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LARGE-GAP MAGNETIC POSITIONING SYSTEM HAVING ADVANTAGEOUS CONFIGURATION

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SUMMARY

Most simple large-gap magnetic positioning systems, which operate in the absence of substantial gravitational acceleration, involve the use of magnetic components on at least two opposite sides of the positioned object. If gravity is present, such systems generally require the magnetic components to be located above the levitated object. These configurations can sometimes interfere with the use of magnetic positioning systems.

A magnetic configuration has been devised in which the positioned object is maintained in a stable orientation and position on one side of an opaque plane surface entirely by means of magnetic components on the other side of the plane. The system is effective with or without gravity, and can operate in any orientation. In this system, the positioned object need only contain a simple dipole magnet. The positioning components consists of a group of permanent magnets creating a magnetic field configuration which stabilizes the levitated dipole in all but one degree of freedom, and a magnetic position sensing and force feedback system to actively stabilize the object in the one unstable direction. The system utilizes very low power at equilibrium and can maintain gaps of 50 mm.

INTRODUCTION

Large gap magnetic suspension systems can have a wide variety of configurations and a wide range of applications[1]. This paper concerns a specific class of large-gap magnetic suspension systems in which all of the components required to achieve suspension are located on one side of an opaque plane barrier and the suspended object is on the other. Of particular interest is a system for use in a gravitational field in which the system components are located below, and the suspended object above, a horizontal plane.

This class of levitation system has a number of potential applications such as the display of objects and the movement of objects within sealed atmosphere enclosures. However, to date there has been little work in this field because in practise it is very difficult to achieve stable magnetic suspension from below or, in the absence of gravity, from just one side of a suspended object.

A brief review of a more conventional suspension system will help to explain this difficulty. Figure 1 shows the well known components of a simple "suspend from above" system[2]. The suspended object is a simple magnetic dipole, in this case with north pole up. The required upward force to counteract gravity is provided by a control magnet positioned above the suspended dipole, with south pole down, so as to attract the suspended dipole. This magnet has an electronically controlled strength, which is varied in response to the signal from the height sensor, so as to achieve stability against displacement in the otherwise unstable vertical direction. This type of system is very common because the components are simple, and especially because the control system consists of just one channel. In other words, this system is naturally stable in five of the six degrees of freedom – it naturally returns from displacement in either of the horizontal directions, it returns to the vertical if the dipole moment is rotated about either of the two horizontal axes, and it is neutrally stable against rotation about the vertical axis.

In the absence of gravity, the system of Figure 1 will not work because the controlled magnet is designed to produce only a controlled attractive force. In the presence of gravity, we may attempt to place the control magnet beneath the suspended magnet, and reverse its polarity, so as to cause a force of repulsion, rather than attraction, as shown in Figure 2. Such a system is fully capable of countering the force of gravity, and in fact such a system is intrinsically stable against displacements in the vertical direction, since the upward magnetic force increases in response to a drop in height. Unfortunately, this system is very unstable with regard to rotation about either horizontal axis, or with regard to displacement in either horizontal direction, meaning that a very sophisticated four channel control system would be required to stabilize the suspended object.

Attempts have been made to simplify the control requirements through the use of more complex suspended magnets[3]. In essence, this approach mechanically couples a number of systems of the type shown in Figure 2, to give the configurations shown in Figure 3a, 3b. Such arrangements employ the natural vertical stability of Figure 2 to achieve orientational stability as well. Even with this improvement, however, such arrangements still require stabilization against displacement in two horizontal directions, which substantially complicates any control system. Moreover, such systems require the force of gravity to achieve stability. Also, the complicated geometry of the magnets can be problematical. Clearly it would be desirable to find an alternate magnet configuration which would make it possible for a simple dipole to be stable in all but one degree of freedom, as is the case for the system of Figure 1, but with the magnets creating the applied field positioned entirely below the suspended object.

PERMANENT MAGNET CONFIGURATION

Figure 4 depicts an idealized permanent magnet configuration and a coordinate system which will be used throughout the remainder of this paper. The configuration consists of two parallel infinitely long bar magnets, each vertically magnetized with north pole up, and each having a uniform magnetic dipole moment per unit length of magnitude ρ (Cms^{-1}). The origin of the coordinate system is equidistant between the magnets and is in the plane containing the center line of both magnets. The x direction lies in this plane, perpendicular to the magnets, and the y direction is also in this plane, but parallel to the magnets. The z direction in this geometry is vertical. As shown, the distance from the original to the center of each magnet is x_0.

By virtue of the symmetry shown in Figure 4, the magnetic field due to these magnets, which will generally be described as $\vec{B}_0 = (B_{x0}, B_{y0}, B_{z0})$, will be purely vertical along the z

axis. In the idealized case where the bar magnets have a height and width which is very small relative to their separation, the vertical field component B_{z0} can be evaluated simply, as expressed in the following relation, in SI units:

$$B_{z0} = \frac{\mu_0}{\pi}\ \rho\ \frac{z^2 - x_0^2}{\left(z^2 + x_0^2\right)^2} \tag{1}$$

Differentiation of (1) with respect to z yields the following useful relation,

$$\frac{\partial B_{z0}}{\partial z} = \frac{2\mu_0}{\pi}\ \rho\ \frac{\left(3x_0^2 - z^2\right)z}{\left(z^2 + x_0^2\right)^3} \tag{2}$$

Figure 5 is a graph of $B_{z0}/\mu_0\ \rho\ x_0^{-2}$ and $\frac{\partial B_{z0}}{\partial z}/\mu_0\ \rho\ x_0^{-3}$, vs z/x_0. As can be seen, B_{z0} is negative for $-1 < z/x_0 < 1$, and positive everywhere else. The region for which $z/x_0 > 1$ is of particular interest because this region is substantially above the bar magnets; it contains a local maximum of B_{z0}, at the point $z/x_0 = \sqrt{3}$, and it maintains a constant magnetic field direction throughout the region. The maximum field strength implies a stable location for a suspended magnetic dipole. Another way to recognize this is to recall that the force on a magnetic dipole is in general given by

$$\vec{F}_m = \left(F_{mx}, F_{my}, F_{mz}\right) = \vec{\nabla}\left(\vec{D} \cdot \vec{B}_0\right) \tag{3}$$

where $\vec{D} = \left(D_x, D_y, D_z\right)$ is the magnetic dipole moment in units of $\mathrm{Cm}^2\ \mathrm{s}^{-1}$. Along the z axis, a free dipole will align vertically with the vertical field and (3) simplifies to

$$F_{mz} = D\frac{\partial B_{z0}}{\partial z} \tag{4}$$

where $D = \left|\vec{D}\right|$. Thus $\frac{\partial B_{z0}}{\partial z}$ is proportional to the vertical force which the magnets of Figure 4 would exert on a freely suspended dipole on the z axis, and the graph of $\frac{\partial B_{z0}}{\partial z}$ in Figure 5 shows that this force is upward for positions below $z/x_0 = \sqrt{3}$, and negative above this point, which is required for stability against displacement in the vertical direction. By virtue of the symmetry about the *YZ* plane in Figure 4, it is apparent that this system is neutrally stable in the *y* direction, and hence it is unstable only in the *x* direction. As already noted, the suspended dipole is orientationally stable and hence this system achieves the goal of positioning a suspended magnetic dipole, with only one unstable degree of freedom.

However, a number of practical issues must be considered in developing a useful system. Obviously, the bar magnets cannot be infinitely long and, furthermore, it is desirable to introduce some positive stability in the *y* direction. Another practical question is whether the actual field strengths from ordinary magnets can produce stability in general, and stable levitation in the earth's gravitational field in particular. Lastly, there is the critical question of whether a practical controlled magnetic force application system can operate from below to stabilize the dipole magnet against displacements in the *x* direction.

These practical issues are addressed below. The main concept of this system, however, is the ideal geometry described above, which has the key feature of providing stable levitation from below with only one unstable degree of freedom. That the system works at all is non-intuitive; indeed most scientists casually examining Figure 4 do not expect an upward force to be possible due to the proximity of opposite poles on the suspended dipole and the bar magnets. The authors do not have a simple intuitive explanation for the results shown in (1), (2) and (4) but it will be shown that the system does have good stability in the vertical direction.

PRACTICAL CONSIDERATIONS

In practise, the truncation of the infinite bar magnets of Figure 4 is no problem at all since the field contribution from portions of the magnets for $|y/x_0| \gtrsim 4$ is negligibly small. Furthermore, achieving a slightly positive stability rather than neutral stability in the y direction can be achieved through a variety of configurations of small magnets. Generally, properly oriented magnets which are placed on the y axis symmetric about the origin will tend to repel the dipole towards the origin and will not impede vertical stability providing their fields are much weaker than the main levitating fields.

To consider the question of field strengths in practical systems, consider the system shown in cross section in Figure 6. Although these magnets have a finite physical extent, and are truncated at $y = \pm 95\ mm$,, equations (1) and (2) still provide a good approximation to the field along the z axis and equation (4) provides a good approximation to the vertical force on the suspended dipole.

The ceramic bar magnets have residual field $B_r = 0.38\ T$, corresponding to a magnetization $M = \frac{B_r}{\mu_0} = 3.024 \times 10^5\ Cm^{-1}s^{-1}$. With the dimensions shown, this yields a magnetic dipole moment per unit length of $\rho = 266\ Cms^{-1}$. The rare earth suspended magnet has a residual field $B_r = 1.08\ T$ corresponding to a magnetization $M = \frac{B_r}{\mu_0} = 8.59 \times 10^5\ Cm^{-1}s^{-1}$. With the dimensions shown, this yields a magnetic dipole moment $D = 5.53\ Cm^2s^{-1}$. The density of this material is $8.304 \times 10^3\ Kgm^{-3}$, yielding a mass of $5.34 \times 10^{-2}\ Kg$ and a gravitational force at the earth's surface of about $F_g = -0.524\ N$.

This information, used in equations 1, 2, and 4 yields the results graphed in Figure 7. The curves showing B_z and $\frac{\partial B}{\partial z}$ vs z have the same shape as in Figure 5, and are shown to provide a quantitative feel for their magnitude. The force F_m passes through zero at $z \simeq 87\ mm$, corresponding to a gap between the top of the ceramic magnets and the bottom of the rare earth magnet of $71\ mm$. This would be the point of stable positioning in the absence of gravity. The curve F_n plots the net force on the suspended magnet in the earth's surface gravitational field. The stability point is shifted to $z \simeq 70\ mm$, which is still well within the useful operating region where the minimum possible elevation is $50\ mm$ to get any levitation. In fact, the magnet could still support a substantial additional weight (or negative weight) without leaving the "well" of stability. At this value of z, the predicted gap between the top of the ceramic magnet and the bottom of the rare earth magnet is $54\ mm$, compared to the value of $50\ mm$ observed in our lab with the actual truncated magnets. Thus the approximations of equations 1, 2, and 4 are useful under these circumstances.

A number of active magnetic system configurations have been tried to stabilize the suspended magnet in the y direction. Figure 8 shows schematically a typical system. The Hall probe is sensitive to magnetic field in the x direction. To first order, the value of this field is proportional to the displacement of the suspended magnet in the y direction. The purpose of the air core electromagnet coils is to provide a restoring force in the x direction only. It is especially important that the coils not impart a torque on the suspended magnet, nor forces in other directions, as this can result in the energizing of oscillation modes in the other degrees of freedom.

This implies that the desired magnetic field from the control coils should be zero at the point of stable levitation, and that its vertical component should have a strong horizontal gradient. The symmetry in Figure 8 ensures that the vertical magnetic control field will be zero wherever $x = 0$, and hence so will be its gradient in the y and z directions implying that any force can only be in the x direction. The correct orientation of the coils results in the field in the x direction being zero as well, ensuring there is no torque applied to the suspended magnet. Thus the desired pure horizontal force can be applied effectively with this configuration.

One problem with the above design is that the Hall probe detects the applied field from the coils, and also is sensitive to tipping of the suspended magnet. Both of these effects can be cancelled out by a variety of methods, but in practice this is often not necessary as the associated effects are not too serious.

A last practical consideration concerns damping. As with other magnetic suspension systems, some type of damping is required to prevent a gradual build up of energy in one or more modes of oscillation. Eddy current damping by a copper plate placed between the magnetic apparatus and the suspended object has been used to improve stability but at large levitation distances the damping forces are small. We have successfully used a simple proportional-derivative controller for the active control axis to introduce damping. The derivative control comes from the time dependent value of displacement of the levitated object which is measured by a Hall effect sensor. A series capacitor is able to differentiate the displacement signal without introducing excessive noise to the control electronics. However this damping is only effective on translation in the y direction and on rotation about the x and y axes.

Another disadvantage of this system is that the coil configuration shown in Figure 8 is a rather inefficient means of providing a horizontal gradient of vertical field, due to the other requirements the coils must satisfy. We have typically had to use a voltage to current amplifier with a 600 W maximum output to provide a stability "well" in the y direction only 1 cm wide. Fortunately, however, at equilibrium, very little dissipation of power is required, so under normal conditions the coils are not required to dissipate much heat as the RMS input power is less than <u>one</u> watt.

CONCLUSIONS

The system demonstrates that stable levitation can be achieved in a simple, innovative way with all components located to one side of the levitated object. The levitated object must contain a powerful magnet dipole. Only one axis of active control is required and the controller can use a very simple proportional-derivative strategy with position signals coming from Hall effect sensors. The rate control provides damping to the system.

An arrangement of economical ceramic permanent magnets provides the primary levitating and stabilizing forces. The levitated object naturally stays within a magnetic potential energy "well" in two of the translational axes. The magnetic dipole aligns with the magnetic field to give moment stability in two rotational directions. However, the levitating object can rotate freely about an axis pointed away from the levitating components and is neutrally stable on this axis.

Within the area in space where the magnetic field defines an appropriate magnetic flux density gradient, levitation is stable and relatively strong. However, if the levitated object is perturbed beyond definite limits, it catastrophically loses stability and is attracted to the primary levitating magnets. Certain types of perturbations lead to oscillations which grow in amplitude with time until the stability bounds are exceeded. Future work is required to improve the stability of levitation by increasing energy dissipation from oscillations. This can be done by adding passive eddy current dampers or by additional active control electromagnetics.

The active control system needs to be modified to allow levitation to start "softly" from a rest state rather than require the levitated object to be placed manually into the magnetic field at the correct location for levitation. Additionally, it is desirable to be able to control some of the levitation parameters such as height above the plane or orientation of the object in space. With continuing development, more applications will be found which will use the unique characteristics of this levitation system.

SYMBOLS

Values are given in SI units.

x, y, z	coordinates of levitation system (m)
x_0	half width of main magnets (m)
$\vec{B}_0$	magnetic flux density, free field (T)
B_r	residual magnetization (T)
$\vec{D}$	magnetic dipole moment (Cm^2/s)
$\vec{p}$	magnetic dipole moment per unit length (Cm/s)
$\vec{M}$	magnetization vector ($Cm^{-1}s^{-1}$) = (Am^{-1})
μ_0	magnetic constant = $4\pi \times 10^{-7}$ (TmA^{-1})
F_{mz}	force on magnetic dipole, vertical (N)
F_g	gravity force on magnetic dipole (N)
F_n	net vertical force = $(F_{mz} - F_g)$

ACKNOWLEDGMENT

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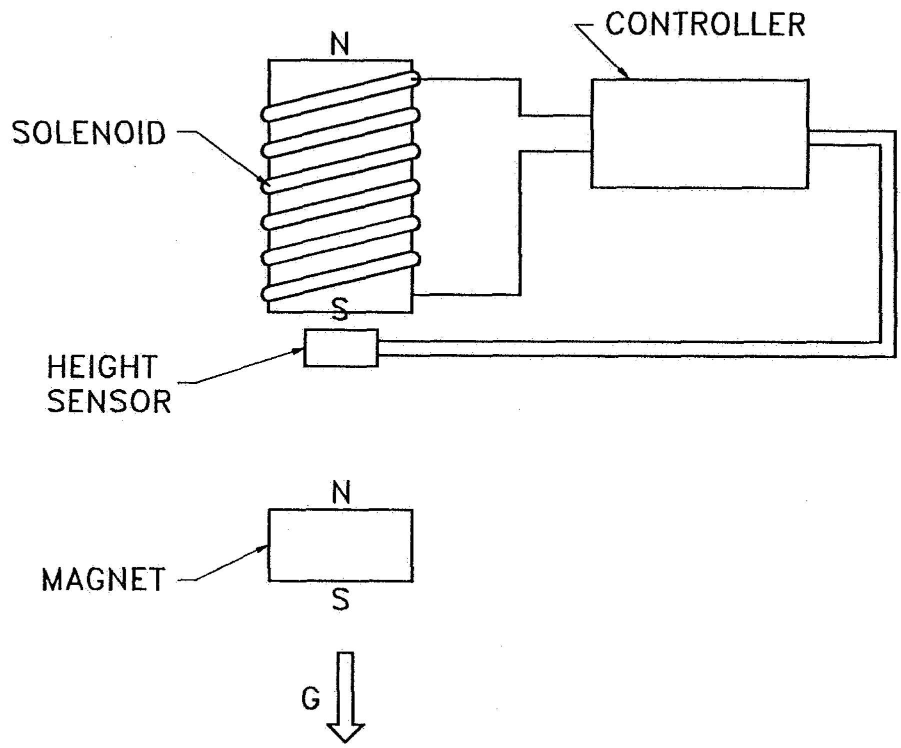

Figure 1. Magnetic levitation by attraction from above in gravity.

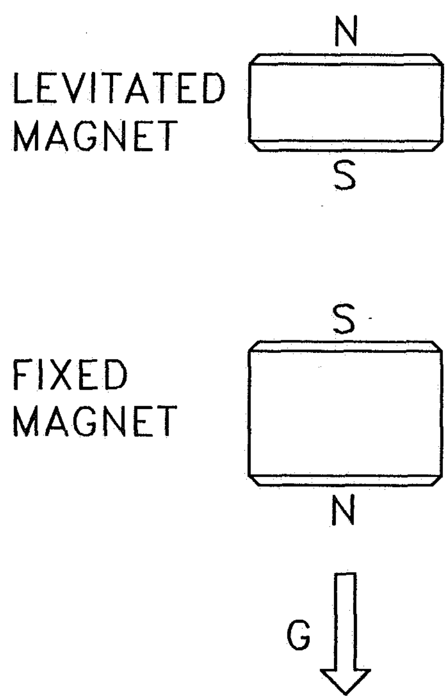

Figure 2 Magnetic levitation by repulsion from below in gravity.

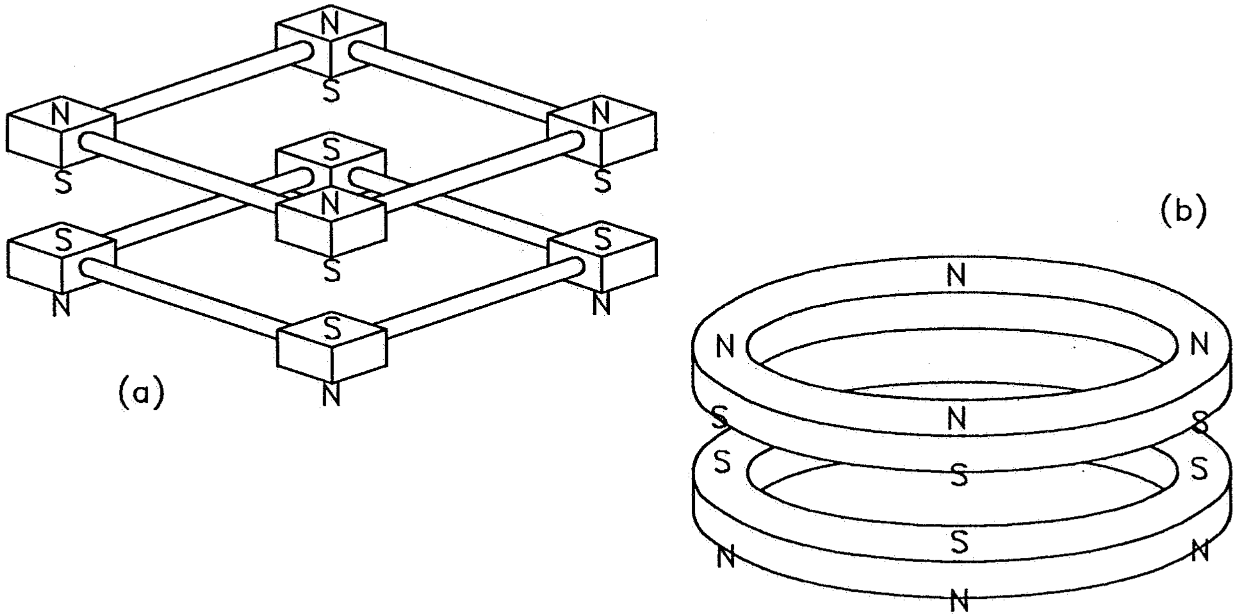

Figure 3 Levitation by repulsion using several magnets in gravity.

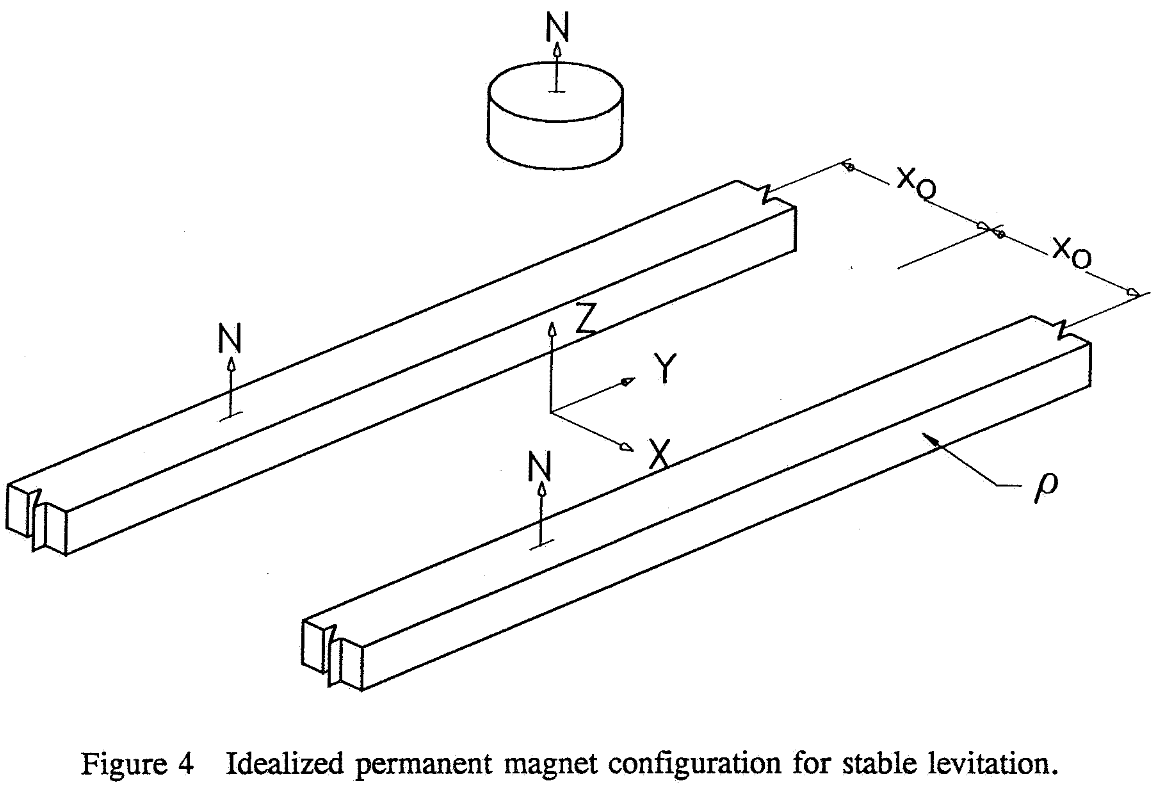

Figure 4 Idealized permanent magnet configuration for stable levitation.

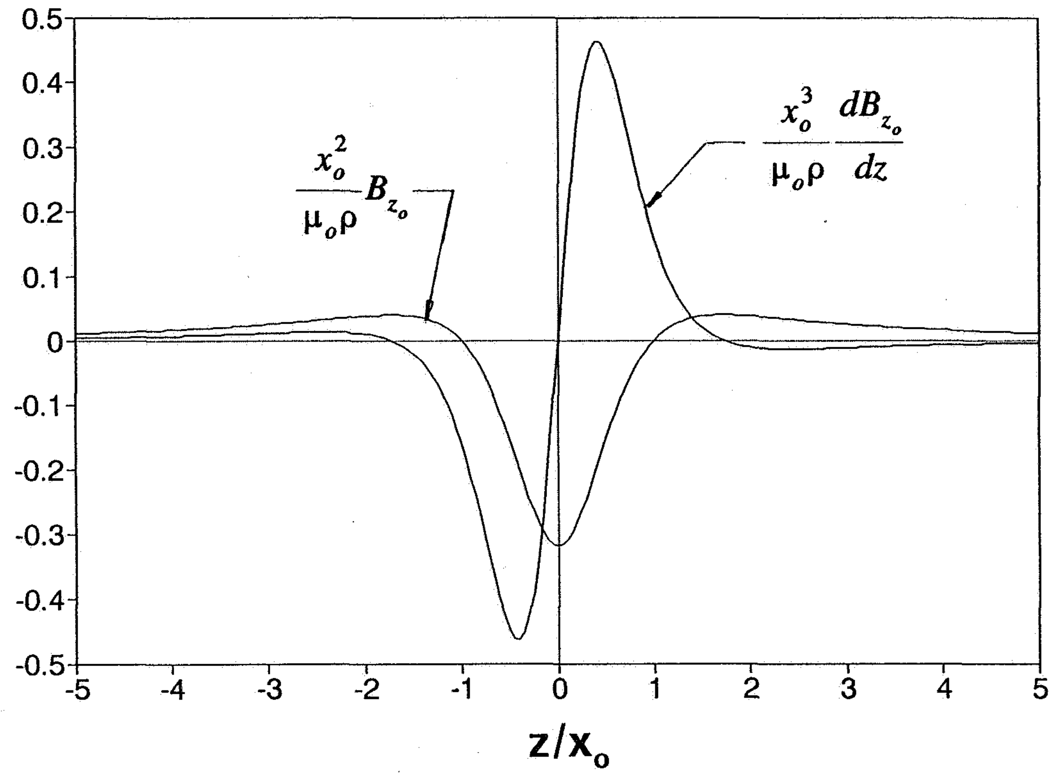

Figure 5 Dimensionless magnetic flux density and density gradient in the vertical (z) direction between two infinitely long horizontal bar magnets spaced $2x_o$ apart.

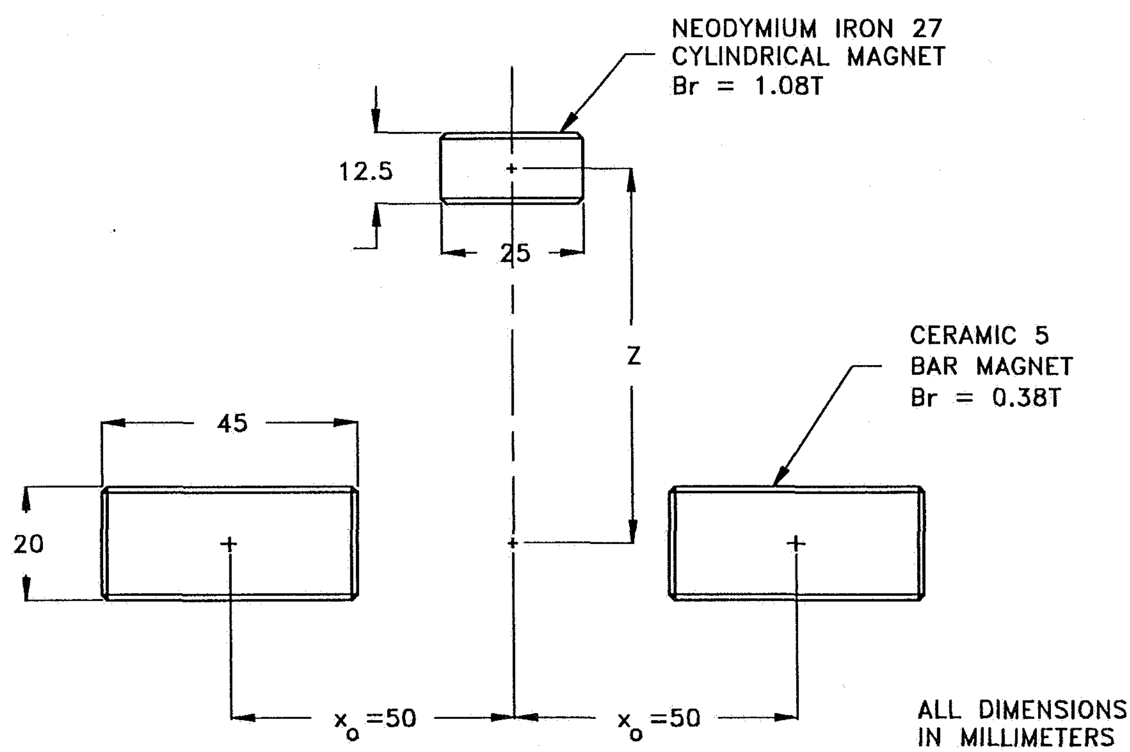

Figure 6 Geometry used for calculating magnetic field strengths.

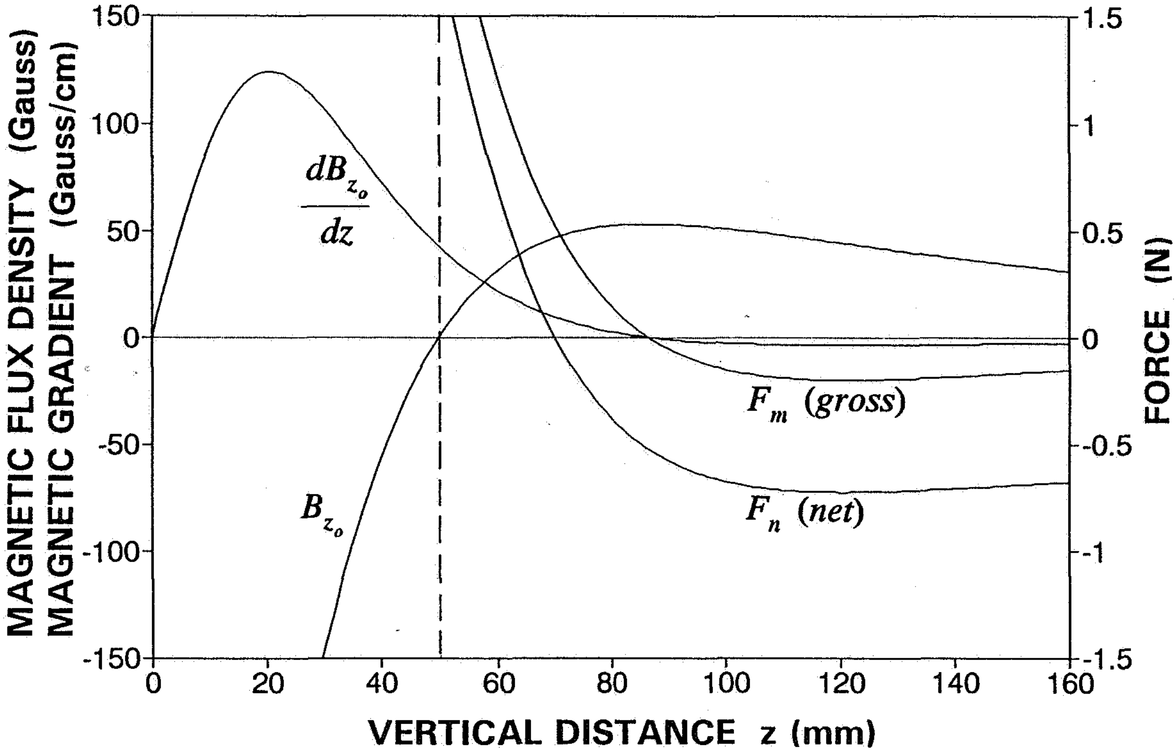

Figure 7 Calculated magnetic flux density and gradient in the vertical direction and the calculated gross and net levitating forces for system geometry shown in Fig. 6. Weight of the cylindrical magnet = 0.5 N.

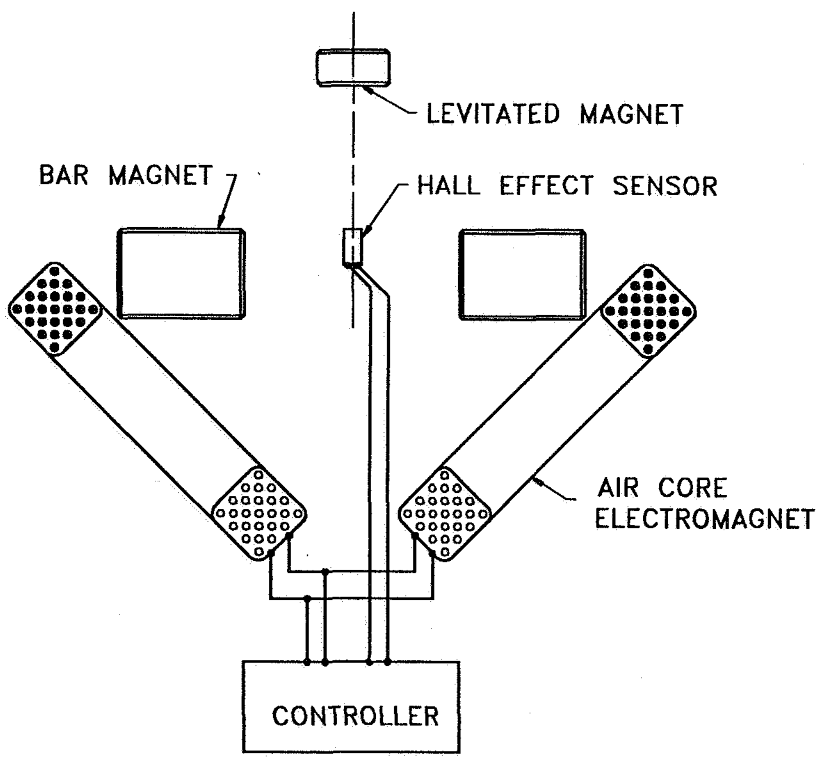

Figure 8 Active magnetic control configuration for the x axis.