Levitation Linear Motors for Precision Positioning

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Keywords: magnetic levitation, linear motor, precision positioning

The author has been active in the development of levitation devices for precision positioning during the last 18 years. Principal among the techniques studied has been the use of two-force or levitation linear motors. By the term levitation linear motor we mean a motor which is capable of creating forces which can be used to independently control translation in two orthogonal directions. These motors have been designed into stages for precision positioning in lithography, scanned probe microscopy, and other precision measurement systems. In such devices, the use of levitation linear motors allows the control of six stage degrees of freedom to nanometer resolution with a single moving part.

This paper presents an overview of the operating principles, electromagnetic configurations, and system level performance of levitation linear motors for precision applications, with connections to the large body of literature in this research area. We classify motion systems with travel under about 10 mm as short-stroke, and devices with travel larger than about 10 mm as long-stroke. Short-stroke multiaxis drives typically use single-pole magnetics, whereas long-stroke devices typically use multipole periodic magnetic structures.

The reason for this is that the magnetic flux return structures for single-pole devices become prohibitively large as the stroke length increases. The paper discusses both classes of levitation systems.

There are a number of physical principles by which levitation motors can operate. These include the main machine types of variable reluctance, electromagnetic induction, and permanent magnet. Of these, for precision positioning, the bulk of practice has utilized permanent magnet devices, with many of these being air-core (pure Lorentz-type) actuators. Some reasons for this preference for permanent magnet devices are presented. Given this predominance, the paper focuses on levitation linear motors of the permanent magnet type.

Short-stroke levitation linear positioners generally use sets of single-force Lorentz actuators (voice coils) configured so as to actuate in multiple degrees of freedom. A ubiquitous example is the compound focus/track actuator for the lens in CD and DVD drives. The actuator for this compound motion is typically a pancake type coil in which the main voice coil used for focus has smaller coils glued onto it which are used for track following. Related short-stroke devices have also been used in robotics and in semiconductor lithography. In these applications, six independent voice coil actuators typically control six degrees of freedom of a suspended short-stroke fine positioning platform. In the lithography application, the platform payload may be a semiconductor wafer or a reticle bearing the master pattern to be imaged.

Long-stroke levitation linear motors typically use periodic magnetic structures. The configuration of such motors is most commonly an iron-free permanent magnet array in the Halbach configuration which is driven by an iron-free multiphase coil set. By properly choosing the phase drive currents, forces in levitation and translation can be controlled. The key physical insight in the design of such levitation linear motors is that coil currents can be located in the spatially varying field of a magnet array so as to provide independently controllable levitation and translation forces. While there are a number of possible magnet array configurations, the four-block Halbach array mounted to a nonmagnetic backing plate is most commonly used.

The paper presents the governing physics of such levitation linear motors, and shows their use in a number of example systems. We also present configurations of levitation linear motors for low stray field environments such as electron beam lithography. The usual planar configuration can also be repackaged in a tubular design. Related stages use levitation linear motors in association with a checkerboard magnet array. Here the levitated stage carries 4 sets of three phase coils which are used to move in the vicinity of an x-y checkerboard magnet array. The 4 sets of coils are used to produce 8 controllable forces to thereby control the six stage degrees of freedom.

In summary, the paper provides a historical overview of the development of magnetically levitated precision positioners, with a focus on those using levitation linear motors. As of 1990 this was a relatively new approach for the precision engineering community, but these types of magnetic suspensions have begun to see wider application. There is a parallel history in the use of linear motors: as little as two decades ago, linear motors were a specialty item, but in the intervening years, their use has become routine. This has been facilitated by advances in capability and by cost reductions in materials and electronics. We can foresee a similar curve coming into play for the application of magnetic levitation techniques, and in particular the use of linear motors to both translate and levitate a moving platform.
Levitation Linear Motors for Precision Positioning

David L. Trumper∗ Non-member

The author has been active in the development of levitation devices for precision positioning during the last 18 years. Principal among the techniques studied has been the use of two-force or levitation linear motors. These motors have been designed into stages for precision positioning in lithography, scanned probe microscopy, and other precision measurement systems. In such devices, the use of levitation linear motors allows the control of six stage degrees of freedom to nanometer resolution with a single moving part.

This paper presents an overview of the operating principles, electromagnetic configurations, and system level performance of levitation linear motors for precision applications. The configuration of such motors is most commonly an iron-free permanent magnet array in the Halbach configuration which is driven by an iron-free multiphase coil set. By properly choosing the phase drive currents, forces in levitation and translation can be controlled. This opens possibilities for novel positioning system configurations and performance capabilities.

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1. Introduction

This paper gives an introduction to levitation linear motors and their application for precision positioning systems. By the term levitation linear motor we mean a motor which is capable of creating forces which can be used to independently control translation in two orthogonal directions.

While there are configurations for capacitive linear motors, the focus of this paper is on magnetic linear devices. The reason for this is that the capacitive duals of magnetic drives are of much lower force density and so are not of direct interest for most macroscopic applications; magnetic drives dominate at the macro-scale. However, capacitive levitation motors may be of greater interest in microscale devices.

In this paper, we classify motion systems with travel under about 10 mm as short-stroke, and devices with travel larger than about 10 mm as long-stroke. Short-stroke multiaxis drives typically use single-pole magnets, whereas long-stroke devices typically use multipole periodic magnetic structures. The reason for this is that the magnetic flux return structures for single-pole devices become prohibitively large as the stroke length increases. The paper discusses both classes of levitation systems.

There are a number of physical principles by which levitation motors can operate. These include the main machine types of variable reluctance, electromagnetic induction, and permanent magnet. Of these, for precision positioning, the bulk of practice has utilized permanent magnet devices, with many of these being air-core (pure Lorentz-type) actuators. Variable reluctance devices tend to have large attraction forces in the axis perpendicular to the main axis of travel. These large spurious forces make levitation problematic and also make it difficult to achieve accurate control along with vibration minimization in a precision machine. The second alternative, electromagnetic induction devices, of necessity dissipate power on the moving platform, which is disadvantageous in a precision machine. Further, it is difficult to control an induction machine to achieve accurately-controlled forces as a function of time, since the machine inherently operates with an AC drive signal on its multiple phases. Balanced machine operation can minimize but not eliminate this AC force signature associated with induction machines. For these reasons this paper concentrates on permanent magnet machines.

For other applications, such as transportation or general manufacturing processes, the alternate motor types are of greater interest. The main type of levitation which has been researched for maglev trains is based upon magnetic induction caused by train-borne superconducting magnets acting upon fixed coils in the track. The most significant current development of this technology is in Japan, at the Yamanashi maglev test track which operates full-size train sets capable of carrying passengers. The Yamanashi test track is the basis for plans for commercializing this technology in revenue service, perhaps within the next decade. In this maglev design, the superconducting magnets also provide field excitation for the linear synchronous motor which drives the train. Permanent magnets cannot achieve the high fields at large air gaps associated with superconducting magnets and thus are not competitive for induced levitation for trains. However, such levitation designs for transportation represent their own specialty, with requirements quite distinct from those for nanometer-level motion control, and so we do not consider these types of motors further in this paper.

Variable reluctance based linear motors have advantages of simplicity and ruggedness of construction and have often been used in general motion systems, typically in association with air bearing support. Levitated versions of such machines can be designed to simultaneously control short-stroke levitation along with long-stroke positioning. A good example is the linear levitated variable reluctance stage designed by Higuchi. However, the large gap-normal forces and small

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air gaps associated with levitated variable reluctance motors lead to fast unstable dynamics in the gap-normal direction and thus they are difficult to precisely control as levitation devices.

Variable reluctance levitation, with integral linear motor drives, is used in the Transrapid maglev train \cite{10} designed in Germany. Here, there is a tradeoff between small gaps which are good for levitation efficiency and associated tight track alignment tolerances, which may lead to expensive maintenance of the guideway. A maglev train using this technology is now operational at the Shanghai airport in China.

The sub-class of permanent magnet flux-steering linear motors referred to as Sawyer motors \cite{7} can be loosely classified with the pure variable-reluctance devices. These motors have been used with air bearings in earlier stages for semiconductor photolithography and in manufacturing applications \cite{8}, for example by the Xynetics corporation, but are not well suited to levitation without air bearing support. The Sawyer motors are also challenging to use for highly precise positioning due to the large offset forces which have high spatial frequencies as the stage is scanned, and so are not considered further herein.

The main sections of this paper now focus on short-stroke and long-stroke levitation linear motors for precision positioning, with the largest emphasis on the long-stroke devices.

2. **Short-stroke Levitation Linear Motors**

Short-stroke levitation linear positioners generally use sets of single-force Lorentz actuators (voice coils) configured so as to actuate in multiple degrees of freedom. A ubiquitous example is the compound focus/track coil for the lens in CD and DVD drives. The actuator for this compound motion is typically a pancake type coil in which the main voice coil used for focus has smaller coils glued onto it which are used for track following. An example of this configuration can be seen in the patent \cite{1}. The configuration of the coil is shown in an image from this patent in Figure 1.

An innovative 6-axis positioner was developed by Hollis at IBM \cite{2}; an image from his patent is shown in Figure 2. Hollis referred to this device as the “Magic Wrist”, and designed it for use as a six-axis robotic end effector. As can be seen in the figure, the wrist consists of six voice-coil actuators configured to control the six suspended degrees of freedom.

Related devices were pioneered for lithography by Dan Galburt \cite{3}. These designs use voice-coil type actuators to levitate in six degrees of freedom a platform carrying a semiconductor wafer. The devices are used to position the wafer during exposure in a lithography machine.

3. **Long-stroke Levitation Linear Motors**

For long-travel levitation linear motion applications, periodic magnetic structures are the norm. Such ideas are developed in the author’s Doctoral thesis research \cite{12} utilizing conventional magnetic arrays interacting with an ironless set of stator coils, and first presented in \cite{13}. Based upon a suggestion of the late Dr. Klaus Halbach, the inventor of the Halbach array, the motor performance was improved by adopting the use of Halbach magnet arrays \cite{5}. The physics of these arrays and their use in levitation linear motors is presented in \cite{14}. Some key results from this paper are summarized below, with some sections adapted directly from \cite{14}.

3.1 **Levitation Linear Motor Physics**

The key physical insight in the design of levitation linear motors is that coil currents can be located in the spatially varying field of a magnet array so as to provide independently controllable levitation and translation forces. For example, consider the four currents (directed into the page) shown below a Halbach array in Figure 3.

While we have shown one particular magnet array in Figure 3, there are a number of magnet array possibilities. Four of these possibilities are shown in Figure 4. In the IAS paper \cite{14} we show that the ideal Halbach array is stronger than the sinusoidal vertical array by a factor of 2, and has zero magnetic field on the back side of the array. Further, the more readily fabricated four block Halbach array has a field within 90% of the ideal Halbach array. For this reason, we have chosen to work with the four block Halbach configuration in the levitation linear motors that we’ve designed. It is also possible to consider more broadly the possible Halbach
configurations with varying horizontal and vertical proportions vis-a-vis conventional iron-based magnet arrays. This motor configuration can be represented by an idealized geometry, as shown in Figure 6, which is suitable for analytical derivation of the motor fields and forces. Here a four block Halbach array is levitated above a multi-periodic surface encoder(41) (42) which are used to measure the stage position.

The magnetization layer is of thickness $\Delta$, and within this layer the magnetization is represented by the Fourier series

$$M = \sum_{n=\pm \infty} \bar{M}_{mn} e^{-jknz} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
3.2 The Flying Puck Stage  The author worked with Doctoral student Won-jong Kim\(^{(30)-(33)}\) on the design of linear motor levitated stages for photolithography. The designed stage is referred to as the Flying Puck, since it consists of a single-part levitated stage, reminiscent of a hockey puck, as shown in Figure 7. This moving stage has four Halbach arrays mounted on its bottom surface. Each of these arrays has an associated stator coil set mounted in the fixed frame; each stator/magnet array set is capable of producing levitation and translation forces as indicated by the arrows in the figure. All levitation forces point in the vertical (z) direction; two of the motor translation forces point in the x-direction, and two of these forces point in the y-direction. This arrangement yields a set of 8 forces which can be coordinated to control all 6 stage degrees of freedom. The stage motion is measured in 3 degrees of freedom (z, \(\theta_x\), and \(\theta_y\)) by capacitance gages and in 3 degrees of freedom (x, y, and \(\theta_z\)) by laser interferometer.

More recently, Kim has continued to study magnetically levitated six-axis positioners. The short-stroke devices reported in (34), (35) use six Lorentz actuators with the coils in the fixed frame and the magnets mounted on the moving stage.

3.3 The Sub-Atomic Measuring Machine (SAMM)  At UNC-Charlotte, Michael Holmes worked with the author\(^{(23)}\), developing an instrument which was called the Angstrom Machine. This device used magnetic suspension to move a platen floated in fluid at neutral bouyancy to provide travel in a cube of 100 \(\mu\)m, with an ultimate positioning noise floor on the order of 50 pm RMS. This stage was used to move a sample under the probe of a scanning tunnelling microscope, and thereby to achieve atomic-resolution images with the stage in suspension\(^{(24)-(26)}\).

This Master’s thesis work demonstrated the utility of combined magnetic/liquid suspension, and led \(^{(27)}\) to the design of a longer-range stage which might be used for precision dimensional measurement of objects such as integrated circuits and photomasks\(^{(28)}\). The stage which was developed is shown in an exploded view in Figure 8. This stage is floated in fluorousilicone oil as was used in the Angstrom Stage, but the stage drives are four levitation linear motors located at the bottom of the chamber as shown in the figure. These four motors drive four corresponding magnet arrays on the levitated stage, utilizing the same physics, and essentially the same configuration as in Kim’s stage discussed above. Thus there are 8 forces to control the six stage degrees of freedom. The advantage of floating the stage in oil is to minimize relative vibration between the stage and housing, and to reduce the power consumption of the linear motors by offloading the platen weight. This configuration is ideally suited to the slow scanning motions of the SAMM stage.

With the linear motor drives, the stage has a working volume of 50 mm by 50 mm in the x-y plane, and travel out of the plane of 100 \(\mu\)m. This makes the stage well-suited to accurate measurements of samples located on the stage. In the first implementation, Holmes used a scanning tunneling microscope for sample feature measurement.

Follow-on work by Dr. Chunhai Wang\(^{(29)}\) and Prof. Robert Hocken replaced the scanning tunneling microscope with a confocal microscope specialized for the measurement of cross-shaped artifacts on a photomask, and this sample was used for intercomparison with measurements taken at the German national standards laboratory (PTB), achieving an agreement on the order of 25 nm. We expect that better agreement can be achieved in the future, with one of the main challenges being standardizing measuring techniques at such high accuracy requirements.

The SAMM stage continues to be operated by Prof. Robert Hocken and his staff at UNC-Charlotte. We are currently planning a refurbishment of the system along with a controller upgrade to replace the original digital signal processing board and interferometer interpolation electronics.
3.4 Levitation Stage Using Checkerboard Magnet Array

Another type of levitation linear motor capable of 6 degree of freedom positioning was developed by John Compter (43). In this work the levitated stage carries 4 sets of three phase coils which are used to move in the vicinity of an x-y checkerboard magnet array. The 4 sets of coils are used to produce 8 controllable forces to thereby control the six stage degrees of freedom. This paper is the first which identifies the parasitic torques associated with the levitation linear motor topology. That is, as the motor is levitated and positioned during a scanning motion, the required levitation currents also can produce torques about vectors lying in the plane of the motor. These undesired torques become important in a device intended for rapid positioning and settling tasks, as they form a disturbance on the stage angular position; the larger the drive forces, the larger these torques become. The use of such stages in manufacturing and photolithography applications is presented in the patent (44).

3.5 Extreme UV Lithography Stage

Dr. Mark Williams started working with the author at UNC-Charlotte, moved with the author to MIT, and completed his Doctorate at MIT in 1998 (15). His thesis considered the design of precision stages for photolithography (16), including the use of Halbach array based motors of designs such as those discussed above. An example of the types of stages he designed can be found in the patent (17).

Following the completion of his Ph.D., Dr. Williams began working on a stage for use in vacuum for motions of the wafer and reticle in Extreme Ultraviolet Lithography (EUVL). The stage design which was used in the EUVL system is documented in (18); a drawing from this patent is shown in Figure 9. In this figure, the lower stage 10 is of a conventional design driven by a ball screw 28 and motor 78. The stage rides on four rolling-element linear guides to effect motion in the x-direction. This lower stage is in the shape of a beam oriented in the y-direction. The cable feeds to the lower stage can be seen as the loop at the left end of the beam. The upper (y-travel) stage is magnetically levitated off this beam with variable reluctance actuators mounted on the towers seen descending at the corners of the stage. The steel rails for these magnetic levitation actuators are mounted in the slots visible on the near edge of the beam, and in similar slots on the far edge of the beam. The upper stage is driven in the y-direction by a linear motor with coils 22 fixed in the beam, and a Halbach magnet array fixed to the bottom of the stage. Although this motor in the EUVL stage is capable of levitation forces, since levitation is handled by conventional variable reluctance magnetic bearings, the motor is driven for pure translation forces by choice of the commutation laws. The cable feed 34 to the levitated stage is managed by a secondary carriage which rides on linear guides 32. The secondary carriage has its own magnet array which is driven by separately controlling sections of the linear motor coils 22. A purely linear motor levitated stage designed by Dr. Williams is described in the patent (19). The stage and stator assembly for this machine are shown in Figures 10 and 11. As shown in Figure 10, the bottom of the stage has three magnet array sets 36 a,b,c. Further the sides of the stage each have corresponding magnet array sets 36 d,e. Each of these magnet arrays interacts with a corresponding linear motor stator 70 a, b, c, d, e to provide scanning and levitation forces. Taken in sets, the linear motors all contribute to the x-directed main scanning motion, and to the control of the other 5 degrees of freedom of the levitated stage. The stators have provisions electrical connections and for water cooling, via the connectors shown at the end of each stator.

3.6 Low Stray-field Levitation Linear Motors

Paul Konkola’s Master’s thesis work (36-38) focused on the principle that since the motor far-field magnetic stray is dominated by the lowest order multipole in the array field expansion, low...
stray fields at a given distance are best achieved by eliminat-
ing the lowest-order multipoles from the array field. Such
cancellation was achieved by superposition of multipoles in
successive segments of the magnetic array. The resulting
magnet array appears as shown in Figure 12.

Because rare earth permanent magnets with magnetization
density $M$ can be modeled as an equivalent lateral surface
current on the order of $10^6$ A/m via $J_{eq} = \nabla \times M$, they are
far more important in a stray field sense than typical air core
motor windings, which might have an equivalent surface cur-
rent an order of magnitude or more smaller. Nonetheless, the
stray field from the stator coils needs to be considered as part
of minimizing the total motor stray flux. Konkola’s motor de-
sign terminated the stator with half current-density windings at
each end in order to reduce the far-field effect.

Konkola’s design calculations indicate that it should be
possible to achieve lower than $2 \times 10^{-7}$ T stray field at a dis-
tance of 150 mm from the motor air-gap plane. This stray
field would be compatible with electron beam lithography re-
quirements. Experimentally-measured stray fields are about
a factor of 10 larger; this discrepancy is believed to be primar-
ily due to dimensional and magnetization angle tolerances in
the permanent magnet blocks.

3.7 Tubular Linear Motors

Halbach arrays can also be configured as a cylinder, as shown in Figure 13 which is
taken from (14). A tubular linear motor utilizing such a cylin-
drical Halbach array was developed by Berhan in his Master’s thesis (20) and further reported in (21). This tubular motor
utilized annular coils in the fixed frame wound on an alu-
minum cylinder, and an interior Halbach cylindrical magnet
array moving on the driven stage. It is also possible to de-
sign a levitation linear motor in this configuration where the
stator coils are broken up into three circumferential segments
and are thereby capable of providing forces in the two lateral
dimensions in addition to the main axial thrust.

4. Conclusions

This paper has provided a historical overview of the de-
velopment of a number of magnetically levitated precision
positioners, with a focus on those using levitation linear mo-
tors. As of 1990 this was a new approach for the precision
engineering community, but these types of magnetic suspen-
sions have begun to see wider application. There is a parallel
history in the use of linear motors: as little as two decades
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vening years, their use has become routine. This has been
facilitated by advances in capability and by cost reductions
in materials and electronics. One can forsee a similar curve
coming into play for the application of magnetic levitation
techniques, and in particular the use of linear motors to both
translate and levitate a moving platform.

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David L. Trumper (Non-member) joined the MIT Department of Mechanical Engineering in August 1993, and holds the rank of Professor. He received the B.S., M.S., and Ph.D. degrees from MIT in Electrical Engineering and Computer Science, in 1980, 1984, and 1990, respectively. He is a member of the IEEE, ASME, and ASPE (currently serving as President of ASPE), is an Associate Editor of Precision Engineering, and is a Corresponding Member of CIRP.