ELECTROMAGNETIC DESIGN CONCEPTS WHICH PROVIDE TO AN OBJECT BEARING AND OPERATIONAL MOTION EFFECTS

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ABSTRACT

This paper provides an overview of electromagnetic design concepts that combine levitation effects and operational motions by using electromagnetic forces on an object. An operational force on an object is produced by utilizing the interaction of the primary and secondary magnetic fields. The magnitude and direction of the manipulation forces are controlled by changing the magnetic flux field distribution locally. Several techniques used to produce gradient field fluxes are presented and illustrated in detail. Secondary magnetic fields can produce useful magnetic forces on an object by positioning current-conductive bodies that interact with the primary magnetic field. The magnetic force on a body can be easily changed by utilizing coiled current-conductive bodies, where the coil loop can be open or closed. This technique allows a commandable positioning force to the moveable object. It can be shown that it is possible to combine a magnetic bearing effect with these operational motions produced by the interaction of the secondary magnetic fields. These techniques can be applied to simplify construction of devices such as actuators, manipulators, rotary pumps and other mechanisms.

INTRODUCTION

Magnetic bearings are used for high precision applications that demand ultra clean, non contacting bearing support. The primary function of a typical magnetic bearing is to provide support to an object only. The rotational operational motion is provided by an electromotor as in the application of a momentum wheel. Many excellent examples of high precision magnetic bearings are outlined in the following references; (Downer et al. 1994), (Williams and Trumper, 1996), (Tieste and Popp, 1997). It is also possible to combine the magnetic bearing and operational motion effects into a single compact and efficient device for lower precision applications. A bearingless electromotor can be produced using this approach (Bichsel, 1992).

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Bodies and objects can be manipulated by applied magnetic fields. The general principals regarding the generation and application of electrodynamic forces on objects will be discussed and several concepts that demonstrate these principals will be presented (Joffe, 1992, 1996). Many types of useful mechanisms such as a magnetic bearing can result from the proper application of electrodynamic forces. The force values and directions depend on the configuration of the bodies, their relative position to each other, and the orientation with respect to the primary magnetic field. Electrodynamic forces can be applied to both magnetic and non-magnetic bodies. Contactless manipulation of objects can be accomplished by the application of an external magnetic field. By properly applying magnetic interaction of forces between multiple bodies located in a magnetic field, simple yet reliable applications for positioning, automated assembly, and part identification can be accomplished (Joffe and Kalnin, 1972), (Davydenco and Kanaev, 1984). The goal of this paper is to expand the understanding and the knowledge of applied magnetic concepts and devices.

ELECTRODYNAMIC FORCES ON BODIES FOR POSITIONING APPLICATIONS

The mechanism for the creation of forces acting on nonmagnetic and ferromagnetic conducting bodies, in alternating magnetic fields, are well known and are based on the external interaction of magnetic fields with the body. For a nonmagnetic current-conductive body the mechanical forces and moments are dependant on the current induced secondary magnetic field. The body is introduced as a ring as shown in Figure 1. to simplify this investigation

The current in the ring can be represented as an alternating magnetic dipole with a moment:

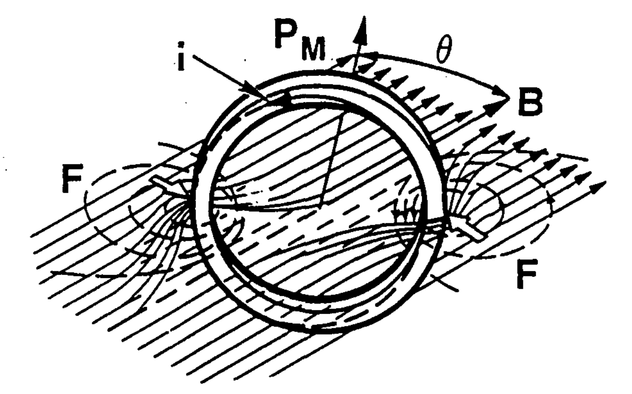


Figure 1. Conducting ring in an alternating magnetic field, for clarity shown in one plane only.

$$P_m = \frac{\omega B_o S^2 \cos(\theta)}{R} \bullet \frac{(-j)e^{jt\omega}}{1 + j\tan\varphi_o} \quad (1)$$

B_0	- Induction of the magnetic field.
$\omega = 2\pi f$	- Circular frequency of an alternating magnetic field.
φ_0	- Angle of phase difference between the induction of an external magnetic field and the induced loop current.
S	- Ring contour area
$\tan(\varphi) = \omega L/R$	- Loop inductive impedance / active impedance.

The magnitudes of L and R are computed in the first approximation taking into account the skin-effect on the circular contour with current in it.

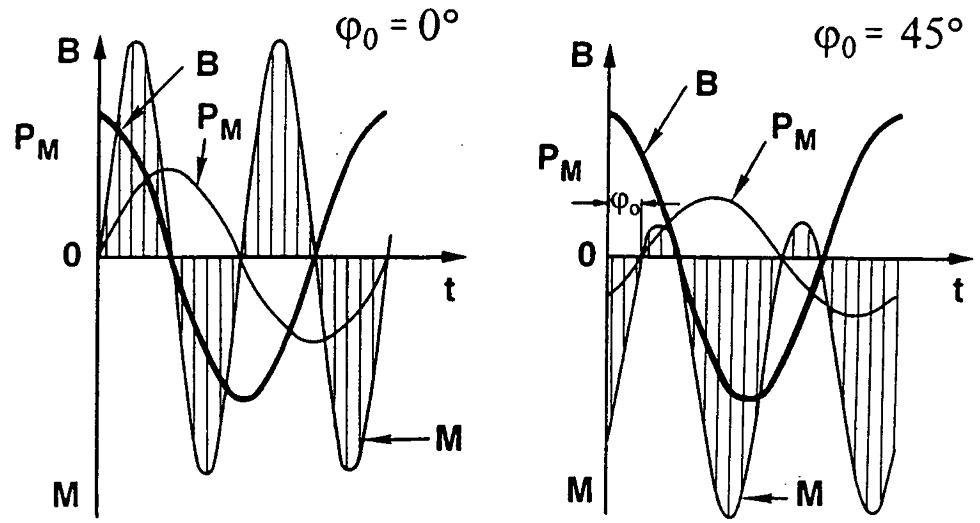


Figure 2. The relation between the magnitude of the moment of electrodynamic force acting on a conductive ring and the phase shift (φ_0) of the magnetic moment (P_m) relative to the induction (B_o) of the magnetic field.

The first result, after some simplification, for the mechanical moment of the ring is:

$$M_{EFF} = \frac{\omega B_o{}^2 S^2 \sin 2\varphi_o}{8R} \bullet \sin 2\theta \qquad (2)$$

The phase angle (φ_o) between the induction of the external (primary) field and the magnetic moment (P_m) formed by the induced ring current I has a significant effect on the magnitude of forces and the moment of force.

Comparing the magnitude of the sum of the moments of the electrodynamic forces on the angle of phase shift, it becomes clear that M is zero at $\varphi_0 = 0°$ and that M is maximum at $\varphi_0 = 45°$. The magnitude of forces on the body depends on the frequency of the magnetic field. The frequency of the magnetic field can be used to change the manipulating forces on a body and the resulting positioning.

An example of a simple positioning system is shown in Figure 3; in this case a body is positioned in a non-uniform magnetic field. The final position of the body is at the location where the electrodynamic force on the body is a minimum.

The electrodynamic force depends upon the gradient of the magnetic field induction, body current-conductivity, body size and body configuration coefficient (K).

The electrodynamic forces between two identical cylinders in a homogenous field are shown in Figure 4 (Joffe and Kalnin, 1972). The measurement data for cylinders made from copper, aluminum, and brass are shown. The force is highest in the high conductivity materials. The force exponentially decreases as the gap between the parts increases. The forces generated also depend on body configurations, orientations, body configuration coefficient K_1 and body orientation coefficient K_2 as shown in Figure 4a and Figure 4b. To overcome gravitational forces, obtaining a levitation effect for a non magnetic conductive body, the AC magnetic field frequency (f) value needs to be selected to produce a sufficient secondary

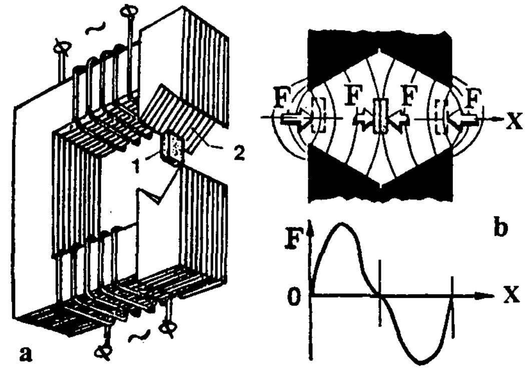
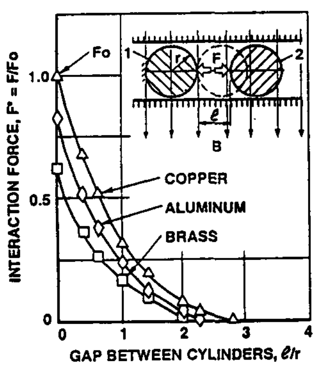


Figure 3. a - Object 1 is positioned in the electromagnetic pole area 2. **b** -The electrodynamic force F positions the body, into the magnetic pole centerline.



a

BODIES / COEFF.	B, F, F, D	H, H	δ = H/2, H, H	D, H	d = D/2, H
K_1	1.00	1.21	1.90	0.67	0.57

b

BODIES / COEFF.	d = D/2, H			δ = H/2, H, H		
K_2	1.00	1.90	2.20	1.00	0.25	1.30

Figure 4. The interaction electrodynamic forces (F) between two nonferromagnetic conductive bodies in a homogenous alternating magnetic field. In the tables are provided examples of the coefficients, as a function of the configuration of the bodies and their positions.

magnetic field in the body. To levitate an aluminum cube of a size 5 x 5 x 5 cm, requires an AC magnetic field with the frequency between the range 60-200 Hz, with the magnetic field induction need to be: 0.2 - 0.4 T.

ALIGNMENT AND ASSEMBLY OF NON-MAGNETIC CONDUCTIVE CONCENTRIC BODIES

Contactless assembly can be accomplished by the application of an external magnetic field on nonmagnetic conductive bodies. An example of an alignment and assembly process is demonstrated with three rings of different diameters as shown in Figure 5. The bodies align as a result of the interaction between the primary magnetic field and the secondary magnetic fields generated by induced currents (I_1 through I_3 in Figure 5, resulting in the final assembly e).

Figure 5 (b) shows the dynamics of interaction of the primary magnetic field of the induced currents in parts 1 through 3. The induced fields in the rings create resistance to the primary field, which results in the primary field being bowed out from the ring area. Zones of increased field induction are generated on the ring periphery and form electrodynamic forces that move the parts onto the axis of assembly (c). As the rings converge there is an interaction of the magnetic fields, they begin to behave as a single body and there is a magnetic loop encompassing all the rings (d). The resulting electromagnetic forces cause further contactless convergence and centering of the rings.

The process can tolerate an initial positioning offset error of approximately 80 percent of the linear dimension between the rings respective axes. This situation would not be possible using a mechanical assembly method. We can see how the operational bearing effect guides and holds the parts in place from the illustrated magnetic assembly process.

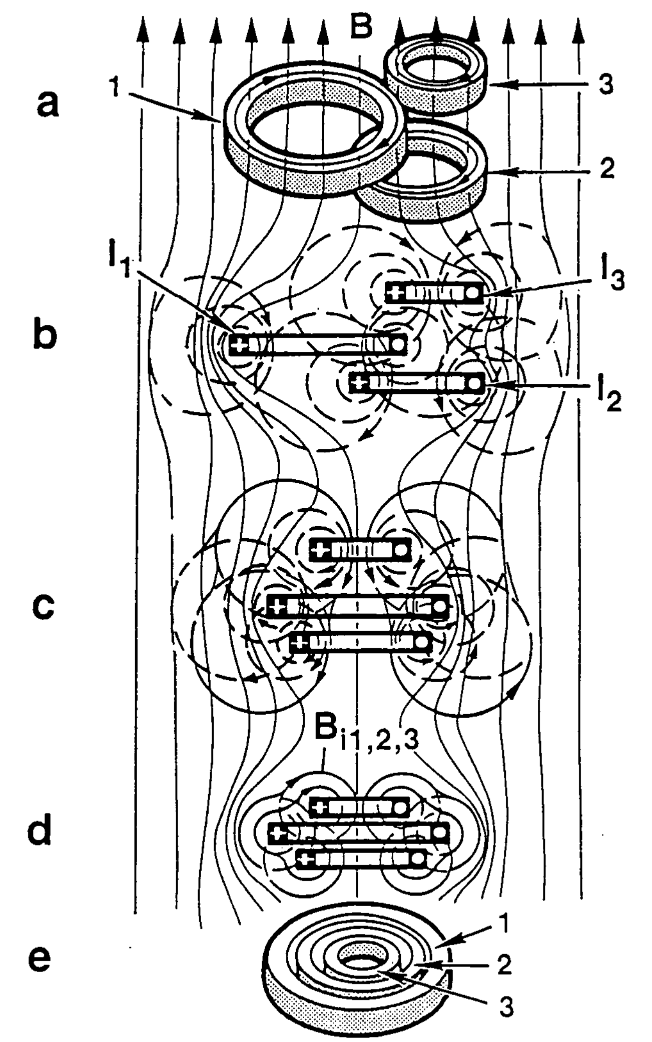


Figure 5. Process of assembly rings under the influence of electrodynamic forces. a, b - initial placement of rings at intermediate positions; c, d - placement of rings at intermediate positions; e - the finished assembly.

The electrodynamic force effect that was shown in Figure 5 (b) and (c) is also illustrated in Figure 6, but for two non-coplanar rings in a magnetic field. The induced current (I) in the rings (1) and (2) generates a secondary magnetic field that creates resistance to the primary field, this interaction produces a electrodynamic force (F_y) that moves the rings toward contactless convergence and centering on the same axis (x).

ELECTROMAGNETIC LINEAR MANIPULATOR CONCEPT DESIGN

Knowledge of the interaction between the primary and secondary magnetic fields is essential to predict the resulting forces that act on the bodies. Many different kinds of devices can be created based on this interaction force effect. An example of a simple manipulator design is presented in Figure 7. The object to be manipulated (1) is positioned between four coils (2, 3, 4, 5). A current (I_1) is induced in the object when a primary electromagnetic field (B) is applied. No interaction force occurs between the object and the coils when the switches (6, 7) for both coil sets are open, as shown in Figure 7a. If, for example, the switch (6) for one pair of coils (2, 3) is closed (Figure 7b), the primary field induces a current (I_2 and I_3) in that set of coils.

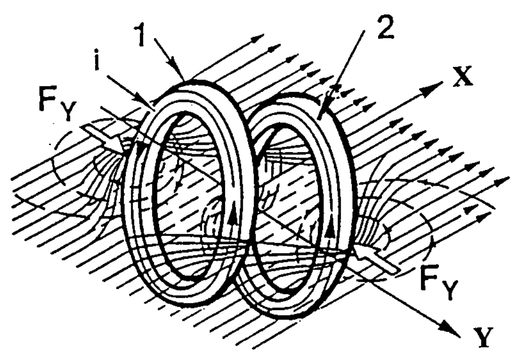


Figure 6. Interaction force effects between two nonferromagnetic conductive rings, in an alternating magnetic field. For clarity, the primary magnetic field and the secondary magnetic fields created by induced currents (I) are shown only in one plane.

An electrodynamic force is created that moves the object to the left as a result of the interaction between the currents in the object and coils. If the switch (7) for the other set of coils (4, 5) is closed while the other switch is open as shown in Figure 7c, the opposite effect occurs, resulting in an electrodynamic force that moves the object toward the right. For simplicity, the illustration does not show the magnetic flux interactions among the primary alternating field (B), the magnetic field-induced currents in the moveable object (1), and the coil system (2, 3, 4 and 5). The electrodynamic force can be changed by varying the gap size between coils and the object, and by varying the coil winding. The operational bearing effects on the body can be controlled to obtain the desired motions and orientations.

ELECTROMAGNETIC POSITIONING MANIPULATOR CONCEPT DESIGN

A complex manipulator can be constructed using an array of coils (refer to Figure 7d). An object can be translated, rotated and positioned in two dimensions using this array of coiled devices (Joffe et al, 1978). The electrodynamic force vs. body position is shown in Figure 7e. Manipulation of the object is accomplished by closing and opening the coil loops under the body. To position a complex T shape as shown in Figure 8, it is necessary to energize a zone that forms a T shape with the coil system. Many translation, rotation and positioning possibilities exist with this type of coiled array.

A coil array system is easily adapted to computerized position control for a wide set of applications for contactless positioning of objects. These kinds of devices could be used for many automation applications, including unmanned object manipulation on a spacecraft.

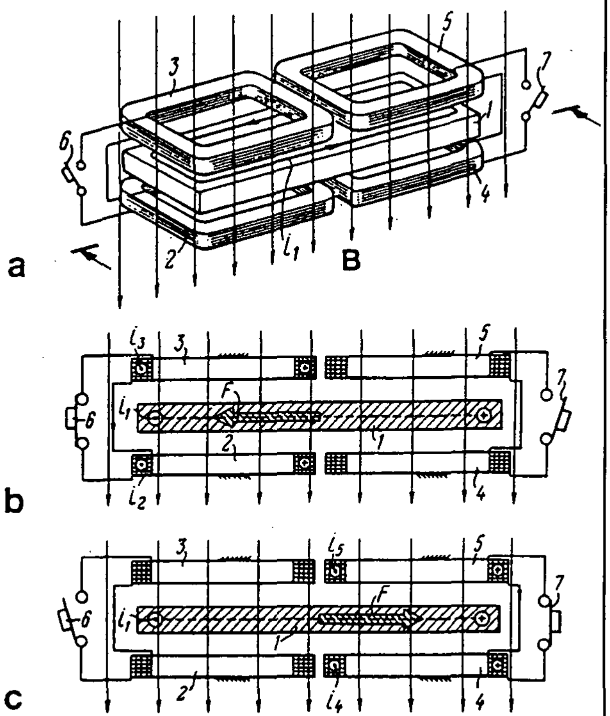


Figure 7. **a** - The concept design of an electromagnetic device for manipulation of an object (1) by electrodynamic force (F). **b, c** - present a cross-section view of the object and the coils system (2, 3, 4, and 5), showing how the electrodynamic force direction is applied to the object by closing and opening the loop of the coil system by operating switches (6, 7).

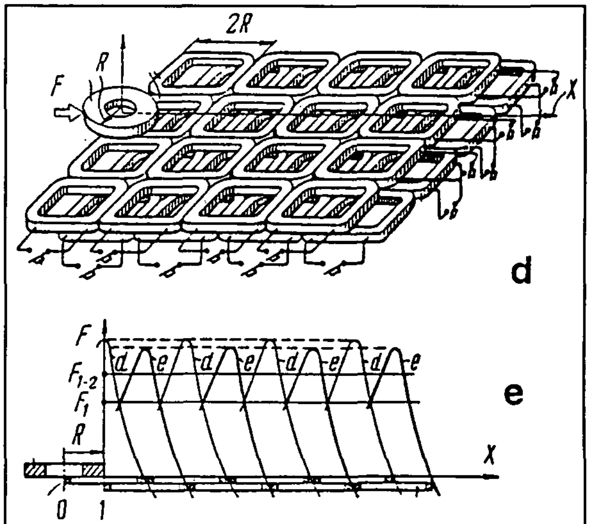


Figure 7. d, e - Multilayer array of coiled devices which allows a force to be applied to an object at desirable position.

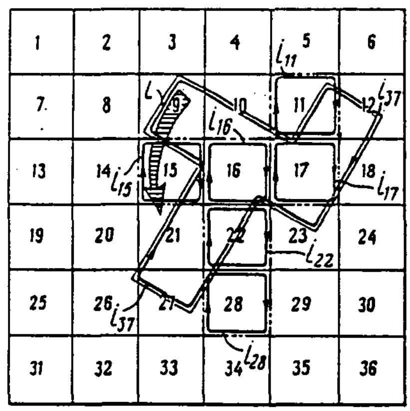


Figure 8. Array of manipulator coils which loop to be closed, to move a T-configuration object into the shown direction.

APPLICATION OF ELECTRODYNAMIC FORCES FOR CYLINDRICAL CONFIGURATIONS

There are several examples of magnetic applications that combine a bearing and operational motion effects. One example is a solenoid system that uses an electroconductive cylinder at the centerline of the electrodynamic forces. The cylinder is moved in the desired direction when the solenoid system is connected to an AC power supply. This device combines the bearing effect and the operation effect. There are several more advanced

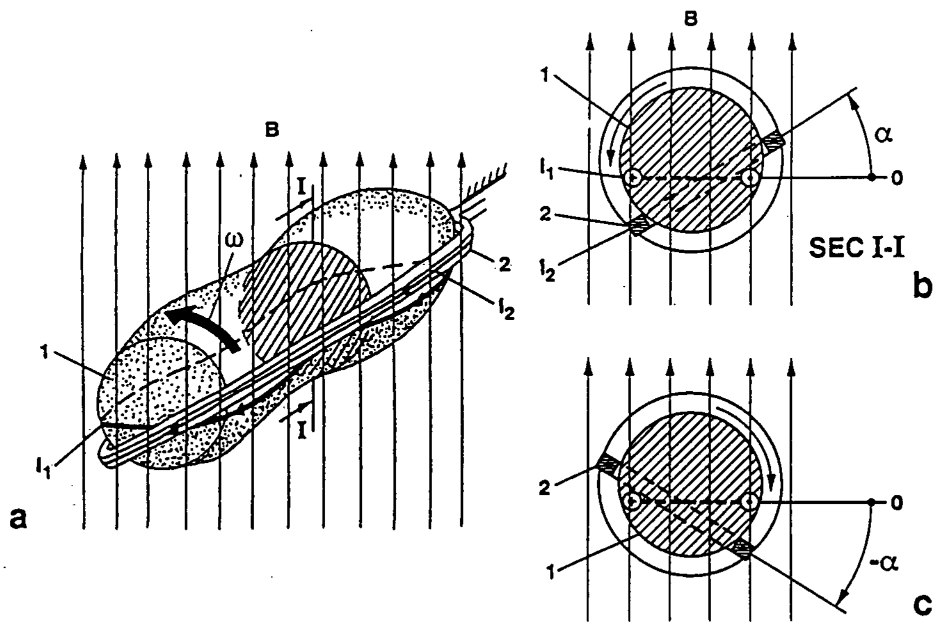


Figure 9. Effects of interaction between a cylinder conductive body (1) and its encompassing conductive frame (2), both of which are in the alternating magnetic field. The interaction force relation between the induced currents in the two bodies creates torque that results in rotation of the cylindrical body.

applications. These include magnetically actuated piston pumps, transportation devices and bearingless motors (Bichsel, 1992).

The forces on the cylindrical body are created by the interaction between the primary field and the induced fields in the body. Several types of useful motions can be produced by interacting with the induced fields. The cylindrical bodies can be rotated and translated. This rotational effect is illustrated in Figure 9 which shows a cylindrical conductive body (1) located inside a conductive frame (2). Applying an alternating primary magnetic field (B) to this system induces currents, and consequently secondary magnetic fields, in both the cylinder and the frame. The induced current in the cylinder is generated ninety degrees from the direction of the primary field. The current position of the frame is dependent upon the angle position of the frame. If the frame is oriented at some angle such as that shown in Figure 9a and 9b, counter clockwise rotation will result. If the frame location has the opposite angle position, as shown in Figure 9c, the cylinder rotation will be clockwise.

From this we can see that varying the position of the frame allows manipulation of the torque speed and direction of rotation of the cylindrical body. A second conductive frame can be placed on the opposite side of the cylinder from the first one, to increase the interaction forces. The cylinder can be levitated when the primary magnetic filed is configured to produce a centering gradient, this technique is used to produce a magnetic bearing effect. The torque value can also be increased by using a winding coil instead of a solid frame loop, which does not come in contact with the rotating cylinder.

CONCLUSION

The primary focus of this paper was to present the application of electrodynamic forces to current-conductive nonferromagnetic objects. There are several configurations discussed that combine magnetic bearing effects along with operational motion effects that are the basis of contactless manipulating of objects. The principals of the electrodynamic force are illustrated on simple body configurations. There are several factors that need to be evaluated for multiple bodies in a magnetic field to determine the forces and torques on a body, and the interaction with the other bodies in the primary magnetic field must be considered. A detailed analysis of the interaction forces between bodies positioned in a magnetic field needs to be done in order to design more effective magnetic devices.

It is clear that there are many applications that can result from these approaches from the concepts and principles presented. It is possible to combine the magnetic bearing and operational motion effects into a single compact and efficient device for lower precision applications. Manipulators and mechanisms to produce simple and complex motions can be constructed using the principals discussed. The contactless aspect of the approach presented lends these concepts to high reliability applications. The use of magnetic interaction forces enables the production of lightweight, efficient, multi-functional mechanisms for remotely controlled applications. An excellent application would be for unmanned spacecraft mechanism applications, where the contactless bearing effects are needed during the manipulation of objects.

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