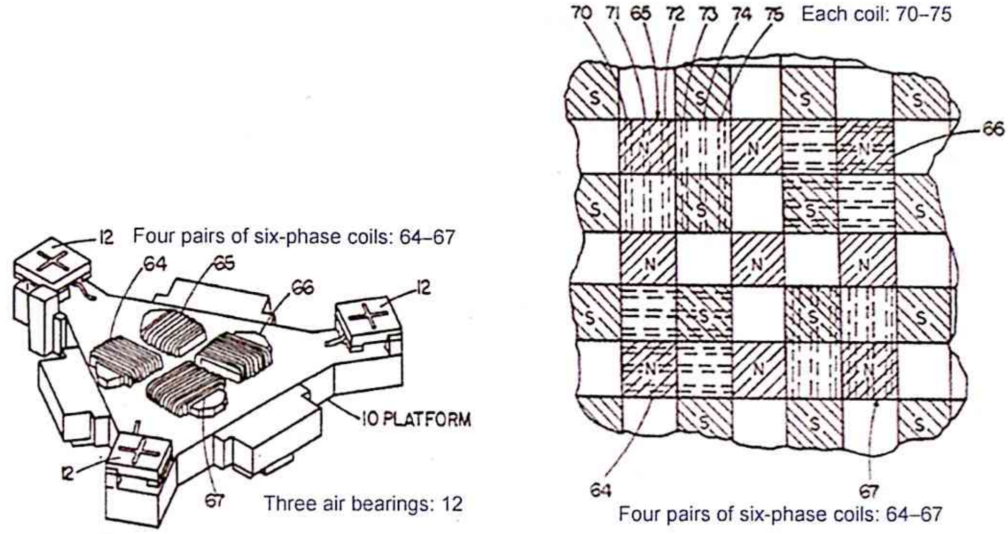
Synchronous planar actuators using polyphase currents can easily control the phase of the multipole sinusoidal magnetic fields generated by the polyphase currents. Therefore, the nonlinear dependence of the driving forces on the mover positions can be weakened, and controllability of the mover motions can be easily improved.

Hinds, proposed a synchronous 3-DOF (x, y, and α) planar actuator as shown in Fig. 2.3.4-4 [Hin87]. The planar actuator has four six-phase windings (two and two for the x– and y–directional drives, respectively), and permanent magnets arranged checker-wise on a plane. This means the planar actuator generates 2-D driving forces like two linear synchronous motors. The mover is suspended by three air bearings. Fujii, Kyushu University, also proposed a similar planar actuator, except that his design had double-layered three-phase armature windings for 2-DOF translational motion control [Fuj02].

Shikayama, Yaskawa Electric Corporation, developed a novel 3-DOF (x, y, and α) synchronous planar actuator with a simple structure as shown in Fig. 2.3.4-5 [TSh06]. The mover has two and two drive units for the x– and y–directional drives, respectively. The drive unit consists of three concentrated armature coils and two four-pole permanent-magnet arrays. Exciting the armature coil generates a multipole magnetic field on the surface of the stationary iron core slotted into a lattice pattern by the teeth, and in length, the pole pitch of the magnetic field generated by the armature is equal to the pole pitch of the permanent-magnet array. Three armature coils are arranged so that the phases of the three multipole magnetic fields generated by the three armature coils are out of phase by 120 deg, and therefore supplying three-phase current to the three armature coils generates driving forces using the same principle as linear synchronous motors. The mover positions are detected by a planar optical encoder that consists of a glass scale mounted on the surface of an iron core and four sensor heads mounted on the mover. The mover is suspended by air bearings and has pneumatic lines. This planar actuator is easily fabricated because of the structurally-simple mover and stator, and can control multiple movers on a single stator.

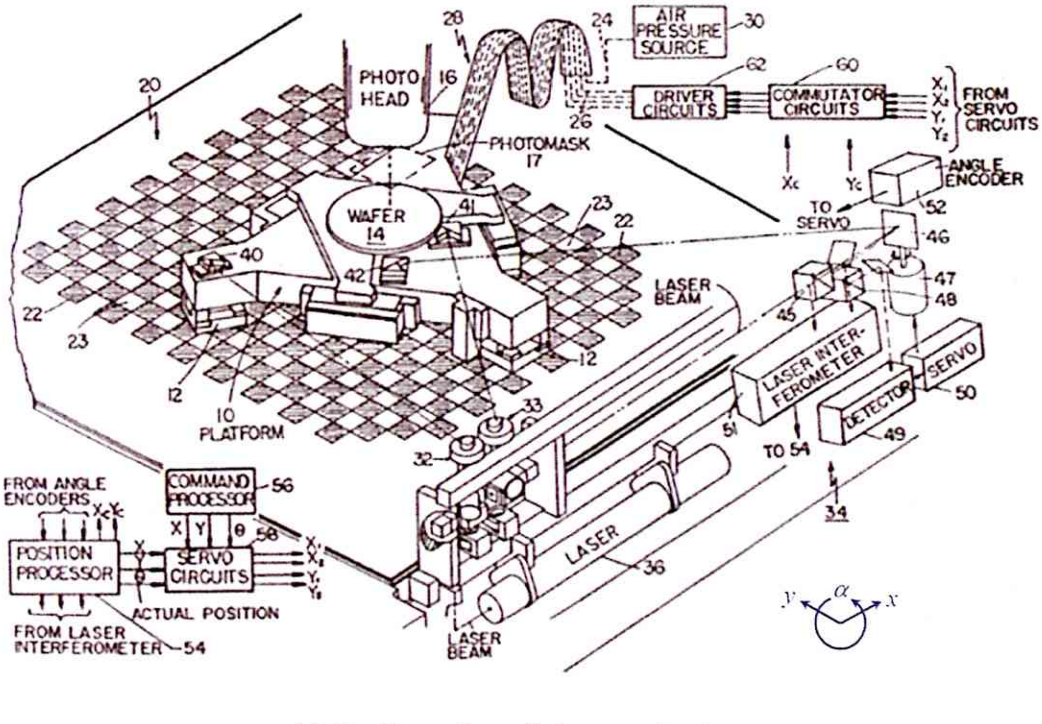
Ohira and Inui, Nihon University, and Koseki, The University of Tokyo, proposed a synchronous planar actuator with a magnetically levitated mover as shown in Fig. 2.3.4-6 [Kos01, Ohi06]. The mover consists of four hybrid electromagnets including four windings with iron cores, four permanent magnets, and a yoke. Controlled attraction forces between the electromagnets and the stationary iron cores suspend and drive the mover in the z–, β–, and γ– directions. The permanent magnets enable the mover to be suspended at a nominal position without excitation of the electromagnets. As stated above, this system is often referred to as "zero-power-controlled magnetic levitation."

The stationary iron cores have 2-D primary windings as proposed by Ohira and as shown in Fig. 2.3.3-1, and exciting the armature windings generates the translational forces in the *x*– and *y*–directions.



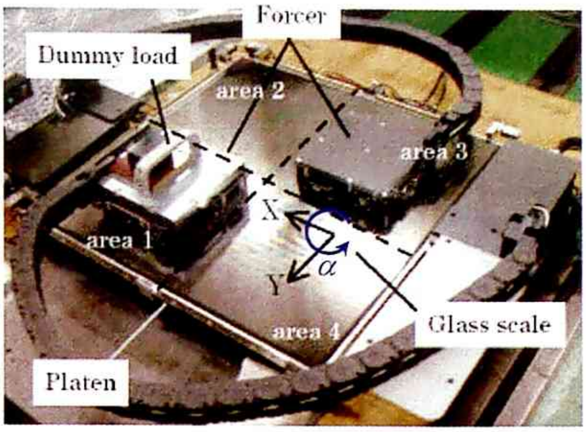
(a) Bottom view of planar actuator.

(b) Top view of magnets and coils.

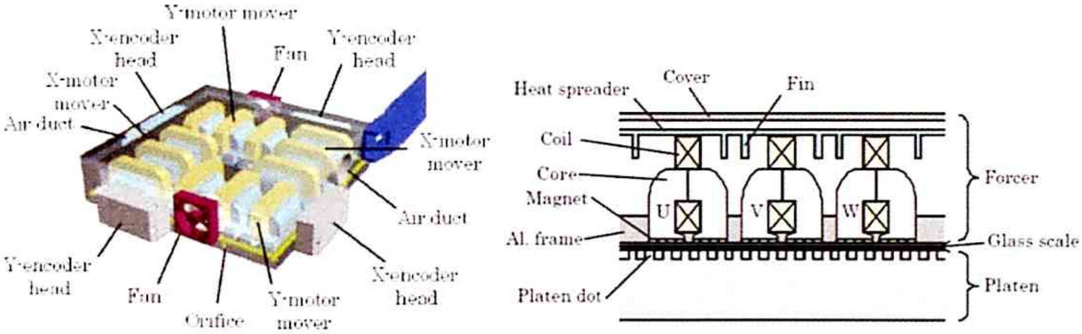


(c) Configuration of planar actuator.

Fig. 2.3.4-4: Synchronous planar actuator proposed by Hinds [Hin87].

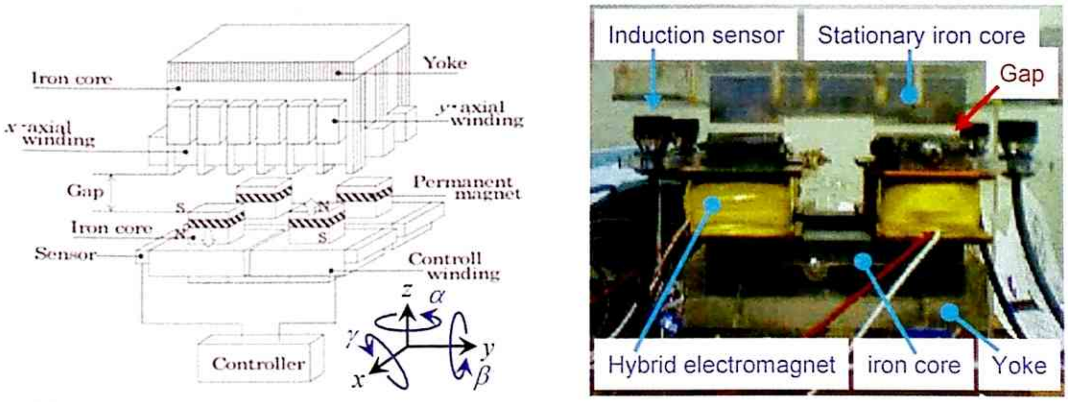


(a) Perspective view of planar actuator.



(b) Configuration of planar actuator. (c) Cross-section view of motor unit.

Fig. 2.3.4-5: Synchronous planar actuator developed by Shikayama [TSh06].



(a) Fundamental structure [Ohi06]. (b) Magnetic levitation [Kos01].

Fig. 2.3.4-6: Synchronous planar actuator proposed by Ohira and Koseki [Ohi06, Kos01].

Jung, Seoul National University, proposed a 3-DOF synchronous planar actuator with a novel 2-D permanent-magnet array as shown in Fig. 2.3.4-7 [Jun02]. The mover has four three-phase concentrated armature coils (two and two for the x– and y–directional drives, respectively). The permanent-magnet array has quasi-Halbach magnetization in both the x– and y–directions, achieved by inserting multiple quarter-sized permanent magnets into Hinds' proposed permanent-magnet array, as a result of which it generates a sinusoidal flux density B_{z1} in both the x– and y– directions as shown in the following equation:

$$B_{z1}(x,y,z)=B_{zm1}(z)\left(\cos\left(\frac{\pi}{\tau}x\right)+\cos\left(\frac{\pi}{\tau}y\right)\right)\ldots\ldots(2.3.4\text{-}1)$$

Equation (2.3.4-1) shows that a simply structured magnet array can subject superimposed magnetic fields upon the x– and y–directional drives for all armature coils anywhere above itself. Therefore, extending the stationary magnet array on a plane enables the movable area of the mover to be widened.

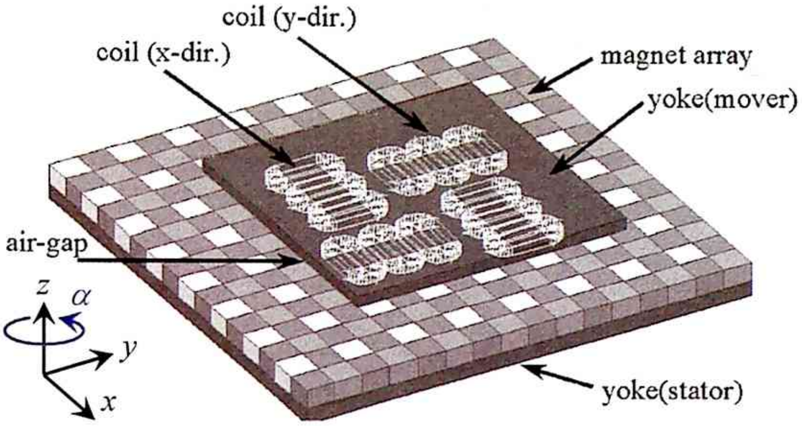
Compter, Royal Philips Electronics, also developed a 6-DOF synchronous planar actuator with a 2-D Halbach permanent-magnet array as shown in Fig. 2.3.4-8 [Com03, Com04]. The permanent-magnet array generates a sinusoidally-distributed flux density B_{z2} in both the x_l – and y_l –directions as shown in the following equation:

$$B_{z2}(x_l,y_l,z)=B_{zm2}(z)\cdot\cos\left(\frac{\pi}{\tau_{PM}}x_l\right)\cdot\cos\left(\frac{\pi}{\tau_{PM}}y_l\right)\ldots\ldots(2.3.4\text{-}2)$$

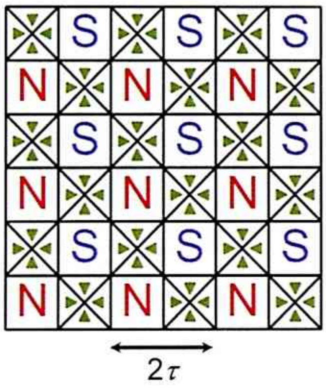
The flux density B_{z2} can also be expressed by the coordinate x–y rotated 45 deg around the z–axis from the coordinate x_l-y_l as shown in the following equation:

$$B_{z2}(x,y,z)=\frac{B_{zm2}(z)}{2}\left(\cos\left(\frac{\pi}{\tau}x\right)+\cos\left(\frac{\pi}{\tau}y\right)\right)\qquad\left(\because\ \tau=\frac{\tau_{PM}}{\sqrt{2}}\right).\ldots\ldots(2.3.4\text{-}3)$$

As mentioned in Eq. (2.3.4-1), Eq. (2.3.4-3) also indicates that the stationary magnet array generates magnetic fields for the x– and y–directional drives anywhere above itself.

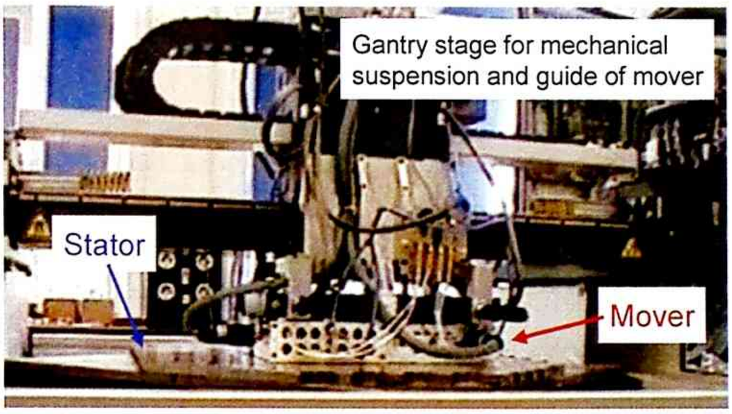


(a) Perspective view of planar actuator.

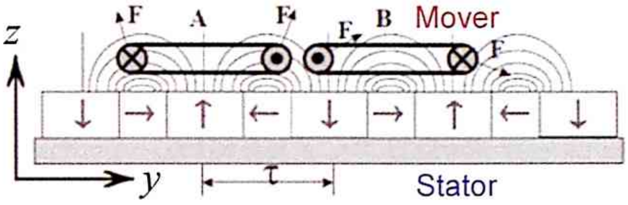


(b) 2-D quasi-Halbach permanent-magnet array.

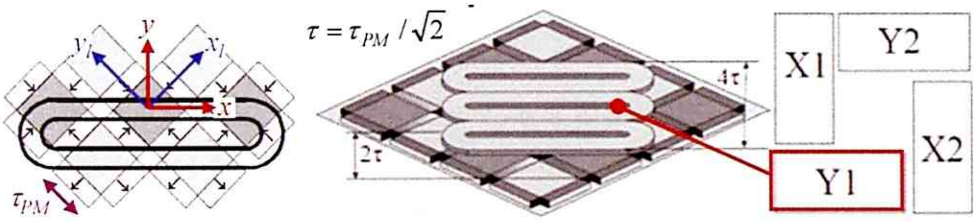
Fig. 2.3.4-7: Synchronous planar actuator proposed by Jung [Jun02].



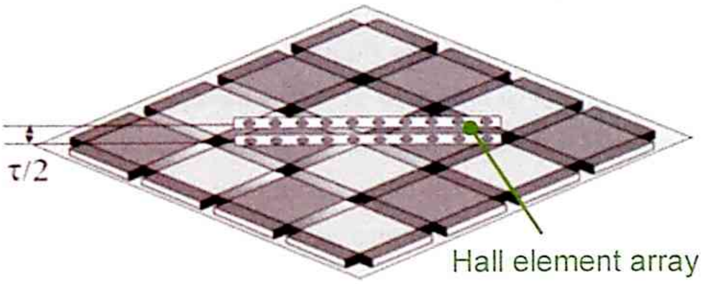
(a) Experimental setup of planar actuator.



(b) Side view of planar actuator.



(c) Four three-phase concentrated armature coils.



(d) Hall element arrays for position sensing of the mover.

Fig. 2.3.4-8: Moving-coil-synchronous planar actuator with 6 DOF developed by Compter [Com03, Com04].

Kim, Massachusetts Institute of Technology, developed a 6-DOF synchronous planar actuator with a magnetically levitated mover as shown in Figs. 2.3.4-9, and 2.3.4-10 [Kim97, Kim98, Tru96]. The planar actuator consists of a mover on which is mounted four Halbach permanent-magnet arrays and four stationary three-phase armature windings. A single magnet array pair and the three-phase current of the armature windings simultaneously generate 2-DOF (x or y, and z) translational forces like a linear synchronous motor. Exciting four three-phase windings (like a combination of four linear synchronous motors) generates independently-controlled 6-DOF driving forces. The 6-DOF mover positions can be detected using a combination of three laser interferometers on a plane and three capacitance sensors on the surface of the stator. Although the planar actuator was reported to have an extremely-high precision in 6-DOF positioning, the movable area is extremely narrow due to the separation of the magnet array pairs and armature windings due to the large displacement of the mover.

Compter, Royal Philips Electronics, also developed a 6-DOF synchronous-type planar actuator with a magnetically levitated mover as shown in Fig. 2.3.4-11 [Com07, Phi06]. The planar actuator consists of a 2-D Halbach-magnetized mover and nine stationary concentrated three-phase armature coils. As shown in Eq. (2.3.4-3), the mover generates 2-D sinusoidal flux density. Measuring the magnetic flux generated by the mover using 27 Hall elements detects the mover positions without need of large or complicate position sensors. The mover can travel over armature coils and Hall elements.

To extend a movable area of a mover on a plane, Oh, Korea Electrotechnology Research Institute, developed a 6-DOF synchronous-type planar actuator that has numerous armature coils (100 three-phase coils) as shown in Fig. 2.3.4-12 [HOh07]. The mover consists of a 2-D Halbach permanent-magnet array. The mover positions are detected using a combination of three laser interferometers and three capacitance sensors. In this planar actuator, increasing the number of the armature coils extends the movable area, but makes the power-supply system more complicated.

Korenaga, Canon Inc., proposed a MDOF (x, y, and α) synchronous planar actuator with only two two-phase armature coils as shown in Fig. 2.3.4-13 [Kor06]. In this planar actuator, lengthening all the armature coils extends the movable area without increasing the number of coils and without complicating the power-supply system. Two two-phase armature coils are arranged over the stator, and the magnetic fluxes generated by the two two-phase current are mutually superimposed. The mover has multiple 2-D Halbach permanent-magnet arrays, which also generate mutually-superimposed magnetic fields for the x– and y–directional drives. For these reasons, the driving forces among the 6 DOF tend to be coupled to one another. Therefore, decoupled control of MDOF driving forces is extremely important.

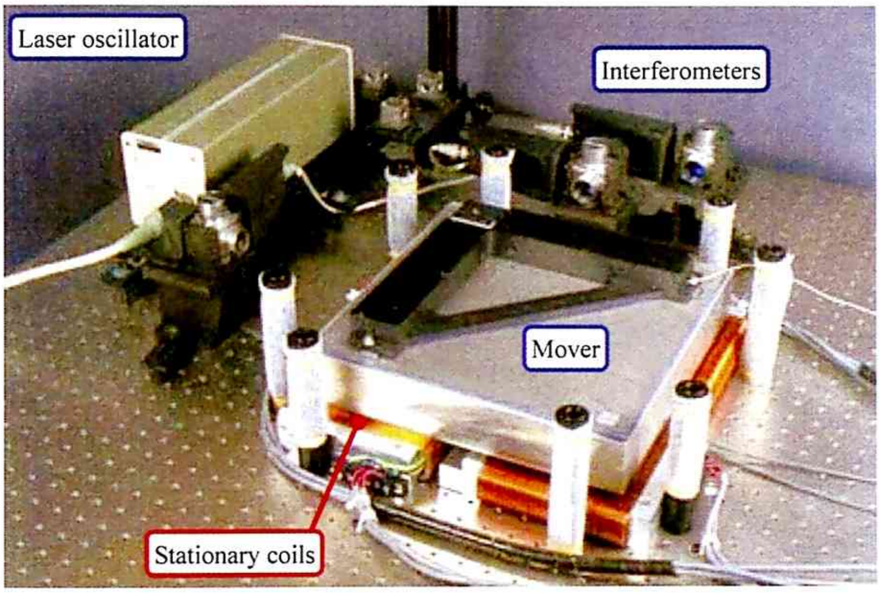
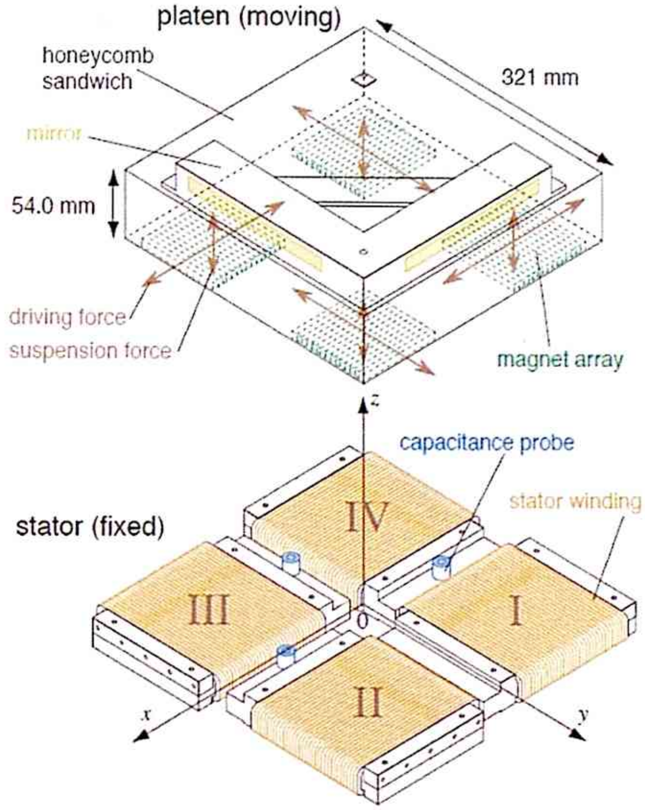
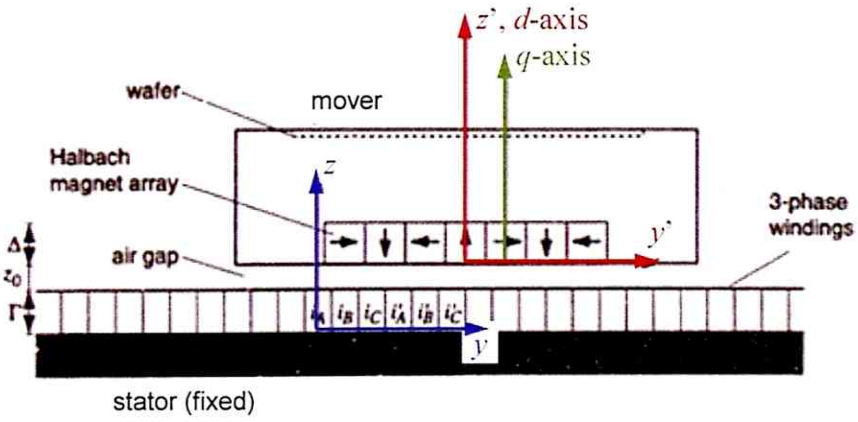


Fig. 2.3.4-9: Prototype of 6-DOF synchronous-type planar actuator developed by Kim [Tru96].

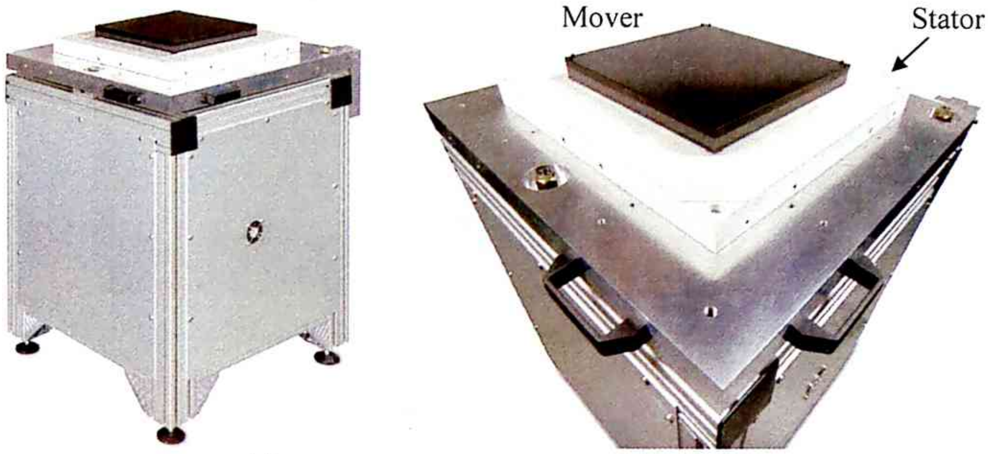


(a) Fundamental structure of planar actuator.

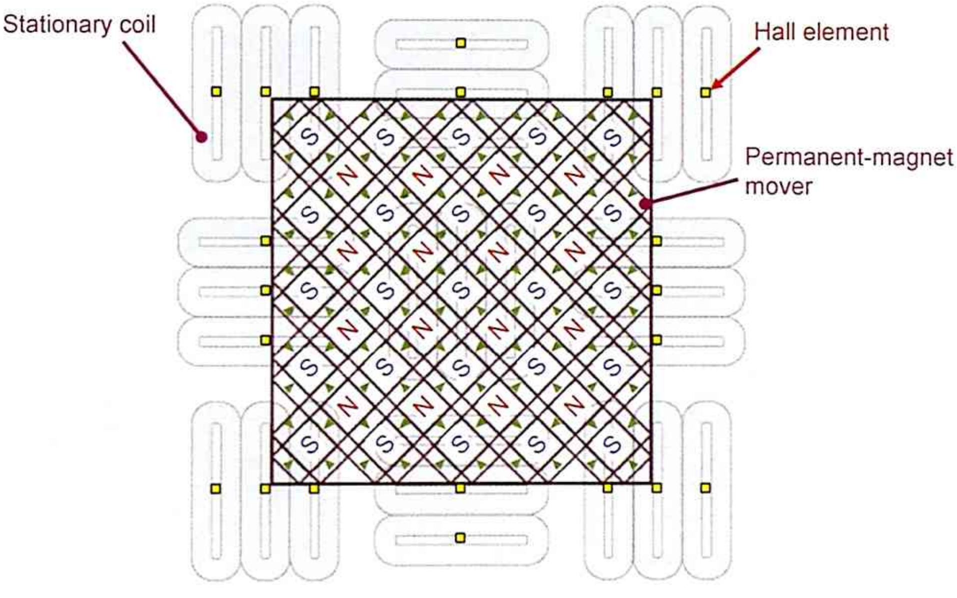


(b) DQ frame attached to mover.

Fig. 2.3.4-10: 6-DOF synchronous planar actuator developed by Kim [Kim97, Kim98].

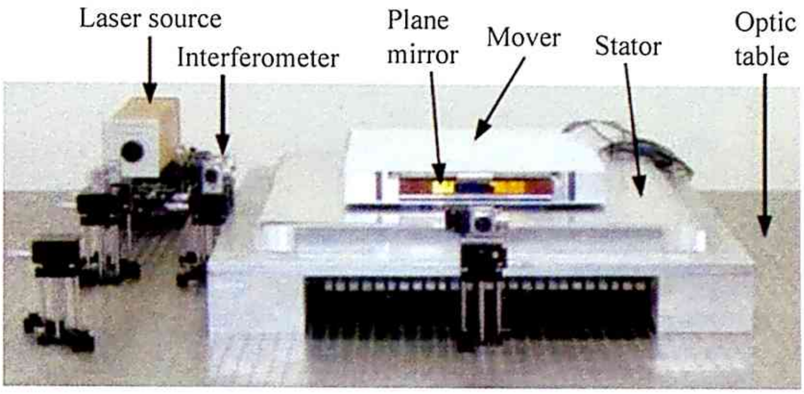


(a) Perspective views of planar actuator.

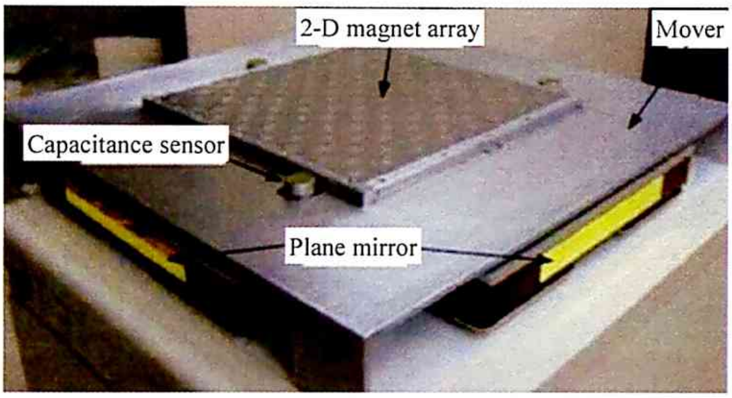


(b) Configuration of planar actuator.

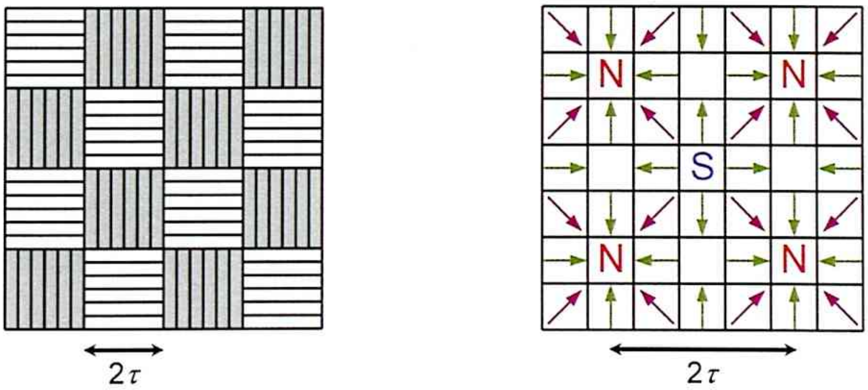
Fig. 2.3.4-11: Moving-magnet-synchronous planar actuator with 6 DOF developed by Compter [Com07, Jan07, Phi06].



(a) Perspective view of planar actuator.

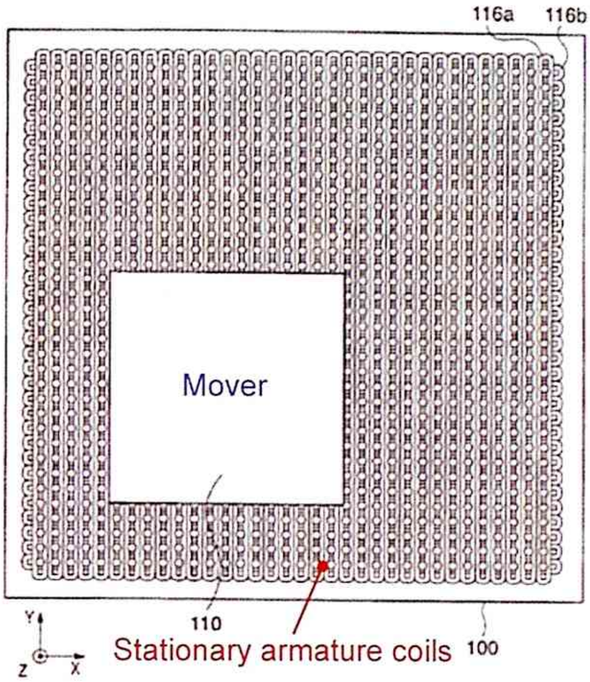


(b) Bottom view of mover.

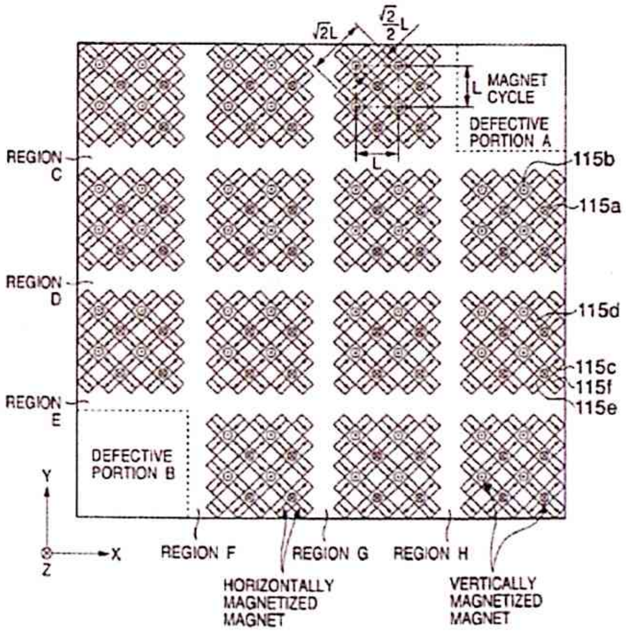


(c) Armature-coil assemblies. (d) Permanent-magnet assemblies.

Fig. 2.3.4-12: 6-DOF synchronous-type planar actuator developed by Oh [HOh07].



(a) Top view of planar actuator.

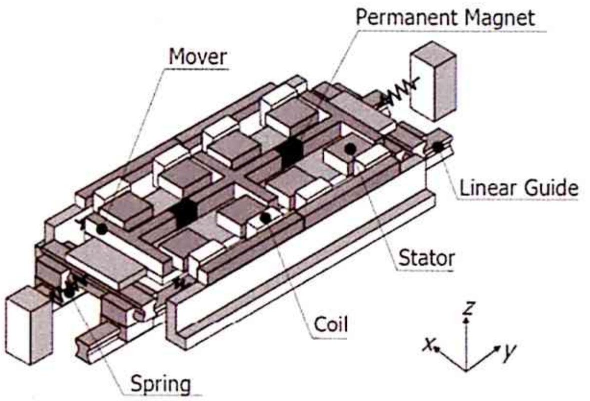


(b) Bottom view of mover.

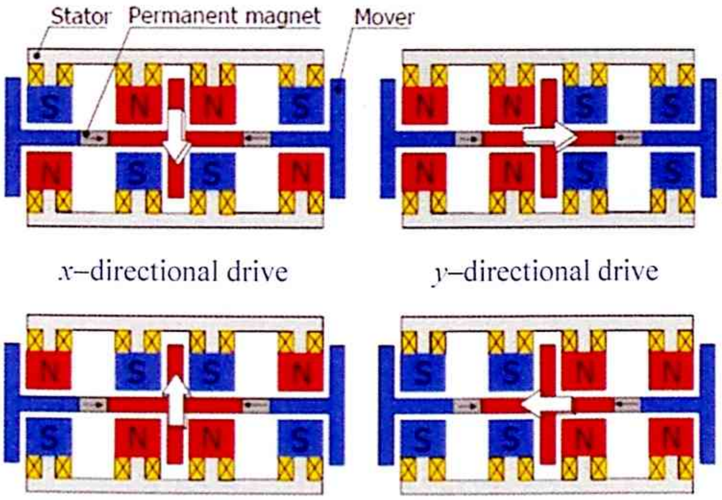
Fig. 2.3.4-13: Synchronous planar actuator proposed by Korenaga [Kor06].

2.3.5. Resonant type

Ebihara, Musashi Institute of Technology, developed a resonant planar actuator as shown in Fig. 2.3.5-1. The planar actuator has a moving iron core containing two permanent magnets, and eight stationary electromagnets. The moving core is suspended and guided by stacked two linear guides, and is connected with the stator through four and two resonant springs in the *x*– and *y*–directions, respectively. Figure 2.3.5-1 (b) shows the excitation patterns of the eight electromagnets for the *x*– and *y*–directional drives. Switching these excitations generates reciprocating motions of the mover in the *x*– and *y*–directions.



(a) Perspective view of planar actuator.



x–directional drive

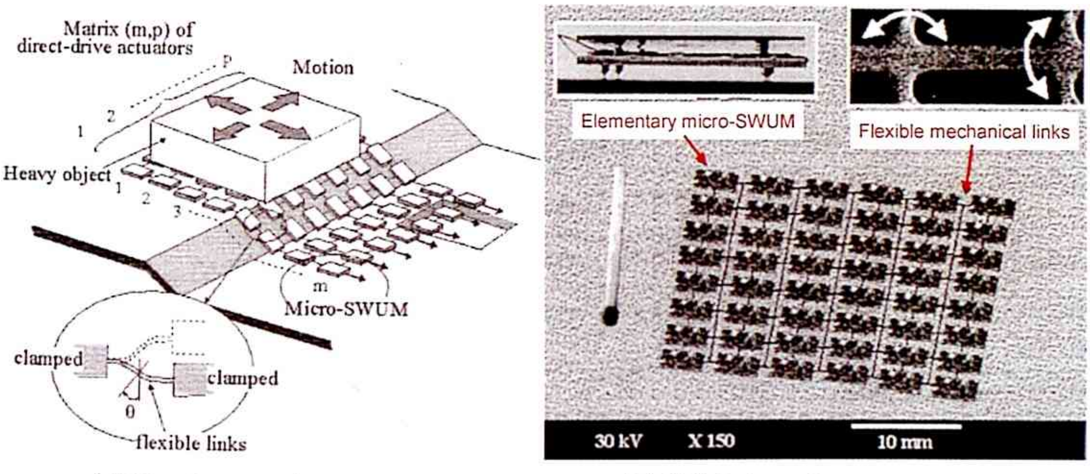
y–directional drive

(b) Drive principle of planar actuator.

Fig. 2.3.5-1: Resonant planar actuator developed by Ebihara [Ebi03, Ebi05].

2.3.6. Piezoelectric Type

Piezoelectric actuators drive the mover by means of the inverse piezoelectric effect, and generally have advantages in terms of precise positioning because of the minute strain output, high-torque driving, and high retaining forces [MDD05]. Fontaine, Bourges Higher National School of Engineering, developed a piezoelectric planar actuator (conveyer) with multiple micro standing-wave ultrasonic motors (micro-SWUM) as shown in Fig. 2.3.6-1 [Fon03]. Selective excitation of multiple bending vibrations of the micro ultrasonic motors drives the mover in the *x*– and *y*–directions. Maeno, Keio University, also developed a piezoelectric planar actuator with four plate-ultrasonic motors [Mae05]. The combination of the four vibrations, which includes three vibration modes, drives the mover in the translational and rotational directions on the plane.

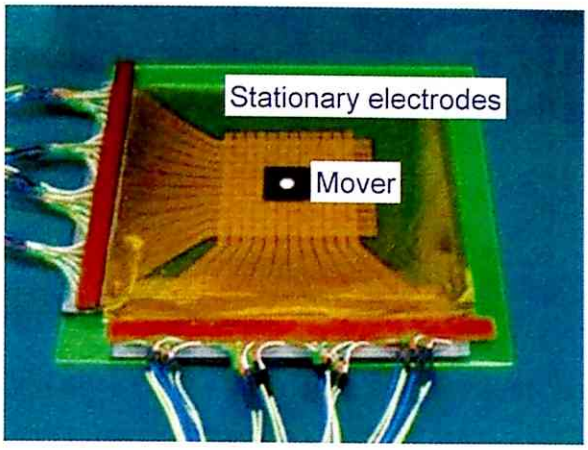


(a) Fundamental structure. (b) SEM view of prototype.

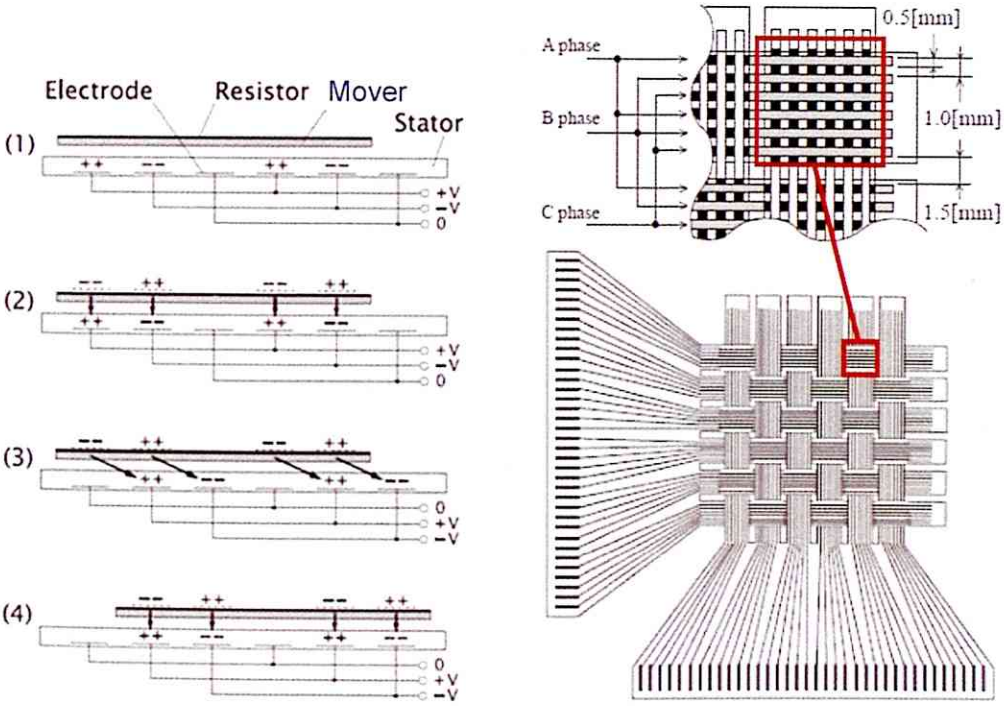
Fig. 2.3.6-1: Piezoelectric planar actuator developed by Fontaine [Fon03].

2.3.7. Electrostatic Type

Electrostatic forces act on various dielectric materials. Generally, the force density acting on smaller objects becomes larger [Act04]. Therefore, electrostatic actuators are often applied to MEMS. In several-cm manipulations, electrostatic forces are often as weak as electromagnetic forces, but electrostatic actuators have an advantage—the mover can consist of only one dielectric material, (for example, paper and film) and the mover structure is extremely simple [Hig06]. Higuchi, The University of Tokyo, developed an electrostatic planar actuator with 2 DOF as shown in Fig. 2.3.7-1 [Hig04]. The mover consists of a PET film coated with carbon black having high resistivity. The stator has three-phase connected mesh electrodes. Figure 2.3.7-1 (b) shows the drive principle of the actuator; (1) first, inducing electric charges on the mover surface, (2) second, generation of attraction forces, (3) third, switching three-phase voltage, and (4) finally, mover translation. Higuchi demonstrated the 2-D drives of the mover [Hig04].



(a) Electrostatic planar actuator.



(b) Drive principle.

(c) Stationary electrodes.

Fig. 2.3.7-1: Electrostatic planar actuator developed by Higuchi [Hig04].

2.4. Other MDOF Actuators

So far, I have introduced previously designed planar actuators, which drive in two translational directions, and a spherical actuator, which drives in two rotational directions. In this section, I will introduce other MDOF actuators that have been studied as follows; 2-DOF actuators that drive in single translational and rotational directions, and 6-DOF actuators.

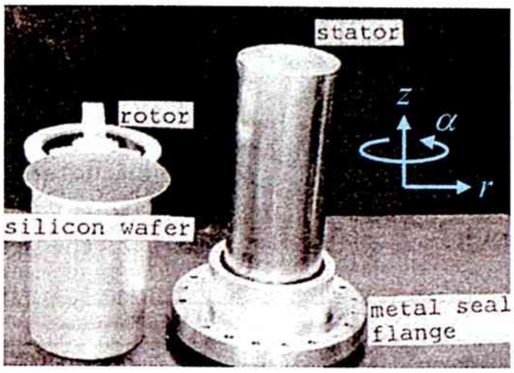
2.4.1. Linear-and-Rotary Actuators

Higuchi, The University of Tokyo, developed a magnetically levitated actuator that drives the mover in the z–translational and α–rotational directions as shown in Fig. 2.4.1-1 [Hig90]. The actuator consists of a moving iron core slotted into the z– or α–directions, and stationary windings with iron cores slotted into them for the z– or α–directional drives, which drives the mover in the z– and α–directions using the same principle as stepping motors. Exciting the windings generates not only driving forces in the z– and α– directions, but also the attraction forces between the mover and stator. To suspend the mover without contact, the mover positions in the r– (radial) and z–directions are controlled by position feedback. The mover positions in the r– and z–directions are measured by induction sensors, and those in the α–direction are measured using a variable-reluctance resolver.

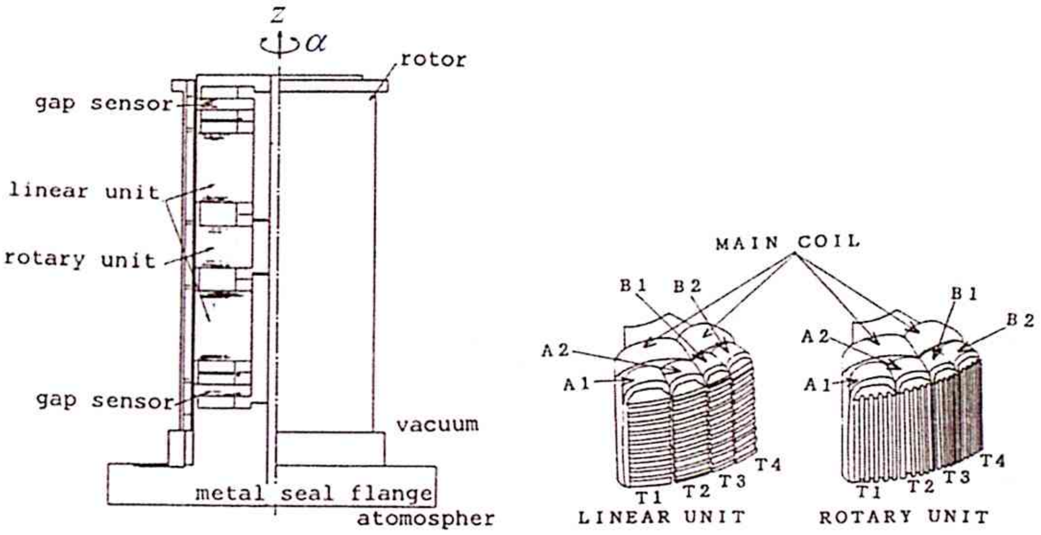
Ebihara, Musashi Institute of Technology, developed a resonant actuator that drives the mover in the z–translational and α–rotational directions as shown in Fig. 2.4.1-2 [Ebi05]. The actuator consists of a moving iron core containing a permanent magnet, and two pairs of four stationary electromagnets with yokes. The moving core is connected with the two stationary yokes through two resonant springs. Figure 2.4.1-2 (c) shows the excitation patterns of the eight electromagnets for the z– and α–directional drives. Switching these excitations generates reciprocating motions of the mover in the z– and α–directions.

Hirata, Osaka University, developed a resonant actuator that drives the mover in the z–translational and α–rotational directions as shown in Fig. 2.4.1-3 [Hir04, Hir05]. The actuator consists of a moving iron shaft mounting two ring-shaped permanent magnets, and a stator that has two E-shaped and two C-shaped yokes. The moving shaft is connected with the stationary part through a resonant spring along the axial direction. Figures 2.4.1-3 (b) and (c) show the drive principle in the z– and α– directions.

The actuator generates the driving forces by unbalancing the magnetic flux distribution generated by the permanent magnets.



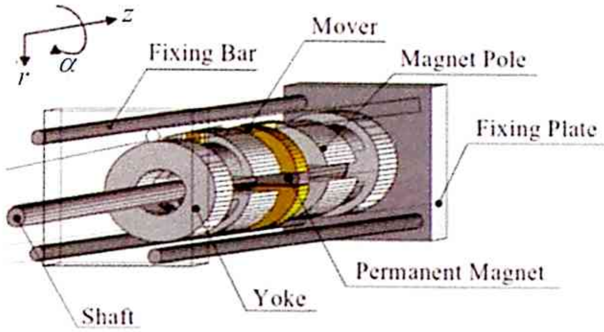
(a) Mover (rotor) and stator.



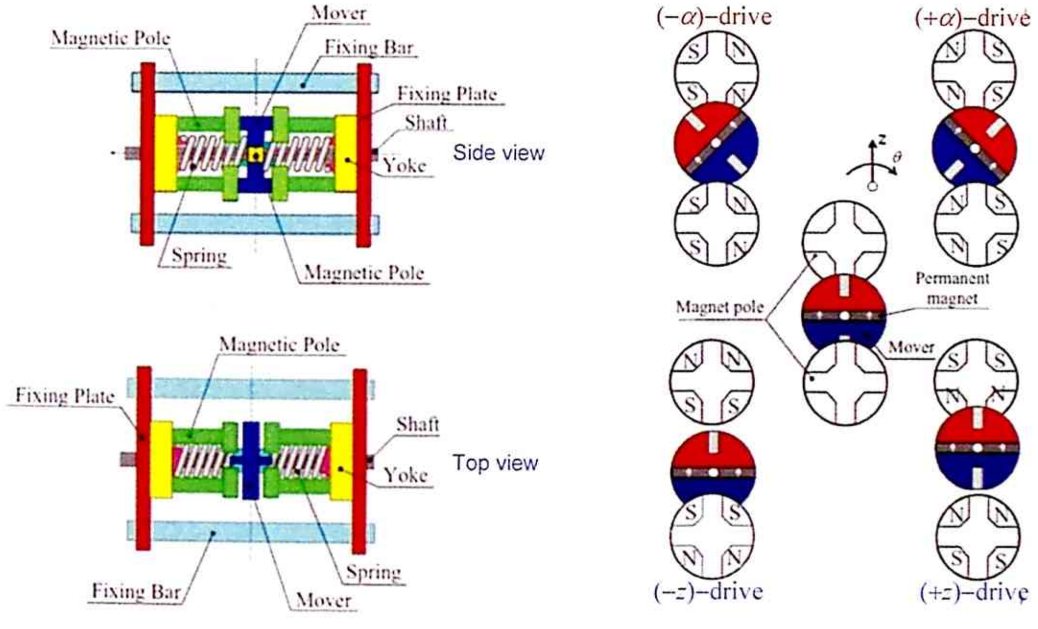
(b) Cross-section view.

(c) Stator windings with slotted iron core.

Fig. 2.4.1-1: Stepping linear-and-rotary actuator developed by Higuchi [Hig90].



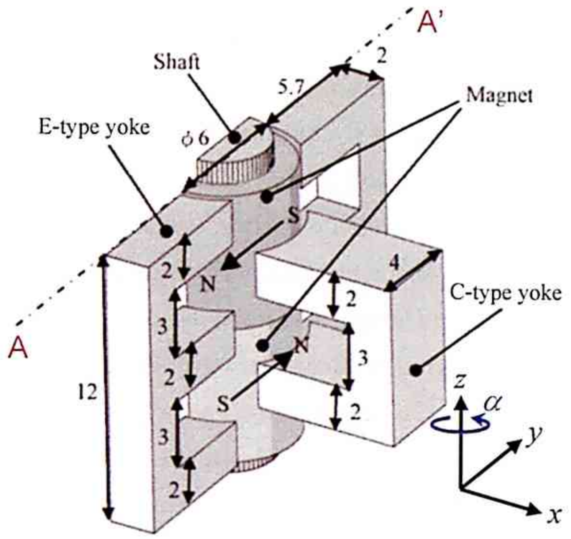
(a) Perspective view of linear-and-rotary actuator.



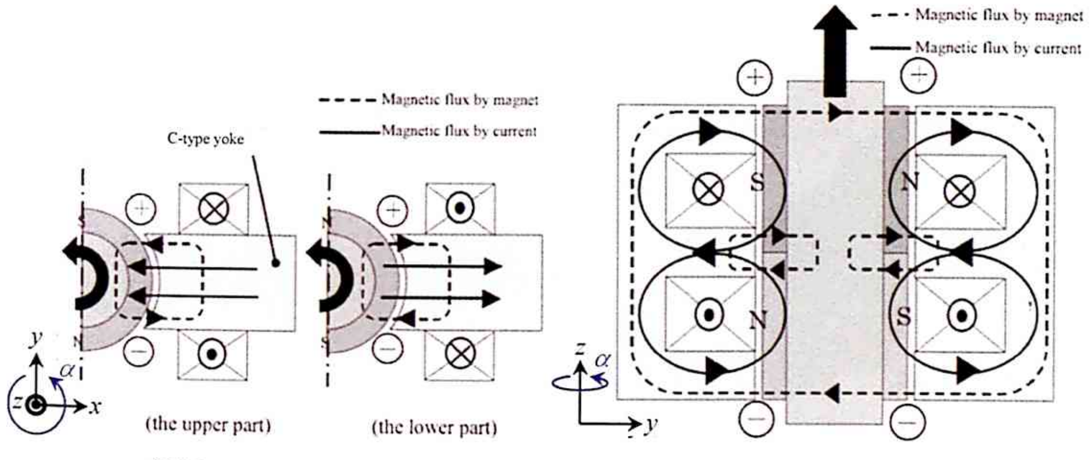
(b) Side and Top views.

(c) Drive principle.

Fig. 2.4.1-2: Resonant linear-and-rotary actuator developed by Ebihara [Ebi05].



(a) Half model of linear-and-rotary actuator.



(b) Torque generation.

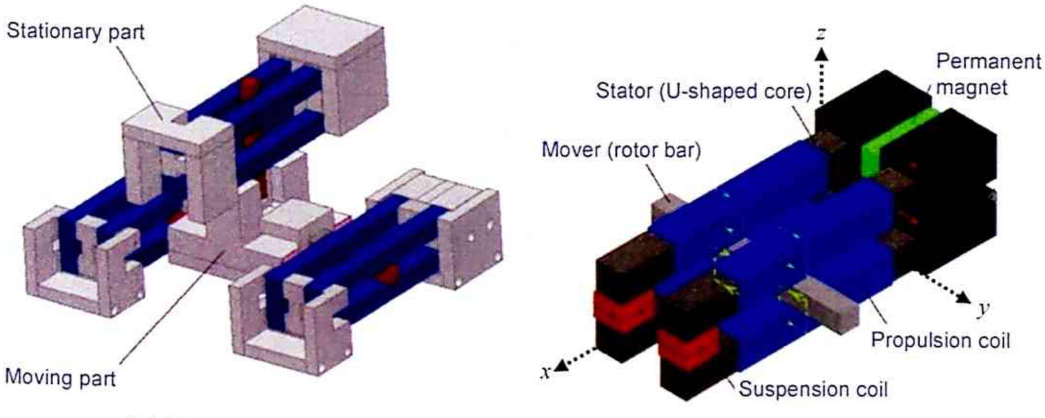
(c) Translational force generation.

Fig. 2.4.1-3: Resonant linear-and-rotary actuator developed by Hirata [Hir04, Hir05].

2.4.2. 6-DOF Actuators

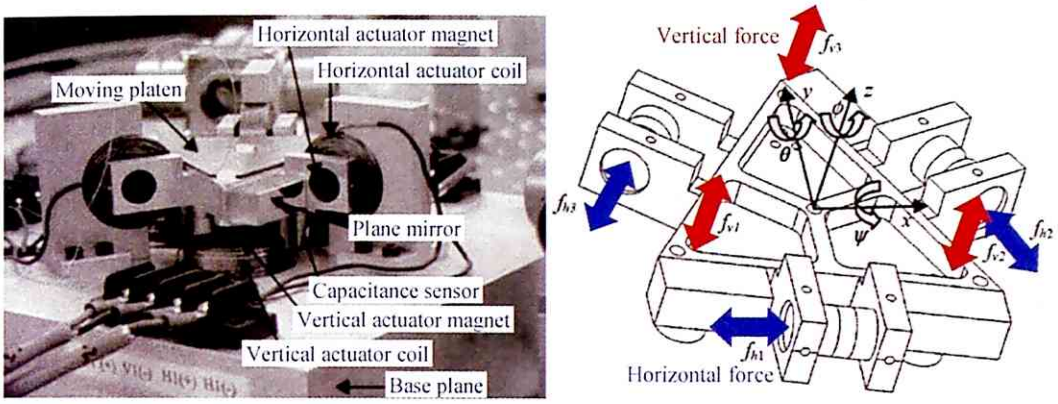
Vandenput, Eindhoven University of Technology, proposed a 6-DOF magnetically levitated actuator with long-stroke manipulation in only the x–direction as shown in Fig. 2.4.2-1 [Van06, Van07c]. The actuator, which has potential for application in optical disc-mastering equipment, has three drive units that generate 2-DOF translational motions. The drive unit consists of two permanent magnets, two U-shaped cores with two propulsion coils and a suspension coil, and a moving core. The permanent magnet creates a bias magnetic flux through the mover, and consequently generates suspension forces equal to the force of gravity acting upon the mover at the nominal position without excitation of the suspension coils. Exciting the suspension coils controls the suspension forces. In the air gap between the mover and stator, the interaction of the magnetic flux and currents of the propulsion coils generates the x–directional forces.

Kim, Texas A&M University, developed a 6-DOF magnetically levitated actuator with a minimum number of drive units required to control 6-DOF motions as shown in Fig. 2.4.2-2 [Kim05]. The drive unit consists of a stationary coil and a mover having one or two permanent magnets. The mover positions with 6 DOF are detected by three laser interferometers and three capacitance sensors.



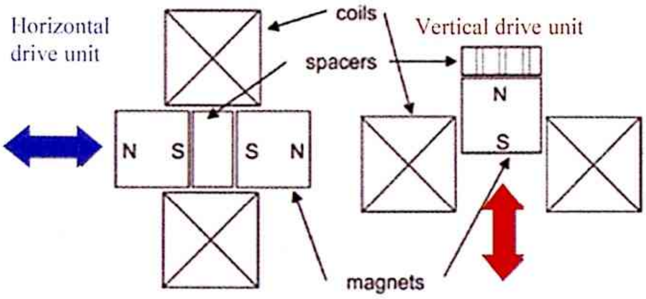
(a) Perspective view. (b) 2-DOF drive unit.

Fig. 2.4.2-1: 6-DOF actuator proposed by Vandenput [Van06, Van07c].



(a) Front view of the actuator.

(b) Directions of driving forces.



(c) Horizontal and vertical drive units.

Fig. 2.4.2-2: 6-DOF actuator developed by Kim [Kim05].

2.5. Classifications of Previous MDOF Drive Systems

All the MDOF drive systems introduced in this chapter can be classified as shown in Fig. 2.5.0-1. First, MDOF drive systems can be classified by the number of moving parts: single or multiple. Single moving-part actuators, such as planar actuators, spherical actuators offer excellent advantages in structural simplicity and drive performance because of their direct drive with MDOF. Second, MDOF actuators can be classified by type of driving force; electromagnetic (versatile use), piezoelectric (small-machine applications for precise positioning), electrostatic (micro or structurally simple machine applications), and magnetostrictive (small-machine applications with high mechanical characteristics). Finally, these kinds of actuators can be classified by their drive principle. This study deals with electromagnetic synchronous planar actuators, which have especially good controllability of their driving forces.

Synchronous planar actuators have a single moving part mounting armature coils or permanent-magnet arrays, and can be classified as these two types. Although moving-coil planar actuators have an advantage in offering an extendible movable area regardless of the number of armature coils, they have some drawbacks; deterioration of driving characteristics caused by the tension exerted by associated wires, and position-detection errors caused by thermal expansion of the mover due to the heat generated by the coils. On the other hand, moving-magnet planar actuators drives are sophisticated because there are no problematic wires, and are suitable for extremely precise positioning.

Tables 2.5.0-1 and 2.5.0-2 show the classifications of previous synchronous planar actuators by magnet array, coil assembly, and DOF of controlled motion. In the latter half of the 1990s, Kim, Massachusetts Institute of Technology, first achieved development of a 6-DOF magnetically levitated planar actuator. The planar actuator consists of a mover mounting multiple one-dimensional permanent-magnet arrays and separated multiple coil assemblies on a stator, which form spatially-separated multiple magnetic circuits. However, the large displacements of the mover cause problems in separating each magnet array from paired coil assembly, and drastically decrease the driving forces. Therefore, the movable area of Kim's proposed planar actuator is quite narrow, as shown in Fig. 2.5.0-2.

Next, Compter, Royal Philips Electronics, developed a 6-DOF magnetically levitated planar actuator with a single-magnet array two-dimensionally modified. The magnet array produces spatially-superimposed magnetic fields for the *x*– and *y*–directional drives. The combination of the magnet array and spatially-separated multiple coil assemblies drives the magnet array (mover) anywhere along a planar region where the coil assemblies are placed, in other words, extending the movable area by increasing that number of separated coil assemblies.

Then, Vandenput, Eindhoven University of Technology, and Oh, Korea Electrotechnology Research Institute, achieved development of 6-DOF magnetically levitated planar actuators with a wide movable area by utilizing numerous separated coils (specifically, 84 and 300, respectively) as shown in Fig. 2.5.0-3. However, the power-supply systems of these planar actuators were complicated.

To eliminate these problems, I propose a novel planar actuator consisting of overlapped 2-D conductors and a single-moving 2-D permanent-magnet array as shown in Fig. 2.5.0-4, which can form superimposed magnetic circuits for a 2-D drive. The configuration of the magnetic circuits can infinitely extend the movable area by lengthening all the conductors without need to increase their number. At the same time, the configuration of the magnetic circuits makes it difficult to independently control the driving forces with each degree of freedom because of the superimposition of the magnetic circuits. This study demonstrates how to design a planar actuator so that MDOF driving forces can be controlled using spatially-superimposed magnetic circuits, and this novel assertion is the main contribution of this thesis.

2.6. Summary of Chapter 2

This chapter introduced previous techniques in motion control with MDOF, their classification, features and technical trends. In particular, this chapter introduced technical details and issues related to synchronous planar actuators, which have especially good controllability of the driving forces, and clarified the position of synchronous planar actuators, which feature in the background to this thesis.

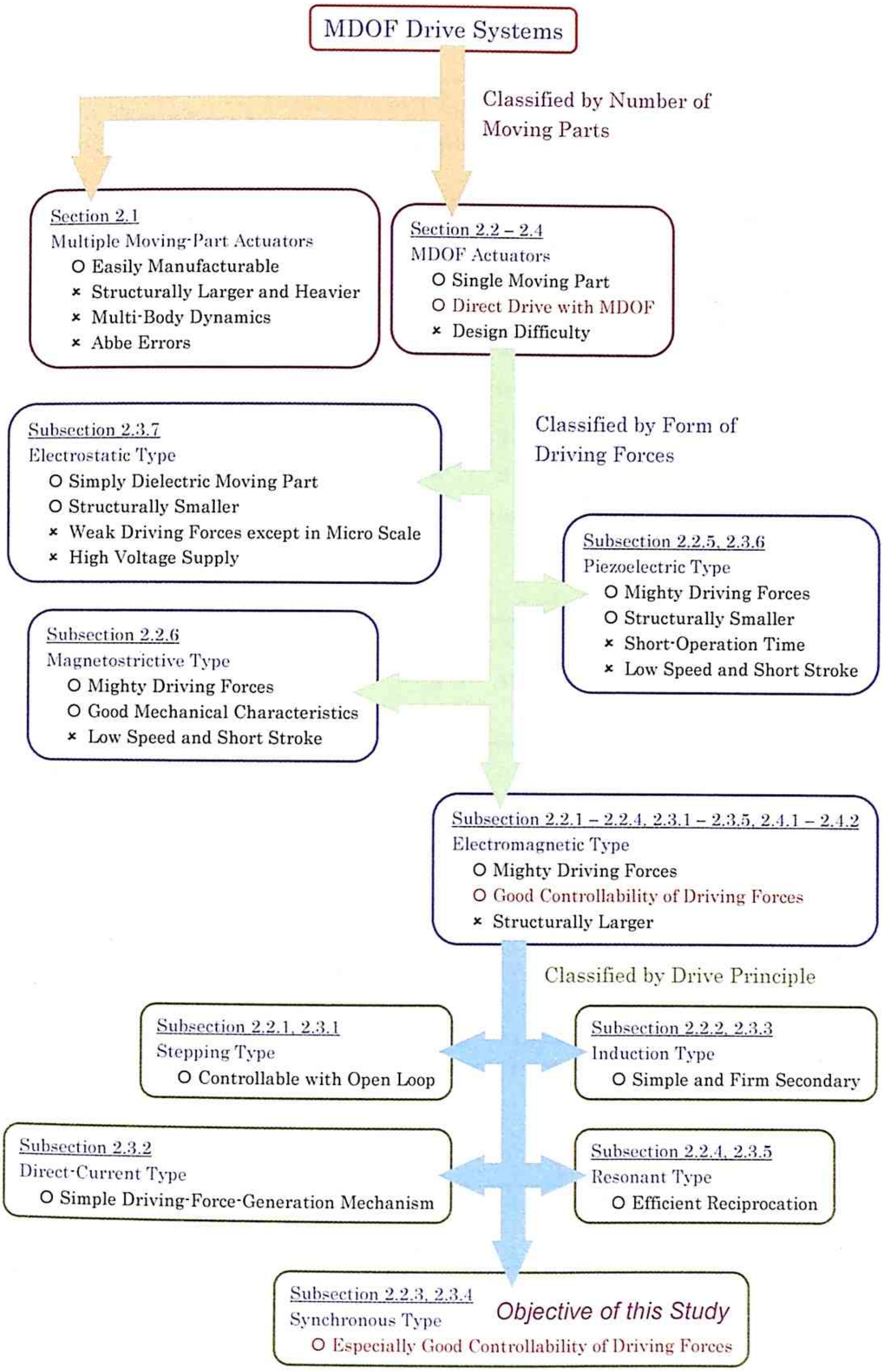


Fig. 2.5.0-1: Classifications of MDOF drive systems.

Table 2.5.0-1: Classification of synchronous planar actuators by mover type, coil, and DOF 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)[1]	Shikayama Compter	3 6	$4 \times 3\phi$ $4 \times 3\phi$
	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			

ϕ :Electrical phase

Table 2.5.0-2: Classification of synchronous planar actuators by magnet array and coil assembly.

Magnet Arrays Coil assemblies	Combination of 1-D Permanent-Magnet Arrays Multiple separated magnetic fields	Single 2-D Permanent-Magnet Array Single superimposed magnetic field
Separated 1-D Coil Assemblies	Shikayama, Kim	Asakawa, Binnard, Jung, Hinds, Ueta, Oh, Compter, Vandenput
Overlapped 2-D Coil Assemblies	Ohira	Fujii[2], Korenaga[2], Ueda (This study)[2]

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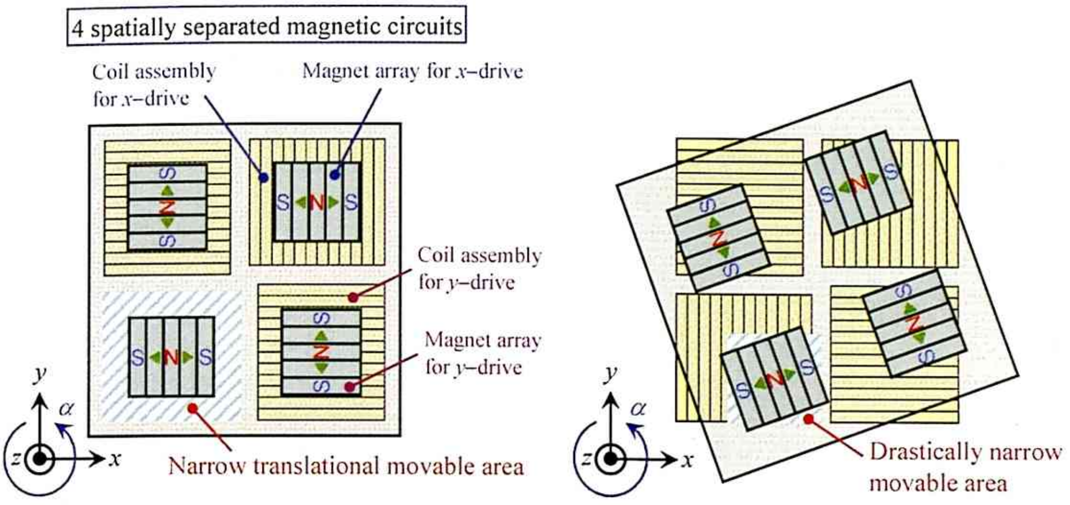
[1] Planar actuator proposed by Ohira has two three-phase windings and "four" hybrid electromagnets.

[2] These planar actuators form spatially-superimposed magnetic circuits.



(a) When not displaced in α.

(b) When displaced in α.

Fig. 2.5.0-2: Movable area of 6-DOF magnetically levitated planar actuator developed by Kim [Kim97, Kim98].

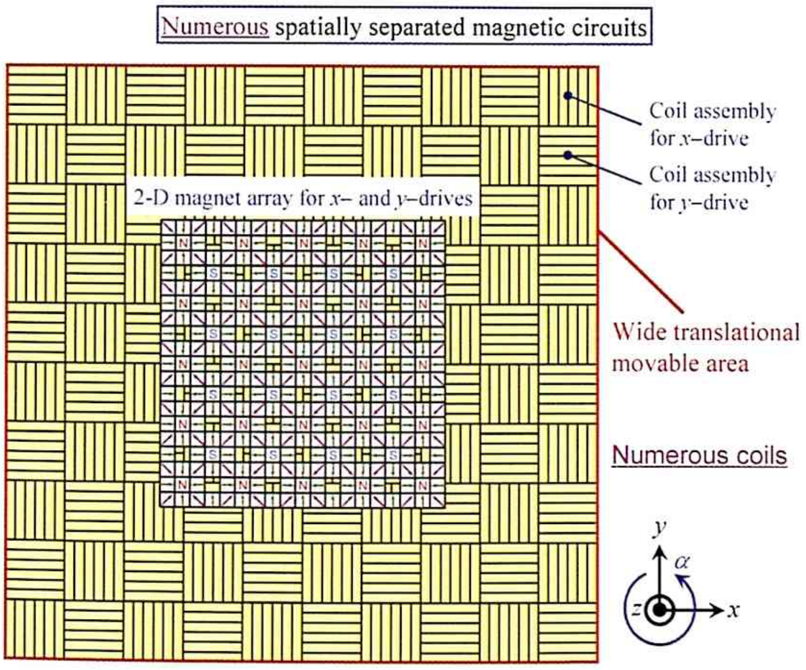


Fig. 2.5.0-3: Movable area of 6-DOF magnetically levitated planar actuator developed by Oh [HOh07].

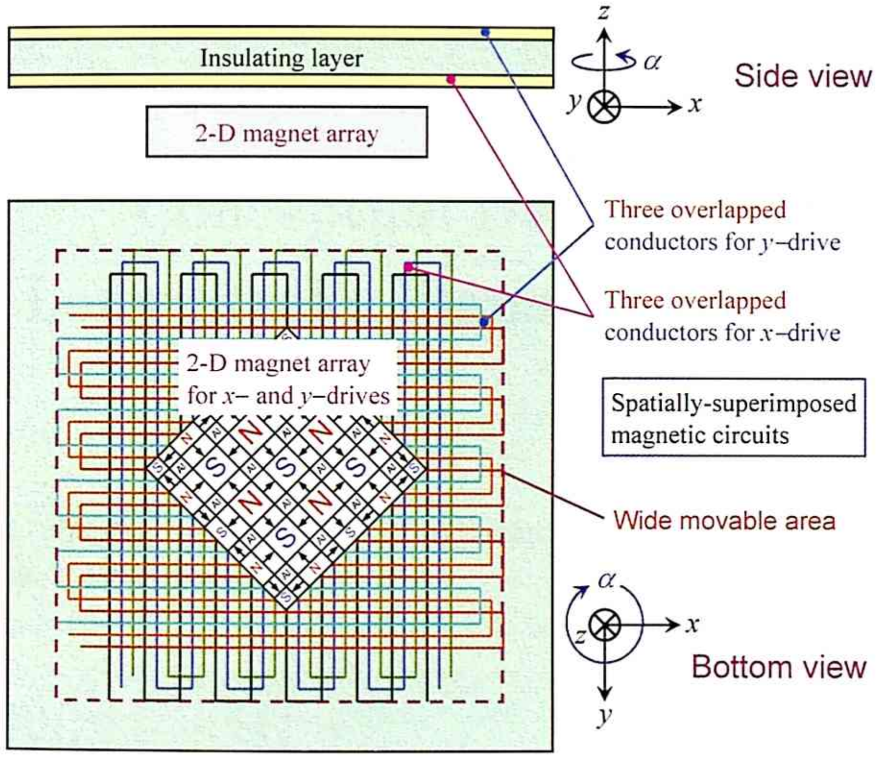


Fig. 2.5.0-4: Conceptual view of MDOF planar actuator proposed in this study.